INFLUENCE OF THERMAL CYCLING ON BOND PERFORMANCE OF REINFORCEMENT IN CONCRETE

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ABSTRACT

As the world strives to move away from fossil fuels, expanding the use of nuclear power has become a crucial part of the solution. The development of advanced nuclear reactors (ANR) holds great promise for lowering nuclear power generation costs while effectively minimizing refuelling downtime. The lasting success of these ANRs hinges on the ability of concrete and steel components to function reliably under prolonged high temperatures. The reinforced concrete containment structures housing the reactor vessels are vulnerable to severe incidents involving exposure to elevated temperatures for extended periods. Such an event can potentially happen more than once during the operation lifespan of reactors. Past research has shown substantial degradation in concrete after prolonged exposure to elevated temperature, resulting in loss of compressive, tensile, and bond properties. However, there are no data available on the influence of thermal load cycling (heating-cooling cycles) on the bond performance.

This paper focuses on the experimental investigation of the bond splitting strength using modified beam-end specimens exposed to cycles of elevated temperatures. The specimen used in the test program simulates the details found in reinforced concrete walls and slabs, which are commonly used in the containment structures of nuclear power plants. The test matrix includes pull-out testing on 10 beam-end specimens after exposure to one, three, or ten thermal loading cycles. Each cycle involves heating the specimens at 4°C/min (7.2°F/min) to a maximum temperature of 930ºF (500°C), followed by cooling down to room temperature. Pull-out testing was done after the prescribed number of heating/cooling cycles at room temperature. The results of the study show that exposure to one cycle of heating/cooling can substantially decrease bond splitting strength, but that further exposure to thermal cycling has a smaller effect.

INTRODUCTION

Advanced nuclear reactors (ANRs), often called "Generation IV" reactors, provide a more cost-effective, efficient, safe and sustainable approach to power generation than traditional nuclear reactors. ANRs operates at much higher temperatures, typically in the range of 1290-1740ºF (700-950°C) . Reinforced concrete containment structures, housing the reactor vessel are vulnerable to severe incidents, such as loss of coolant, vessel rupture, core meltdown, during their lifespan. Such an event can potentially expose the concrete to high temperatures. The long-term success of these ANRs hinges on the ability of concrete and steel elements to function reliably under prolonged exposure to high temperatures.

Diederich and Schneider (1981), Morley and Royles (1983), Esfahani and Rangan (1998), Lamond and Pielert (2006), Haddad et al. (2008) and Sharma et al. (2019) have reported that exposure to elevated temperatures causes substantial degradation in concrete, which adversely affects the bond (interaction) between concrete and steel in reinforced concrete elements. The bond degradation increases the likelihood of bond splitting failures with notably reduced strength under tension loads. Multiple elevated temperature exposures may lead to more bond degradation. Since ANRs may undergo repeated cycles of heating and cooling during their lifespan, it is important to understand the influence of repeated thermal exposures on the bond performance. ACI CODE 349-13 derives its basis from ACI CODE 318-19 and gives more or less the same design provisions for bond development, leaving special consideration related to thermal loading to the designer. Furthermore, as per ACI CODE 349-13 and ASME BPVC-23, design criteria for concrete containment structures adopt a preventive approach, restricting the concrete surface exposure no more than 177ºC (350ºF). ACI CODE 216.1-14, EN 1992-1-2-23 and fib CEB-FIP bulletin-38 explain concrete material degradation due to the fire loading but do not laydown any guidelines for effects on concrete due to elevated temperatures. Engineers mostly rely on experimental testing, experience-based judgment and customized design to fulfil their specific needs when handling high-temperature applications.

