A REVIEW OF EXPERIMENTAL FACTORS INFLUENCING BOND STRENGTH AT ELEVATED TEMPERATURES


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After a fire, engineers must determine if a building should be demolished or repaired based on its condition and ability to support future loads. Evaluating the structure's strength post-fire is essential. High temperatures can degrade concrete properties—such as compressive and tensile strength, and the bond between rebar and concrete. These properties are vital for assessing the building's safety and design. Evaluating bond strength at elevated temperatures is complex, as the heating procedure, heating rate, and cooling process influence the bond after exposure to fire. Although researchers recognize these factors, the extent of their impact remains a topic of debate. After a fire, researchers typically evaluate residual bond strength using pullout and beam tests to assess material deterioration. This measurement is expressed as the ratio of bond strength at high temperatures (ranging from 20 °C to 800 °C) to the bond strength at ambient temperature, which is usually around 20 °C.

This paper reviews the literature on bond strength at elevated temperatures, investigating the factors that affect this strength. It discusses the bond-slip curve and the impact of different experimental variables, including the heating procedure, rate and duration, cooling method, rebar properties, specimen characteristics, and the residual bond strength following high-temperature exposure.

Keywords: bond, elevated temperature, pull-out test, beam test, residual bond strength

1. INTRODUCTION

The bond between rebar (reinforcing steel) and concrete refers to the adhesion and mechanical interlock between the two materials, which allow force transfer between the two materials. This mechanism enables reinforced concrete to act as composite materials to resist applied loads. As a result of this bond, the forces in the steel and concrete change along the length of the rebar, leading to different strains in the two materials and causing relative displacement, known as slip (*fib* Bulletin No. 10, 2000). This mechanism ensures satisfactory structural performance of concrete elements, allowing for ductile failure with adequate warning (Morley, and Royles, 1980).

Factors influencing bond strength are known under normal conditions, but measuring their effects remains a topic of ongoing research. Material characteristics—like concrete strength, aggregate type, and admixtures—along with testing methods significantly affect bond strength performance (ACI Committee 408,2003; Diederichs and Schneider, 1981). At high temperatures, the physical properties of concrete change significantly (Abuhishmeh etal.,2024), which weakens the bond between the concrete and the reinforcing rebar (Lublóy and Hlavička, 2017), affecting the structural behavior and compromising the overall structural integrity.

This review paper examines the effects of elevated temperatures on the bond between rebar and concrete, exploring the bond degradation and studying the factors that impact bond strength under thermal stress. Understanding this behavior ensures buildings' safety and durability in extreme thermal conditions.

2. CHARACTERIZING BOND-SLIP BEHAVIOR AT ELEVATED TEMPERATURES

Bond test samples can fail in two ways: pullout failure and splitting failure, unless the rebar fails. The *fib* model code 2010 represents these modes in *Figure 1* as the bond-slip curve, summarized in the following equations.:

$$\tau_b = \tau_{bmax}\left(\frac{s}{s_1}\right)^{\propto} \; for\ 0 \le s \le s_1 \quad (1)$$

$$\tau_b = \tau_{b\,max} \; for\ s_1 < s \le s_2 \quad (2)$$

$$\tau_b = \tau_{b\,max} - \left(\tau_{bmax} - \tau_{bf}\right)\left(\frac{s-s_2}{s_3-s_2}\right) \quad for\ s_2 \le s \le s_3 \quad (3)$$

$$\tau_b = \tau_{bf} \; for\ s_3 \le s \quad (4)$$

where

τ_{bmax} = *maximum bond stress*

s = slip

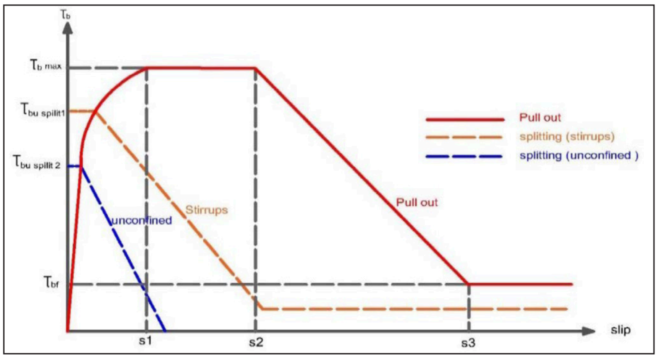


Figure 1: Fib model for Bond-Slip curve (The fib Model Code 2010).

