Impact of fire exposure on the rebar-concrete bond strength

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Abstract

Structural fire resistance is a primary aspect of a passive fire engineering design measure that allows a structure to withstand intense fires. Generally, concrete structural elements perform well under these conditions due to their non-flammable nature. However, fire incidents require a deeper understanding of concrete behavior and structural mechanics to improve fire design. Structural elements exposed to fire and heat show reduced strength; this reduction must be evaluated to determine whether to demolish or repair a building based on its condition and capability to support future loads.

Evaluating the post-fire strength characteristics, including compressive, tensile, and bond strengths, is essential for determining the structure's safety. Prolonged exposure to high temperatures can degrade concrete properties, particularly the bond strength between rebar and concrete. This paper investigates the bond strength of materials after exposure to fire. The study explores the effects of temperatures ranging from 20 °C to 500 °C, following the ISO 834 fire curve, on compressive, tensile, and bond strengths. Cylindrical pull-out specimens were heated to specific temperatures and held for 2 hours. Afterward, they were cooled for one day before testing. The results indicate that bond strength decreases by approximately 72% at 500 °C, about twice the reduction observed in compressive and tensile strengths.

Keywords: bond, elevated temperature, pullout test, residual bond strength
Kulcsszavak: tapadás, magas hőmérséklet, kihúzóvizsgálat, maradó tapadószilárdság

1. Introduction

Structural fire resistance is a key aspect of fire safety, often regarded as a passive measure that allows a structure to withstand intense fires [1]. Concrete performs well in fire due to its incombustibility, but real-fire scenarios emphasize the need for a deeper understanding of concrete behavior and structural mechanics to improve fire design in reinforced concrete structures [2].

The bond between rebar and concrete is formed through adhesion, mechanical interlock, and friction [3]. Bond-mechanism, ensures that reinforced concrete acts as a composite material. Under normal temperatures, factors affecting bond strength are well understood, but quantifying their effects remains an active research area. Material properties, such as concrete strength, aggregate type, admixtures, and testing methods, significantly influence bond performance [4, 5].

Bond evaluation becomes more complex at elevated temperatures as the heating becomes dominant; the physical properties of concrete undergo significant changes due to temperature gradients [6]. Fire causes heat to penetrate the concrete, raising its temperature and leading to thermal expansion, moisture evaporation, pore pressure buildup, and mechanical property degradation [7]. This effect weakens the rebar-concrete bond [8], leading to endangering of the overall structural integrity. Structural engineering thus, must ensure these factors do not affect the structure's primary functions [7].

2. Literature review

Morley and Royle's [9] tested the four conditions of the stabilized temperature procedure, these tests indicate that specimens subjected to stress during the heating cycle demonstrate slightly greater strength than those not stressed, as shown in *Fig. 1*. Diederichs and Schneider [5] studied the impact of bar surface properties using plain rebar and two types of deformed bars. Their tests revealed significant bond strength deterioration in all specimens. Additionally, the tests showed that deformed rebar followed similar temperature-bond relationships as plain rebar but with improved performance, as shown in *Fig. 2*. The results also indicated that corroded plain rebar outperformed new, as-rolled rebar.

Haddad *et al.* created specimens with plain and fiber-reinforced concrete using three fiber types. Below 600 °C, fibers improved residual bond strength by preventing crack propagation and spalling. The best performance was seen in concrete with only Hooked Steel fibers, followed by a mix of hooked steel and brass-coated steel fibers, hooked steel and polypropylene, and Brass-coated steel fibers alone [10].

Xiao *et al.* studied specimens with high-strength rebar and concrete, finding a significant bond decline and increased peak slip beyond 400 °C [11]. Haddad and Shannis, using high-strength concrete with pozzolanic material replacing 10%, 15%, and 25% of cement, observed bond deterioration at 600 °C and 800 °C — up to 24% at 600 °C and 74% at 800 °C. However, using up to 25% natural pozzolana at temperatures up to 60 °C improved crack resistance and maintained bond strength without adverse effects [12].