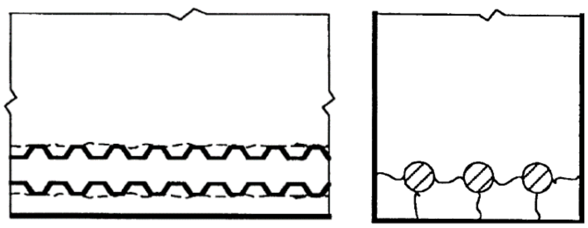
This paper focuses on the experimental investigation of bond splitting using modified beam-end specimens after multiple exposures to elevated temperatures. Besides the physio-chemical and mechanical properties of the constituent materials, the bond strength depends upon bar geometry, cover condition, level of confinement, and extent and duration of thermal exposure. The specimens were heated to 930ºF (500ºC), and pull-out tests were conducted after one, three, or ten heating and cooling cycles. The results of the study include the bond strength reduction due to thermal cyclic loading and the associated failure mode.

BOND PERFORMANCE AT ELEVATED TEMPERATURE

According to ACI PRC-408-03, force transfer from a deformed bar to the surrounding concrete in a reinforced concrete (RC) member under tension load occurs by: (1) Frictional force arising from the roughness of the interface, (2) Adhesion between the bar and the concrete, and (3) Bearing of the ribs against the concrete surface. In the presence of adequate concrete cover, appropriate bar spacing, and sufficient confining or transverse reinforcement, pull-out failure occurs which allows full activation of bond strength. This failure mode is characterised by shearing along the surface at the top of the ribs, which results in the bar being pulled out of the concrete. Conversely, small concrete cover, small bar spacing, and the absence of confining / transverse reinforcement, leads to splitting failures with lower bond strength. This type of failure is characterized by longitudinal cracks along the complete length of the bar. The pull-out and splitting crack mechanisms are schematically shown in Figure 1.

Concrete mechanical properties degrade when exposed to elevated temperatures. The extent of damage in concrete is highly dependent on the nature, intensity and duration of thermal exposure. Concrete, being weak in tension, relies primarily on the steel reinforcement in regions resisting tensile load. Bond that is essential for transferring forces between the concrete and the steel deteriorates with increasing temperature. Figure 2 presents data from past research showing the reduction in bond strength as a function of temperature for different types of test specimens. It is clear that the influence of elevated temperature and fire on bond can differ in important ways. In several cases, the test specimens undergoing pull-out failure under ambient conditions experience bond splitting in post-fire or post-elevated temperature exposure. The bond strength is influenced by factors such as concrete material composition, compressive strength, clear cover, and the level of confinement of the pull-out bar.

Thermal degradation in concrete is a complex phenomenon. Variables such as rate of heating, maximum temperature, duration of exposure, cooling, and subsequent heating cycles effects concrete performance. Fire exposure is an intense event that is relatively short lived but involves extreme gradients and temperatures. Sharma et al. (2021) conducted tests on reinforced concrete (RC) beams under fire loading and found a loss in bond strength ranging from 35% to 45% after just 90 minutes of exposure to high temperatures. In contrast, the loss of bond strength in RC elements that experience low rates of heating and prolonged heat exposure is much less, as illustrated in Figure 1b. The containment structures used in advanced nuclear reactors (ANRs) operate at high temperatures and are vulnerable to repeated high-temperature exposure throughout their lifespan.



a. Shear cracks due to bar pull-out b. Splitting cracks

Figure 1. Pull-out vs splitting cracking, ACI-408 (2003).

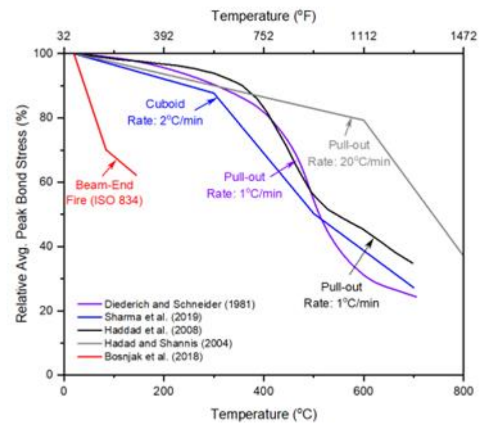


Figure 2. Bond degradation with elevated temperature.