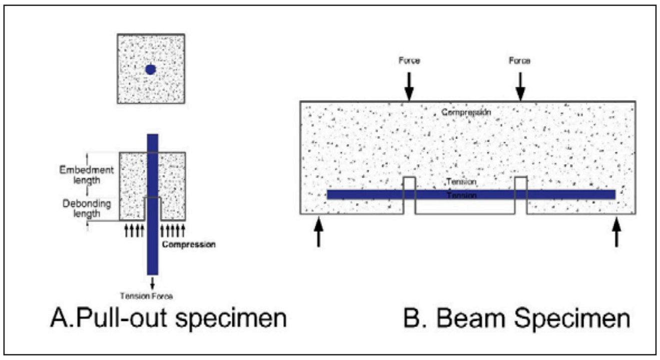


Figure 2: Shapes of specimens for bond strength testing.

The bond strength deteriorates at elevated temperatures, leading to a flattening and nonlinearity of the bond stress-slip curve. Scholars have suggested modifications to the *fib* bond-slip model (*fib* Model Code, 2010) to account for the effects of temperature, such as those proposed by (Lublóy and Hlavička, 2017) and (Aslan and Samali, 2013); these modifications are shown in *Table (1)*. These modifications involve revised formulas for the local bond stress–slip relationship, which depends on the temperature to which the specimen is exposed, the type of aggregate, and the concrete's strength classification (high or low).

3. EFFECT OF EXPERIMENTAL VARIABLES ON BOND STRENGTH UNDER HIGH TEMPERATURES

3.1. Characteristics of the Specimen

Research commonly divides Bond strength specimens into two main categories: direct pullout and beam tests (Zheng etal., 2023), as shown in *Figure 2*. Typically, pullout test specimens are either prisms or cylinders. Several studies (Sharmaa etal., 2019; Muciaccia and Consiglio, 2021; Banoth and Agarwal, 2020; Lublóy and Hlavička, 2017) have investigated pullout specimens under elevated temperatures, while other researchers have used beam specimens for bond tests such as (Ghazaly etal., 2018; Xiao etal., 2014; Ghajari and Yousefpour, 2023; Bošnjak etal., 2018) , with preference in terms of behavior to beam specimens, as it replicates stress conditions found in actual structures in contrast to pullout tests (Das etal., 2023). In a pullout test, the concrete is subjected to compression, while the rebar experiences tension; however, in actual structures, both components are in tension. This difference results in variations in the bond strength evaluation under both normal and elevated temperatures, which limits the practical applicability of models based on pullout tests. Therefore, it is essential to establish correlations between pullout test results and structural performance (Cairns and

Table 1: Modified fib Model Parameters at Elevated Temperatures

Variables	Lublóy and Hlavička, 2017					Aslan and Samali, 2013	
Aggregate type	quartz confined		quartz and expanded clay confined			-	-
Type of concrete	HSC		HSC			HSC	NSC
Temperature range °C	20 -400	400 - 800	20 -500	500 - 700	>800	100-800	
s_1 mm	1.00		1.00			0.5	1
s_2 mm	3.00		3.00			2	3
s_3 mm	CR		CR			CR	CR
∝	0.4		0.4			∝	∝
$\tau_{b\,\max}$	$2.5 f_{ck}{}^{0.5}$	$f_{ck}{}^{0.4}$	$2.0 f_{ck}{}^{0.5}$	$f_{ck}{}^{0.4}$	0	$\frac{\tau_{b\,\max.T}}{\tau_{b\,20}} =$ $\mathbf{1.0538}\left(\frac{f'_{cT}}{f'_{c}}\right) - \mathbf{0.0255} \quad \mathbf{30\ mm} < l_b \leq \mathbf{100}$ f'_{cT} ***has diiferent equations for HSC and NSC*** $\tau_{b\,\max.T}$ *varies for different embedment lengths (l_b).*	
τ_{bf}	$f_{ck}{}^{0.5}$	-	$f_{ck}{}^{0.5}$	-	-	$0.4\tau_{b\,\max.T}$	$0.4\tau_{b\,\max.T}$