Sharma *et al.* proposed a linear model based on test results to estimate the reduction in residual bond strength of normal-strength concrete at elevated temperatures [13]. Ergün *et al.* developed mathematical equations that focus on the impact of rebar properties, considering different steel grades (S220a, S420a, S500a) [14]. Haddad *et al.* created an empirical model for high-strength concrete, examining the effects of various fiber types in the mix, including plain concrete, steel fibers (brass-coated or hooked), and high-modulus polypropylene fibers [10].

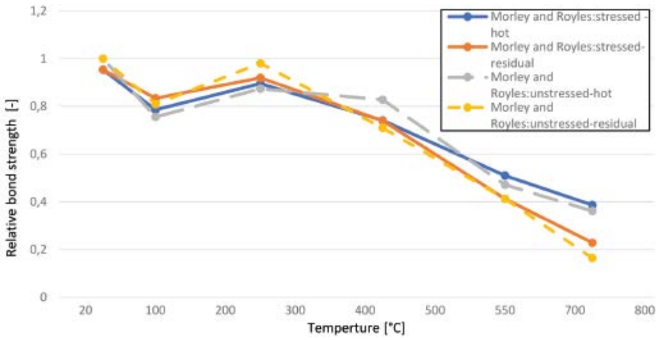

Fig. 1 *Relative bond strength response to elevated temperatures using the stabilized temperature method according to Morley and Royle's [9]*
1. ábra *A relatív tapadószilárdság alakulása emelkedett hőmérsékleten a Morley és Royle [9] által alkalmazott stabilizált hőmérséklet módszer szerint*

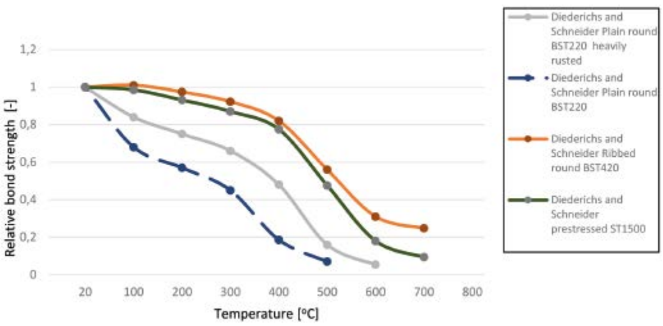

Fig. 2 *Influence of rebar rib characteristics on residual relative bond strength at elevated temperature [5]*
2. ábra *A betonacél bordáinak jellemzőinek hatása a magas hőmérsékleten maradó relatív tapadószilárdságra [5]*

3. Experimental program

The authors conducted an experimental study to examine the impact of high temperatures on bond, tensile, and compressive properties. The oven depicted in *Fig. 3* was used, and the ISO 834 fire curve in *Fig. 4* was followed. The temperature range varied from 20 °C to 500 °C.

Fig. 3 *Oven during the heating stage*
3. ábra *Kemence a felfűtési szakaszban*

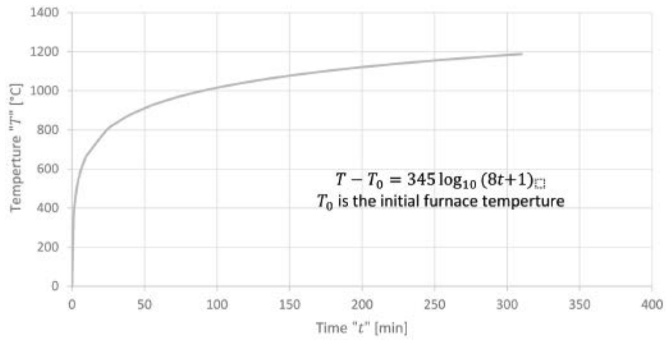

Fig. 4 *Heating rates adopted according to ISO 834 standard fire curve*
4. ábra *Az ISO 834 szabvány szerinti tűzgörbéhez alkalmazott felfűtés*

3.1 Concrete mixture

The mix compositions are given in *Table 1*. Type CEM I cement was adopted, quartz sand and gravel aggregate were used.