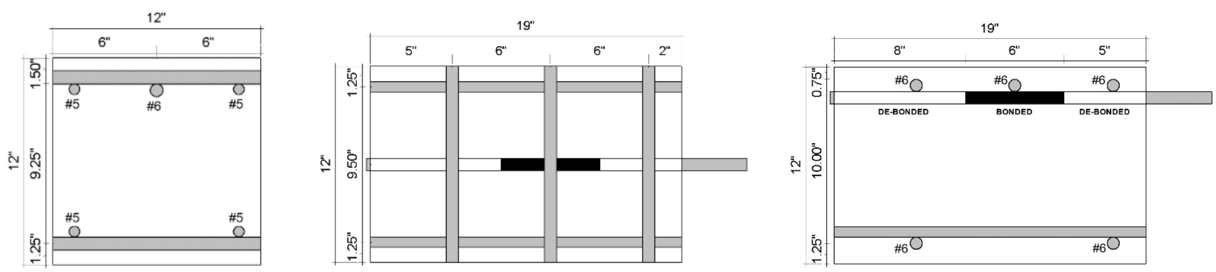
Limited research has been conducted on the effects of thermal cyclic loading on the performance of concrete at elevated temperatures. Khoury (2006) studied the strains in heated concrete during two thermal cycles, focusing on three types of concrete used in advanced gas-cooled reactors (AGRs). He discovered that concrete experiences both expansive and contractive strains during these heating and cooling cycles. Notably, concrete compressive strength loss was most pronounced after the first thermal cycle, while subsequent cycle resulted in only a minimal additional degradation in strength. Morley and Royles (1983) examined the impact of pre-existing mechanical loads on bond performance during heat application. Their findings suggest that the presence of mechanical loads during heating does not have an important influence on bond behaviour. This study will investigate the effects of thermal cycling on bond strength in reinforced concrete (RC) elements.

EXPERIMENTAL INVESTIGATION

Test Specimen

Bosnjak et al. (2018) suggest that modified beam-end specimens provide more realistic conditions for studying bond performance than pull-out specimen. The beam end specimen consists of a rectangular concrete block and is used as a standard test method for comparing the bond strength of steel reinforcing bars to concrete, ASTM A944-20. To simulate the conditions of a reinforced concrete wall or slab, stirrups in the standard beam-end specimen are replaced with the orthogonal reinforcement. These modified beam-end specimen used in this study are hence provided with steel reinforcement is both directions: longitudinal and orthogonal.

The specimen consisted of a 20” x 12” x 12” (510 mm x 305 mm x 305 mm) rectangular concrete block, as shown in Figure 3. A 0.75” (19 mm) diameter (d_b) bar was used as the test bar, which depicts the main longitudinal reinforcement in the RC member. The clear cover to the bar from the top concrete surface was 1.50” (38 mm) ($2d_b$). The bar was not bonded to the concrete over two lengths: over five in. (130 mm) at the loaded (pull-out) end of the bar, and over nine in. (230 mm) at the unloaded end of the bar. Bond was prevented by encasing the bar with aluminium-fiberglass corrugated sleeving before concrete was placed. The sleeving prevents the pull-out bar from contacting the surrounding concrete. An anchorage length (bonded length) of six in. (150 mm) ($8d_b$) was provided in between the de-bonded lengths. In Figure 3(b), the white part of the pull-out bar depicts the de-bonded lengths and the black part depicts the bonded length. Additionally, a 0.75” (19 mm)) diameter bar was also provided perpendicular to the pull-out bar in the centre of the bonded region depicting the orthogonal reinforcement that would be present in a slab or wall. To maintain the integrity of the specimen during pull-out testing, skeleton reinforcement was provided that consisted of a 0.625” (16 mm) longitudinal bar in each corner of the specimen and a 0.75” (19 mm) orthogonal bar in each de-bonded region. Moreover, to grip the bar during pull-out testing and to measure rear-end displacements, 5” (130 mm) protruding length was provided in the beginning and 0.5” (12 mm) at the end of the specimen. Normal strength limestone aggregates-based concrete was used. The average concrete compressive strength (f'_c) before heating the specimen was 4,100 psi (28 MPa). To avoid explosive spalling of concrete, 1.5 lb per yd^3 (0.9 kg/m^3) of 0.25” (6 mm) length, polypropylene fibers were added to the concrete mix. Grade 100 steel bar was used for pull-out bars. All other skeleton steel reinforcement was Grade 60.