Remark: CR: clear distance spacing between ribs

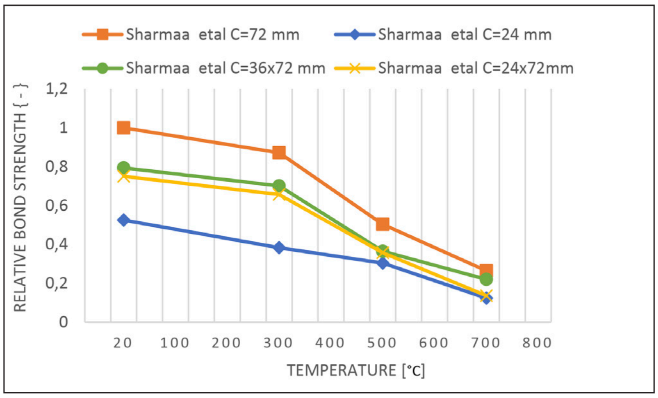


Figure 3: Residual bond strength (Sharmaa et al. to reference bond strength with c=72) as a function of temperature

Abdullah, 1995). Furthermore, new studies are needed to analyze bond behavior in beam specimens.

3.2. Influence of concrete cover on bond strength specimens

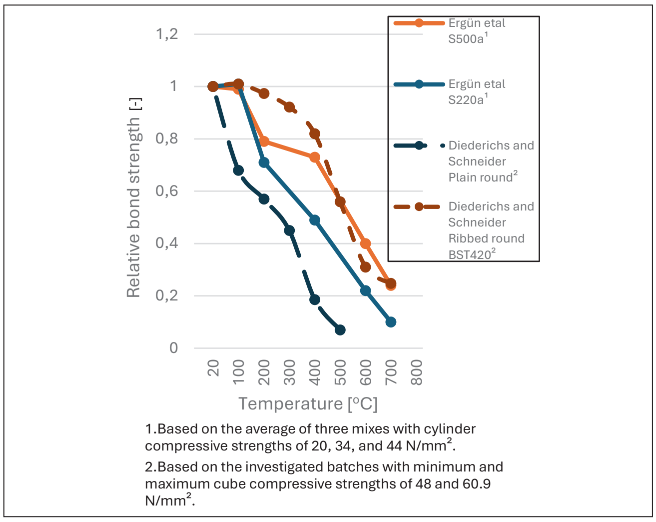
Experiments conducted on concrete specimens with varying cover sizes at different temperatures show that larger concrete covers are more likely to fail through pull-out. This failure happens because the concrete in direct contact with the rib experiences compressive stress; in contrast, specimens with smaller concrete covers tend to fail due to tensile splitting (Sharmaa etal., 2019; Muciaccia and Consiglio, 2021; Morley and Royles, 1983).

The study by (Sharmaa etal., 2019) , which is depicted in *Figure 3,* demonstrates that both maximum and minimum cover sizes of prism samples significantly impact bond strength. Larger cover sizes result in higher bond strength; this effect is maintained at both ambient and elevated temperatures. However, the bond strength enhancement due to larger cover becomes less pronounced at higher temperatures, particularly at 500 °C and 700 °C. Because the strength and stiffness of the concrete decline with temperature increases.