Material	Type	Mass, kg/m³
Aggregate	0/4 mm	780
	4/8 mm	372
	8/16 mm	706
Cement	CEM I 52.5	350
Water	-	175

Table 1 *The concrete mixes.*
1. táblázat *Beton összetételek*

3.2 Test setup

Cylindrical pull-out specimens with a diameter of 120 mm and a height of 100 mm were prepared. The cylindrical shape allowed for uniform stress distribution during testing and consistent heating throughout the thermal cycles. The bonded length was 40 mm, while the unbonded length on both sides was 30 mm. Ribbed steel bars with a 12 mm diameter were used, and slip was measured with three linear variable differential transformers (LVDTs) at the loaded end of the bar, along with one LVDT at the free end. An automatic data acquisition system was used to record the data transmitted by the LVDTs. Details of the pull-out tests are shown in *Fig. 5*.

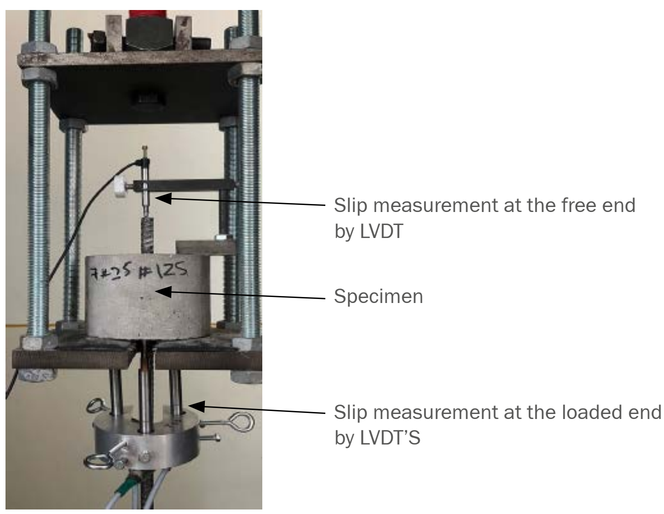

Fig. 5 *Test setup*
5. ábra *Kísérleti elrendezés*

3.3 Heating procedure

After demolding the specimens one-day post-casting, they were immersed in water for six days. On the test day, the specimens were heated to different temperatures (20 °C, 150 °C, 300 °C, 500 °C) and maintained at each temperature for two hours. After heating, the specimens were gradually cooled to laboratory temperature over one day. Subsequently, compressive strength on cylinder specimens was measured using a concrete compression testing machine, tensile strength was measured using the three-point flexural test, and pull-out tests were conducted.

4. Test results

4.1 Compressive strength

Compressive strength was measured after heating on 200x100 mm cylindrical specimens, as shown in *Fig. 6*. *Table 2* and *Fig. 7* show the measured compressive strength values and the relative residual compressive strength (the compressive strength ratio after heating to the compressive strength at 20 °C) of the concrete specimens as a function of the maximum temperature. At 500 °C, the deterioration reached 33%, exhibiting a nearly linear decline across the temperature range tested.