a. Cross-section. b. Top. c. Side.

Figure 3. Schematic view of the modified beam-end specimen designed to simulate bond in walls and slabs.

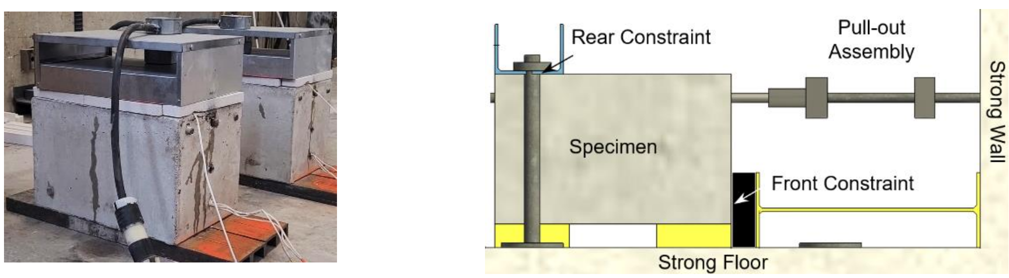
Test Program

The test program consists of pull-out testing on 10 small-scale concrete specimens. The test matrix is outlined in Table 1 and includes a reference test (without heating) as well as tests conducted after one, three, or ten cycles of heating. Three nominally-equivalent pull-out specimens were tested for each case subjected to elevated temperature. Radiant heaters were used to heat the specimens. These powerful heaters emit infrared radiation that directly warms the concrete surface. The top surface of the specimen, which is closest to the pull-out bar and has a concrete cover of 1.5” (38 mm), was heated. Figure 4 illustrates the heating and pull-out test setup. During each heating cycle, the specimens were heated at a rate of 7.2°F/min (4°C/min) to a maximum temperature of 930°F (500°C). This temperature was maintained for two hours before the specimens were allowed to cool back to room temperature. The temperature profile used to heat the specimens is illustrated in Figure 5a. This temperature profile was repeated three or ten times to achieve the desired thermal cycling. The pull-out tests were performed on the specimens in their cold state, which is commonly referred to as the residual state. Constraints were applied at the front face of the specimen, extending from the ground to a height of 5” (130 mm), and at the top face, toward the rear. These constraints were carefully positioned away from the bonded region to ensure they did not interfere with the stress field of the pull-out bar during mechanical load application.

Table 1: Test matrix for pull-out testing.