3.3 Influence of rebar properties on bond strength at elevated temperature

Diederichs and Schneider (1981) investigated the influence of bar surface properties using plain rebar and two types of

Figure 4: Influence of rebar rib characteristics on residual bond strength at elevated temperature



deformed bars; the tests showed a significant deterioration in bond strength for the specimens. Also, the tests they conducted, as well as tests by (Ergün etal., 2016), demonstrated that deformed rebars exhibited temperature-bond relationships like those of plain rebars. However, in both studies, deformed rebars performed better than plain rebars, as illustrated in *Figure 4*. (Hertz, 1982) investigated how bar diameter affects bond strength degradation in pull-out specimens subjected to elevated temperatures. The conclusion was that when the temperature rose to 500 °C, the diameter of the rebar had a relatively small impact on the degradation of bond strength. A recent study by (Muciaccia and Consiglio, 2021) examined samples with four and eight-diameter embedment lengths using a constant force method. The findings revealed no significant difference in bond strength for specimens featuring centered bars. The difference occurred when the rebar was positioned at the edge or side and diminished when evaluating bond strength as a function of temperature .

3.4 Impact of thermal treatment on bond strength

Bond strength is influenced by the testing procedures used. To evaluate the effect of temperature on bond strength, as shown in *Figure 5,* researchers typically use two primary methods: the stabilized temperature procedure and the constant load procedure (Diederichs and Schneider, 1981; Muciaccia and Consiglio, 2021). The stabilized temperature procedure includes different stress scenarios based on whether the specimen is stressed during heating and its temperature state (hot or cold) during testing, leading to four unique testing scenarios with different impacts on bond strength, as shown in *Figure 5;* Morley and Royle's tested the four conditions shown in *Figure (6)*, the result indicate that specimens subjected to stress during the heating cycle demonstrate slightly greater strength than those not stressed (Royles and Morley, 1983). This increased strength is primarily attributed to the confinement provided by the loading. In the constant load procedure, specimens are continuously loaded while heated until failure occurs. The constant load procedure is essential for evaluating a structure's capacity to bear its weight during a fire (Muciaccia and Consiglio, 2021). Muciaccia and Consiglio analyzed the two procedures; again, the findings revealed that the reduction in bond strength is more pronounced during the constant load procedure (Muciaccia and Consiglio, 2021).

A rapid rate or slow heating rate can be adopted depending on experiment requirements; the rapid rate can be adopted using the ISO standard fire curve to simulate the behavior of fire in practice (ISO 843, 2019); also, a slow rate can be used in the experiment; this will eliminate the resulting stress from the different movement between the hot outer surface and the colder core of the specimen, and as a result, this test procedure will isolate and demonstrate the effect of temperature on bond strength alone (Morley and Royles, 1980).

(Banoth and Agarwal, 2020) measured bond strength using two methods: one with a slow heating rate of 2 °C/min and another with a fast-heating rate, following the standard of ISO 834 to reach the required temperature. There was a substantial decrease in bond strength for the samples that were heated faster. This indicates that faster heating rates result in quicker bond strength degradation as shown in *Figure 7.* Lee et al. found similar results in samples tested by