Fig. 6 *Compression strength test*
6. ábra *Nyomószilárdság vizsgálat*

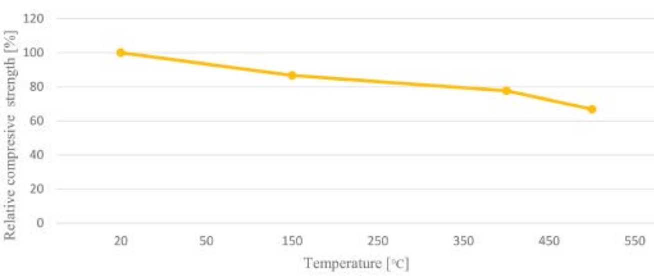

Fig. 7 *Residual compressive strength at elevated temperature*
7. ábra *Maradó nyomószilárdság magas hőmérsékleten*

Temperature	20 °C	150 °C	400 °C	500 °C
Compressive strength (N/mm²)	53.95	46.74	41.90	36.06*
Residual compressive strength [%]	100.00	86.63	77.66	66.83
Tensile strength (N/mm²)	6.15	5.75	5.05	4.14
Residual tensile strength [%]	100.00	93.49	82.11	67.38
Bond strength (N/mm²)	20.97	20.88	10.42	5.92
Residual bond strength [%]	100.00	99.57	49.69	28.23

**The average of two specimens was taken as one of the specimens spalled.*

Table 2 *Measured strength at elevated temperature*
2. táblázat *Mért szilárdság magas hőmérsékleten*

4.2 Tensile strength

Tensile strength was measured after the heating procedure on 70x70x250 mm prism specimens, as shown in *Fig. 8*. *Table 2* and *Fig. 9* display the measured tensile strength values and the relative residual tensile strength (the ratio of tensile strength after heating to tensile strength at 20 °C). At 500 °C, the deterioration of the tensile strength reached 33%.

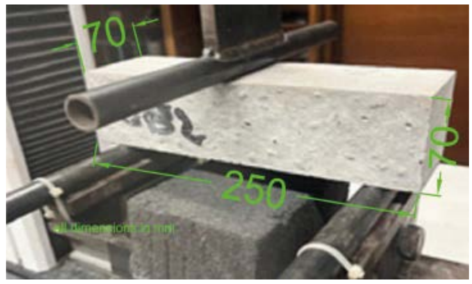

Fig. 8 *Flexural-tensile strength test*
8. ábra *Hajlító-húzószilárdság-vizsgálat*

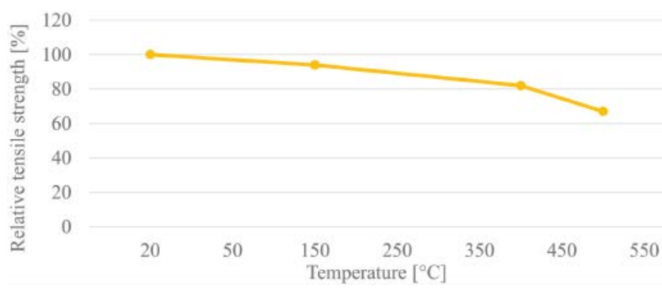

Fig. 9 *Residual tensile strength at elevated temperature*
9. ábra *Maradó szakítószilárdság emelt hőmérsékleten*

4.3 Bond strength

Bond strength was measured after the heating procedure on 120x100 mm cylindrical specimens, all exhibiting splitting failure, as shown in *Fig. 10*.

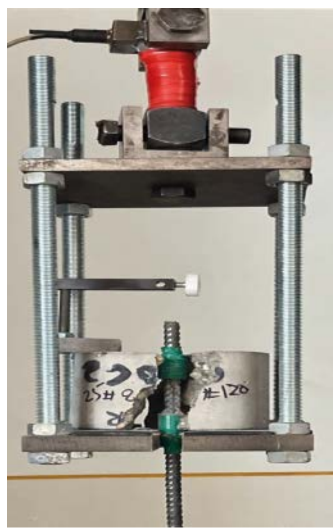

Fig. 10 *Splitting failure of pullout cylinder specimen*
10. ábra *Hengeres próbatest hasadási tönkremenetele kihúzó vizsgálatnál*

Since the bond length is less than 5 d_s, the applied load, F, was converted to average bond stress, τ_b the bonded length using the uniform bond stress approach as follows:

$$\tau_b = \frac{F}{\pi d_s l_b}$$

Where:
F is the applied tensile force on the rebar,
d_s is the diameter of the rebar, and
l_b is the bonded length, which is 40 mm in the present study.