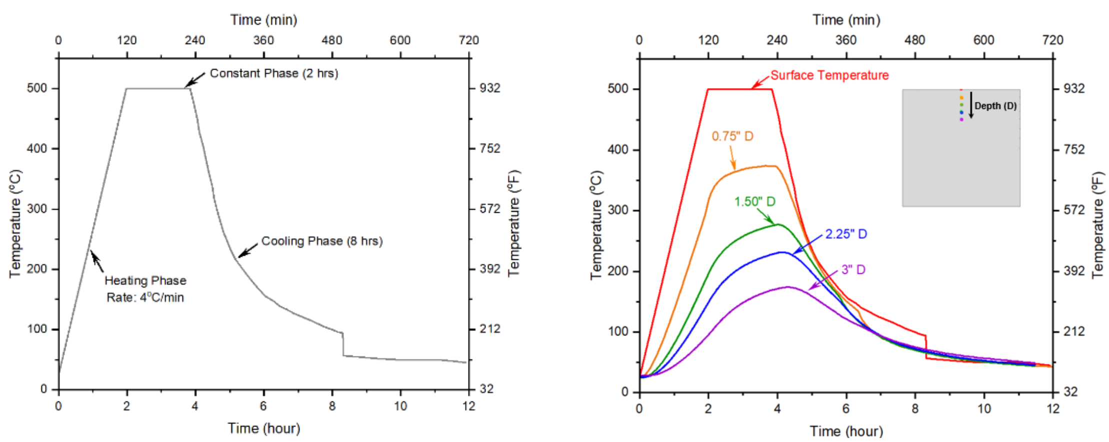
Ser	Description		Thermal Cycle (#)	Pull-out Test (#)
1.	Reference test	Ref	0	3
2.	After 1 heating cycle	T1	1	3
3.	After 3 heating cycle	T3	3	3
4.	After 10 heating cycle	T10	10	1

To observe the profile of temperature penetration through the depth of the specimen during a heating cycle, K-type thermocouples were placed at 0.75” (19 mm) intervals from the top surface to a depth of 3” (76 mm) along the pull-out bar in the centre of the bonded region before placing concrete. The pull-out tests were conducted in oil pressure control. The pull-out force was measured using a calibrated load cell, while the displacements at both the front and rear ends of the bar were recorded with calibrated potentiometers. The results include the observable temperature-induced cracking during each thermal cycle, load versus rear-end displacement for each case, and the associated observable cracking during the pull-out testing.



a. Thermal load application. b. Pull-out test setup.

Figure 4. Heating and pull-out test setup.



a. Temperature profile for heating. b. Heat penetration through depth.

Figure 5. Heat application and penetration through depth.

RESULTS AND DISCUSSION

Heat Penetration

Figure 5b illustrates a temperature penetration profile during one heating cycle. The surface beneath the heating panel experienced temperatures similar to those emitted by the heating panel. It can be noticed that due to poor heat conductive properties of concrete combined with heat loss from the sides, there was a noticeable lag in the temperatures recorded at deeper levels. Even after two hours of holding the temperature at 930ºF (500ºC), the maximum temperature observed at 0.75” (19 mm) depth was 705ºF (374ºC). At the level of the top of the pull-out bar, which is 1.5” (38 mm) from the exposed concrete surface, the maximum temperature observed was 532ºF (278ºC). Temperatures of 450ºF (232ºC) and 345ºF (174ºC) were recorded at 2.25” (57 mm): at the level of the bottom of the pull-out bar and 3” (76 mm), respectively. The time at which the peak temperature is reached at a certain level inside the concrete increases with increasing depth. Thus, as soon as the heater is switched off, the surface temperature starts to drop. However, the heat front keeps moving inside the concrete and the temperature inside the concrete keeps increasing for some time before it starts to reduce.

Due to the heat-resisting and insulating properties of concrete, combined with low thermal conductivity and high heat capacity, relatively slow temperature propagation was observed. Upon cooling, the surface of the concrete cools faster than the inside of concrete, resulting in tensile thermal stresses that lead to concrete cracking. The thermal degradation of concrete is influenced by the temperature exposure, which means the surface concrete directly beneath the heater had experienced maximum degradation. The concrete surrounding the pull-out bar experienced less degradation due to the lower temperatures involved. The concrete below the pull-out bar was exposed to relatively lower temperature might had experienced the least temperature effects.