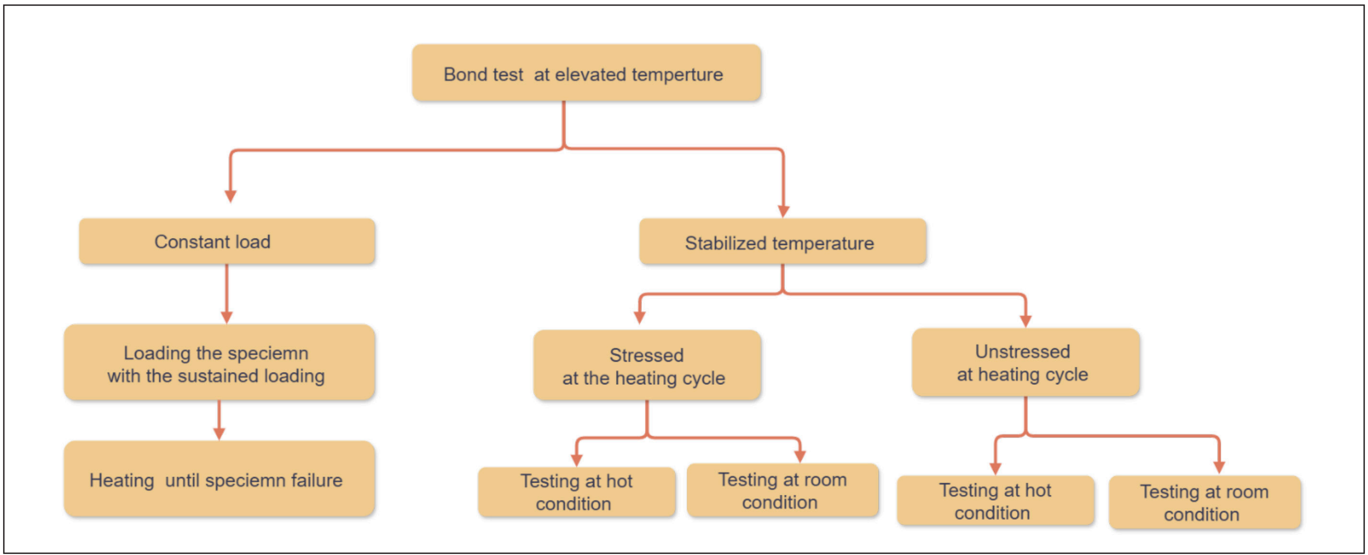


Figure 5: Experimental Procedure for Bond Testing at Elevated Temperatures

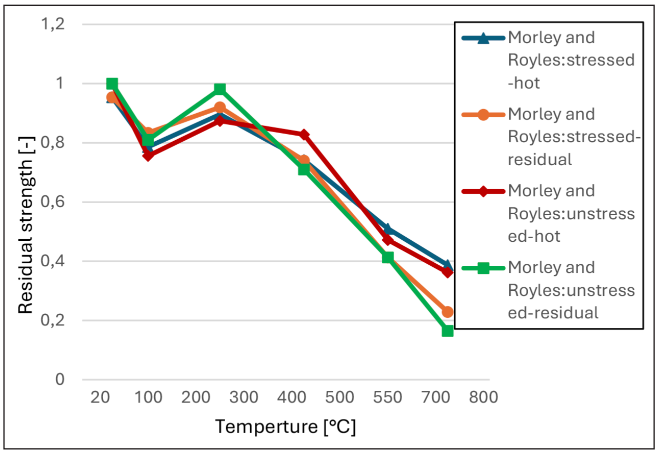


Figure 6: Bond Strength Response to Heat Using Stabilized Method (Morley and Royles, 1980)

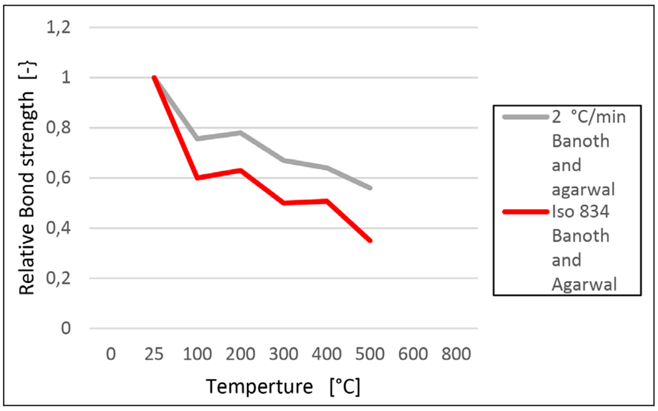


Figure 7: Heating Rate vs. Residual Bond Strength according to (Banoth and Agarwal, 2024)

applying 2 °C/min and 15 °C/min; Lee et al. also found that the cooling method using water or air did not significantly impact the bond strength of samples with uncoated rebar (Lee et al., 2018).