Table 2 and *Fig. 11* display the measured bond strength values and the relative residual bond strength (the ratio of bond strength after heating to bond strength at 20 °C); at 500 °C, the deterioration of the bond strength reached approximately 72%.

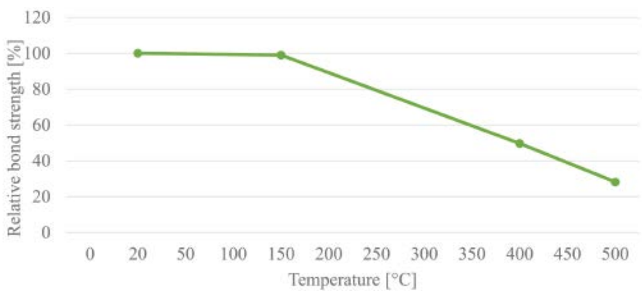

Fig. 11 Residual bond strength at elevated temperature
11. ábra Maradó tapadószilárdság magas hőmérsékleten

The following bilinear equation describes the degradation of bond strength:

$$Residual\ bond\ strength = \begin{cases} -0.0033 \cdot T + 100.066 \ if \ T \leq 150°C \\ -0.2039 \cdot T + 130.155 \ if \ 150°C < T \leqq 500°C \end{cases}$$

4.4 Bond-slip curve at elevated temperature

The stress-slip relationships for the pull-out failure mode and splitting failure are illustrated in *Fig. 12.* As depicted in *Fig. 12,* elevated temperatures cause deterioration of bond strength, resulting in a reduction in the ascending branch.

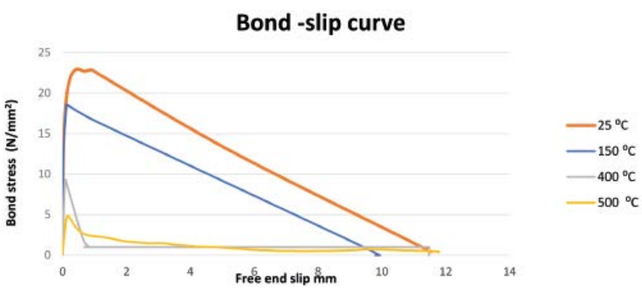

Fig. 12 Bond-slip curve at elevated temperatures
12. ábra Tapadás–csúszás görbe magas hőmérsékleten

5. Conclusion

This paper examines the effects of rising temperatures according to the ISO 843 standard fire curve, focusing on a temperature range between 25 °C and 500 °C. We investigated the impact on bond, compressive, and tensile strength using pullout, cylinder tests, and prism specimens. After heating the specimens and maintaining the target temperature for 2 hours, all tests were conducted in their residual state after a cooling period of one day. Based on our findings, we can conclude that:

I. As the temperature rises, the compressive, tensile, and bond strengths decrease across all examined temperatures. However, the decline in bond strength becomes more pronounced than the reduction in compressive and tensile strengths at temperatures of 400 °C and above.

II. At 500 °C, the deterioration of compressive strength reached 33%, exhibiting a linear decline across the temperature range tested.

III. At 500 °C, the deterioration of the tensile strength reached 33%.

IV. Half of the bond capacity was degraded when the temperature reached 400 °C.

V. The residual bond strength at 500 °C is approximately 28.23% of the reference capacity under laboratory conditions. The bond showed a significant decline of around 72%, twice the deterioration observed in tensile and compressive strength at elevated temperatures.

VI. The degradation of bond strength can be expressed using the following equations:

$$Residual\ bond\ strength = \begin{cases} -0.0033 \cdot T + 100.066 \ if \ T \leq 150°C \\ -0.2039 \cdot T + 130.155 \ if \ 150°C < T \leqq 500°C \end{cases}$$

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