Cracking In Concrete

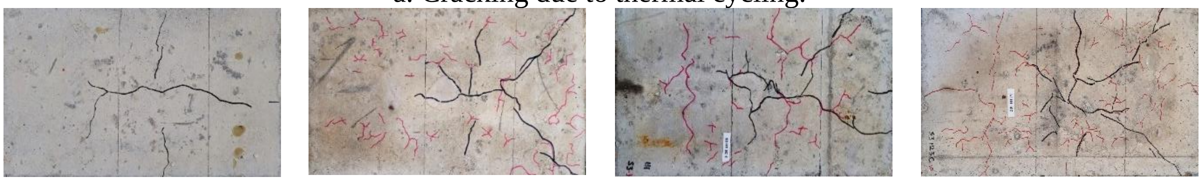
Figure 6 illustrates the crack pattern observed during the heating and subsequent pull-out tests. Thermally-induced cracks are highlighted in red, while cracks that appeared during the pull-out test are marked in black. The effects of thermal cycling are evident. As the number of thermal cycles increased, the extent of thermal-induced cracking also grew. After one heating cycle, the cracks appeared scattered, but after three or ten heating cycles, the cracks were more interconnected and pronounced, indicating progressive material degradation due to thermal cycling at high temperatures. Additionally, a change in the concrete surface color from grey to a greenish-grey was observed during the heating experiments.

The black zig-zag horizontal cracks shown in Figure 6b can be characterized as bond-splitting cracks related to the pull-out tests. In the specimen that was not heated, splitting failure was observed during the pull-out test. During the pull-out tests conducted after thermal cycling, bond splitting failure remained the dominant failure mode, but the extent of cracking increased. The cracks mainly propagated along the pre-existing thermal cracks. Furthermore, the degradation of concrete led to an increase in the width of these existing thermal cracks.

No Heating

1 Cycle 3 Cycles 10 Cycles

a. Cracking due to thermal cycling.



a. Splitting crack due to mechanical loading.

Figure 6. Crack Pattern due to thermal and mechanical loading.

Load versus Rear-end Displacement

The results of the tests conducted on the ten specimens are summarized in Figure 7 and Figure 8. The relationship between load and rear-end displacement is shown in Figure 7. In the reference tests, which involved a specimen without heating, splitting failure was observed, providing a useful baseline for comparison with the results from specimens that underwent thermal cycling, which were also expected to exhibit concrete splitting failures. After only one thermal cycle, a large drop in load, from 30.2 kips (134.3 kN) for the reference test (Ref) to 17.9 kips (79.6 kN) for the test (T1), was observed. This is attributed to the cracking of concrete during the first heating and cooling cycle. The subsequent thermal cycles led to only minor losses in strength. The average peak loads observed for specimens tested after three cycles (T3) and ten cycles (T10) were 16.1 kips (71.6 kN) and 13.8 kips (61.4 kN). A large drop in stiffness due to thermal cycling load was also observed. The loss in stiffness may be attributed to the expansion and contraction associated with heating and cooling during thermal cycling. This process facilitates the opening and closing of thermally induced cracks and also increases their width.

To analyse the degradation in bond strength resulting from thermal cycling, peak bond stress (Equation 1) is plotted against the number of thermal cycles in Figure 8. The normalized average peak bond stress is calculated by dividing the average peak bond stress values from the thermal loading cases by the reference case.

$$\tau = L/\pi l_d d_b \tag{1}$$

where;

L = load (kN)

l_b = bonded length (mm) d_b = diameter of the pull-out bar (mm)