3.5 Residual bond strength of concrete after high thermal exposure

Generally, the failure mode will determine whether bond strength depends on compressive or tensile strength (*fib* Bulletin No. 72 , 2014). Research conducted by (Morley and Royles, 1983) and (Lublóy and Hlavička, 2017) found that the effect of temperature on bond strength is more pronounced than its effect on compressive strength.

Figure 8 shows the residual bond strength results from tests by (Lublóy and Hlavička, 2017) and (Morley and Royles, 1983). The bond strength decreased with increasing temperature, about 30% deterioration up to 200 °C. At 600 °C, considered critical for the structural integrity of Portland cement concrete, deterioration ranged from 65% to 90%, primarily due to the decomposition of calcium hydroxide around 450 °C. Additionally, mixes containing expanded clay and quartz gravel, tested by Lublóy and Hlavicka, experienced a more significant bond strength reduction beyond 150 °C.

Sharma et al. suggested a linear relationship derived from test results, which conservatively exhibits the reduction in relative bond strength of normal-strength concrete at high temperatures (Sharmaa et al 2019). The following equation represents the model:

$$\tau_{buT} = \tau_{bu,20}\left(1 - \frac{T-20}{780}\right) \tag{5}$$

where:

T_{buT} is the residual strength at T (°C)
$T_{bu,20}$ is the bond strength at (20 °C) using the *fib* Model Code 2010 equation.

Additionally, (Ergün et al , 2016) introduced mathematical equations that focus on the impact of rebar properties, considering different steel grades (S220a, S420a, S500a). The following equation represents the model:

For S220a T>200 0C

$$S_T = \left[0.618X\left(\left(\frac{T}{1000}\right)^2\right) - 1.681X\left(\frac{T}{1000}\right) + 1.036\right] X\ RBS_{(T=20^0C)} (R = 0.99) \tag{6}$$

For S420a T>200 ^{0}C

$$S_T = \left[-0.821X\left(\left(\frac{T}{1000}\right)^2\right) - 0.0268X\left(\frac{T}{1000}\right) + 1.023\right] X\ RBS_{(T=20^0C)}\ (R = 0.98) \tag{7}$$

For S500a T>200^{0}C

$$S_T = \left[-0.629X\left(\frac{T}{1000}\right)^2 - 0.352X\left(\frac{T}{1000}\right) + 0.905\right] X\ RBS_{(T=20^0C)}\ (R = 0.96) \tag{8}$$

ere

temperature in ^{0}C
$S_{(T=20\,^0C)}$ is the residual at 20 ^{0}C.

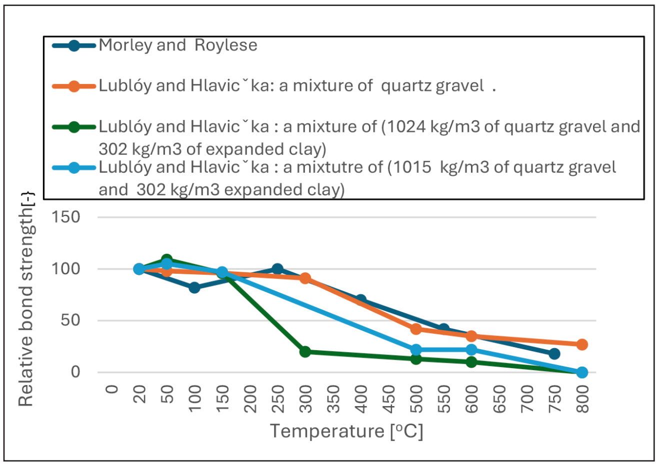


Figure 8: Residual relative bond strength at different temperatures for different concrete mixes

Haddad et al. prepared specimens using plain concrete and concrete reinforced with fibers, incorporating three different types of fibers to create various mixes. Below 600 °C, adding fibers enhanced the residual bond strength by helping prevent crack propagation and spalling. The highest residual bond performance was observed in the concrete mix containing only Hooked Steel fibers (Haddad et al, 2008).

4. CONCLUSIONS

This work reviews the available literature on bond strength at elevated temperatures, including factors such as testing methods and empirical models. It can be concluded from the scientific papers included in this literature review that:

1. Most studies utilized pull-out specimens; therefore, further research is needed to link pull-out behavior to actual structures.
2. Additional research is necessary, mainly through beam tests, to comprehend the actual mechanisms influencing residual bond strength at elevated temperatures.
3. Researchers use various methods in their experiments, such as stabilized temperature and constant load procedures. While much of the current research focuses on the constant temperature method and its impact on residual bond strength, there is an increasing demand for studies that compare this method with the constant load procedure. Existing studies indicate that the reduction in bond strength is more significant under the constant load procedure.
4. A larger cover results in greater bond strength at both ambient and elevated temperatures; however, the decrease in residual bond strength with temperature is similar after 500 °C.
5. The heating rate is a crucial factor because faster rates of heating lead to more rapid degradation of bond strength
6. Cooling using air or water does not influence the residual bond strength of uncoated rebar.
7. Mild and deformed rebars show similar residual bond strength curves, but plain rebars deteriorate more quickly.
8. The diameter of the rebar has little to no effect on the residual bond strength.
9. The concrete mix composition, including aggregate type, pozzolanic content, and fiber type and amount, affects residual bond strength. Further research using beam specimens and different heating methods is needed to explore these factors, along with the development of more models to predict bond strength at elevated temperatures.

5. REFERENCES

Abuhishmeh, K., Jalali, H. H., Ebrahimi, M., Soltanianfard, M., Cesar Ortiz Correa, J. S. (2024), „Behavior of high strength reinforcing steel rebars after high temperature exposure: Tensile properties and bond behavior using pull-out and end beam tests”, *Engineering Structures*, 305, https://doi.org/10.1016/j.engstruct.2024.117730

ACI committee 408 (2003), „ Bond and Development of Straight Reinforcing Bars in Tension”, ACI 408R-03.

Aslan, A.,Samali, B. (2013), „Predicting the bond between concrete and reinforcing steel at elevated temperatures”, *Structural Engineering and Mechanics*, 48(5),pp. 643-660, https://doi.org/10.12989/sem.2013.48.5.643

Banoth, I., Agarwal, A. (2020), „Effect of Heating Rate on Bond Behavior Between Steel and Concrete at Elevated Temperatures”. *Advances in Structural Engineering*, 74, pp. 89-98,https://doi.org/10.1007/978-981-15-4079-0_8

Banoth, I., Agarwal, A. (2024), „Bond between deformed steel rebars and concrete at elevated temperatures”, *Fire Safety Journal,* 145, https://doi.org/10.1016/j.firesaf.2024.104133

Bošnjak, J., Sharma, A., Öttl, C. (2018), „ Modified beam-end test setup to study the bond behavior after fire”, *Materials and Structures*, 51, https://doi.org/10.1617/s11527-018-1138-7

Cairns, J,Abdullah, R. (1995), „ an evaluation of bond pullout test and their relevance to structural performance”, *The Structural Engineer*, 73(11).

Das, A., Bonšjak, J., Sharma, A. (2023), „ Post-fire bond behaviour of reinforcement in concrete considering different bonded lengths and position of rebars”, *Engineering Structures*, 296, https://doi.org/10.1016/j.engstruct.2023.116908

Diederichs, U., Schneider, U. (1981), „Bond strength at high temperatures”, *Magazine of Concrete Research*, 33(115),pp.75-84,https://doi.org/10.1680/macr.1981.33.115.75

Ergün, A., Kürklü, G., Baspınar, M. S. (2016), „The effects of material properties on bond strength between reinforcing bar and concrete exposed to high temperature”, *Construction and Building Materials*, 112,pp. 691–698. http://dx.doi.org/10.1016/j.conbuildmat.2016.02.213

fib Bulletin No. 10 (2000), „ Bond of reinforcement in concrete”, https://doi.org/10.35789/fib.BULL.0010

fib Bulletin No. 72 (2014), „Bond and anchorage of embedded reinforcement: background to the fib Model code 2010”, https://doi.org/10.35789/fib.BULL.0072