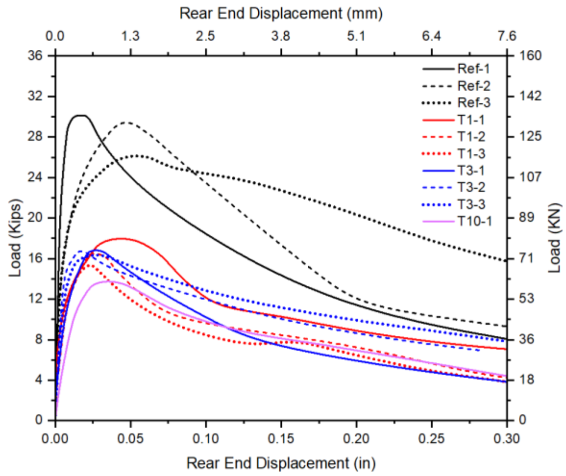
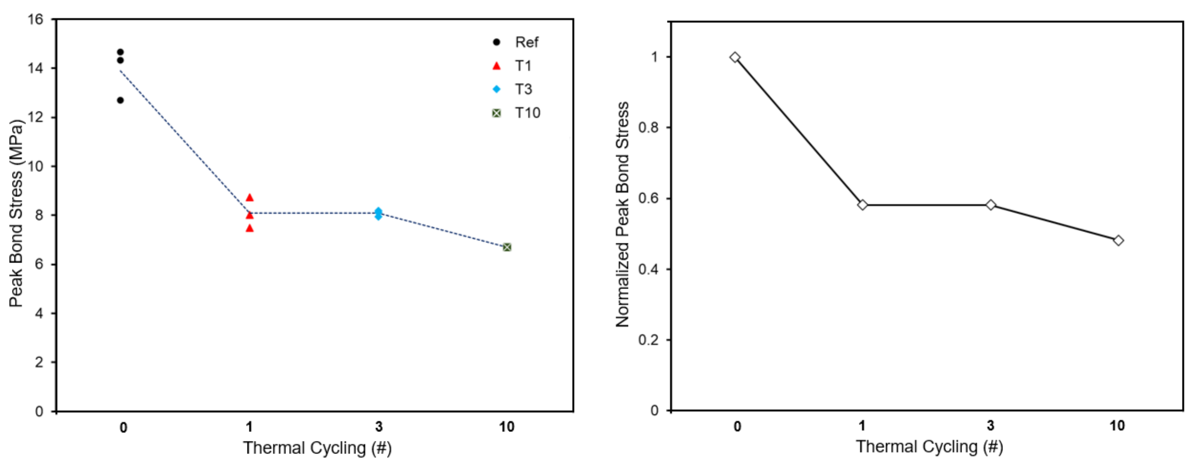


Figure 7. Load vs rear-end displacement.

The results show strong degradation in bond strength upon exposure to elevated temperatures. The first thermal cycle incurred the maximum bond loss. The residual bond strength after the first thermal cycle was 59% of the initial bond strength (reference). This loss may be attributed to the chemical and mechanical changes in concrete, loss of moisture, differential strains between concrete and steel, and thermal micro and macro cracking in the concrete microstructure due to prolonged high temperature exposure. Tests conducted after three thermal cycles showed similar results, with no reduction in bond strength. However, after ten thermal cycles, there was an additional reduction of 14 percentage points in bond strength, resulting in a residual bond strength that was, on average, 45% of the initial value. This shows that subsequent thermal cycling continues to degrade the bond properties but at a relatively lower rate. The cycles of expansion and contraction and thermal crack opening and closing during the heating and cooling of concrete in each cycle likely contribute to this additional loss in bond strength.



(1 MPa = 0.145 ksi)

a. Peak bond stress vs thermal cycling. b. Normalized peak bond stress vs thermal cycling.

Figure 8. Effects of thermal cycling on the bond strength.

CONCLUSIONS

The effects of thermal cycling on the bond splitting strength of steel reinforcement was investigated using modified beam-end specimens designed to simulate details representative of walls and slabs. Tests were conducted after thermal cycling involving high-temperature exposure followed by cooling. The influence of one, three, or ten cycles of heating up to 500ºC (930ºF), holding for two hours, and cooling to ambient temperature was analyzed. The results of this experimental study affirm the findings of prior work that showed high temperature exposure deteriorates concrete and increases the chances of concrete splitting failures at smaller bond forces. Results showed that most of the bond strength loss occurs after the first thermal cycle (on average a 41% loss). The bond strength reduction is much smaller under subsequent thermal cycles. Three thermal cycles resulted in no measurable bond loss, whereas exposure to ten thermal cycles resulted in additional strength loss (55%, on average, relative to unheated condition).