Ghajari, F. A., Yousefpour, H. (2023), „Residual bond-slip behavior in reinforced concrete members exposed to elevated temperatures”, *Structural Concrete*, 24, pp. 3281–3298, https://doi.org/10.1002/suco.202200927

Ghazaly, N., Rashad, A., Kohail, M., Nawawy, O. (2018), „Evaluation of bond strength between steel rebars and concrete for heat damaged and repaired beam-end specimens”, *Engineering Structures*, 175, pp.661–668, https://doi.org/10.1016/j.engstruct.2018.08.056

Haddad, R., Alsaleh, R., Al-Akhras, N. (2008), „Effect of elevated temperature on bond between steel reinforcement and fiber reinforced concrete”, *Fire Safety Journal*, 43(5), pp. 334–343, https://doi.org/10.1016/j.firesaf.2007.11.002

Hertz, K. (1982), „ The anchorage capacity of reinforcing bars at normal and high temperatures”. *Magazine of Concrete Research*, 34(121), pp.213-22, https://doi.org/10.1680/macr.1982.34.121.213

ISO 834 (2019), „ Fire-resistance tests - Elements of building construction”.

Lee, J., Sheesley, E., Jing, Y., Xi, Y., Willam, K. (2018), „The effect of heating and cooling on the bond strength between concrete and steel reinforcement bars with and without epoxy coating”, *Construction and Building Materials*, 177, pp.230–236. https://doi.org/10.1016/j.conbuildmat.2018.05.128

Lublóy, É., Hlavička, V. (2017), „Bond after fire”, Construction and Building Materials, 132, pp.210-218. http://dx.doi.org/10.1016/j.conbuildmat.2016.11.131

Morley, P. D., Royles, R. (1980), „ The Influence of High Temperature on the Bond in Reinforced Concrete”. *Fire Safety Journa*l, 2,pp. 243 - 255. https://doi.org/10.1016/0379-7112(79)90024-9

Morley, P. D., Royles, R. (1983), „ Response of the bond in reinforced concrete to high temperatures", *Magazine of Concrete Research*, 35(123),pp. 67-74,https://doi.org/10.1680/macr.1983.35.123.67
MSZ EN 1991-1-2. (2002), „ Actions on structures – Part 1–2: General actions – Actions on structures exposed to fire".
Muciaccia, G., Consiglio, A. N. (2021), „Local bond properties of reinforcement in concrete subjected to elevated: Effects of clear cover, bonded length and heating and loading procedure", *Engineering Structures*, 230, https://doi.org/10.1016/j.engstruct.2020.111594
Royles, R., Morley, P. D. (1983), „ Further responses of the bond in reinforced concrete to high temperatures", *Magazine of Concrete Research*, 35(124), pp.157-163, https://doi.org/10.1680/macr.1983.35.124.157
Sharmaa, A., Bošnjakb, J., & Bessertc, S. (2019), „ Experimental investigations on residual bond performance in concrete subjected to elevated temperature". *Engineering Structures*, 187, pp.384-395, https://doi.org/10.1016/j.engstruct.2019.02.061
The *fib* Model Code (2010), „The fib Model Code for Concrete Structures 2010".
Xiao, J., Hou, Y., & Huang, Z. (2014), „ Beam test on bond behavior between high-grade rebar and high-strength concrete after elevated temperatures", *Fire Safety Journal*, 69, pp.23-35. https://doi.org/10.1016/j.firesaf.2014.07.001
Zheng ,Y., Fan, C., Ma, J., Wang, S.(2023), „Review of research on Bond–Slip of reinforced concrete structures", *Construction and Building Materials*, 385, https://doi.org/10.1016/j.conbuildmat.2023.131437

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