RECOMMENDATIONS

This paper examined the influence of thermal cycling on the bond splitting strength of small-scale concrete wall specimens using a specific temperature profile. In this profile, the heating rate was kept constant at 4°C per minute, with a maximum exposure temperature of 500°C (930ºF). Future studies may explore the effects of higher heating rates and varying temperature exposures on the bond splitting strength. Additionally, the clear cover over the pull-out bar has an important impact on bond performance at elevated temperatures and should be further investigated. Other factors, such as the type of concrete (normal strength, high strength, and self-consolidating); aggregate type; and confinement conditions should also be explored to understand and improve bond performance at elevated temperatures. To further this research, the authors are currently exploring the effects of various clear cover and confinement conditions on bond performance under elevated temperatures.

REFERENCES

ACI Committee 318. (2019). *Building Code Requirements for Reinforced Concrete*, American Concrete Institute, Farmington Hill.

ACI Committee 349. (2013). *Code Requirements for Nuclear Safety-Related Concrete Structures and Commentary*, American Concrete Institute, Farmington Hill.

ACI Committee 359. (2018). *ASME Code Requirements for Concrete Containments*, American Concrete Institute, New York.

ACI Committee 408R. (2003). *Bond and Development of Straight Reinforcing Bars in Tension*, American Concrete Institute, Farmington Hill.

ACI-TMS Committee 216.1. (2014). *Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies*, American Concrete Institute, Farmington Hill.

ASME BPVC-III.2. (2023). *Code for Concrete Containments*, American Society of Mechanical Engineers, New York.

ASTM-A944. (2020). *Standard Test Method for Comparing Bond Strength of Steel Reinforcing Bars to Concrete using Beam-end Specimens*. American Society of Testing and Materials, West Conshohocken.

Bosnjak, J., Sharma, A. and Ottl, C. (2018). “Modified beam-end test setup to study the bond behaviour of Reinforcement in Concrete after Fire, Materials and Structures, 51, pp 1-10.

CEB-fib Bulletin No.38. (2007). *Fire Design of Concrete Structures - Materials, Structures and modelling*, State-of-Art Report prepared by the Working Party 4.3-1, Lausanne. ISSN 1562-3610.

Diederich, U. and Schneider, U. (1981). “Bond Strength at High Temperature”, Magazine of Concrete Research, 33, pp 75-84. ISSN 0024-9831.

EN-2, Part 1-2 (2010). *Design of Concrete Structures, General Rules-Structural Fire Desig*n, European Committee for Standardization, Brussels.

Esfahani, M. and Rangan, B. (1998). “Local Bond Strength of Reinforced Bars in Normal Strength and High-Strength Concrete”, ACI Structural Journal, V.95, No.2, pp.96-106.

Khoury, G.A. (2006). “Strain of heated concrete during two thermal cycles. Part 1: strain over two cycles, during first heating and at subsequent constant temperature”, Magazine of Concrete Research, V.6, pp. 367-385.

Khoury, G.A. (2006). “Strain of heated concrete during two thermal cycles. Part 2: strain during first cooling and subsequent thermal cycle”, Magazine of Concrete Research, V.6, pp. 387-400.

Lamond, J.F. and Pielert, J.H. (2006). “Significance of Tests and Properties of Concrete and Concrete-Making Materials”, ASTM International, West Conshohocken, STP 169D.

Morley, P. and Royles, R. (1983). “Response of the bond in reinforced concrete to high temperatures”. Magazine of Concrete Research, 35, pp 67-74.

Sharma, A., Bosnjak, J. and Bessert, S. (2019). “Experimental investigations on residual bond performance in concrete subjected to elevated temperatures”, Engineering Structures, 187, pp 384-395.

Sharma, A., Bosnjak and Tonidis, M. (2021). “Post-fire performance of RC beams with critical lap-splices - Experimental investigation and numerical validation”, Building Engineering, 34:102045.