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Time–temperature analysis of bond strength of a rebar after fire exposure

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Abstract

The extent of damage to a steel-reinforced concrete structure due to fire exposure must be evaluated before deciding whether to reuse, reinforce, or abandon the structure. Understanding the long-term effects of high temperature on steel-reinforced concrete structures is also important for predicting the service life of a structure in a high-temperature environment. These effects include changes in strength, stiffness, toughness, bond strength of the rebar, and so on. The change in the bond strength of rebars is studied herein. The experimental results of postfiring pullout tests show a substantial decrease in bond strength if the exposure temperature reaches 200 °C or higher. The current investigation proposes a procedure, based on a single function, to calculate changes in bond strength for predicting residual bond strength of a rebar due to exposure to constant or fluctuating high temperatures. This forecasting method is termed temperature–time analysis and offers excellent agreement with the experimental results.

Keywords: Bond strength; Fire exposure; High temperature

1. Introduction

Under normal environmental exposure, the temperatures concrete is subjected to are below 50 °C. However, for many engineering problems involving concrete, higher temperatures from 50 °C to several hundred degrees Celsius can become extremely important. Investigation of concrete at high temperatures is most relevant to problems associated with fire resistance in concrete buildings. Concrete has excellent durability in this regard, and is an effective shield for other structural materials, such as reinforcing steel. Nevertheless, the response of concrete to high temperature needs to be analyzed to determine service life in high-temperature environments. Reuse and reinforcement of fire-damaged concrete structures also require characterizing the response of concrete to high temperatures.

The fire resistance of concrete depends on its geometry, ingredients, reinforcement, water content, and other factors. The hardening of concrete because of hydration can be accelerated at higher temperature if its water content is abundant. However, high temperatures, especially above 100 °C, cause water migration and dehydration if the moisture supply from outside is insufficient [1]. Internal stress and thus micro- and macrocracks are generated due to the inhomogeneous volume dilatations of ingredients and the buildup of vapor pressure in the pores. The properties of the concrete will then be changed [2,3], including strength, stiffness, toughness, bond strength, and more. All property changes are critical in evaluating the status of a concrete structure that has suffered fire exposure. Although the effects of high temperature on concrete structures have been extensively studied, most of these studies only considered the effects of constant temperature exposure or in cases of fluctuating exposure, those of the maximum temperature. Exposure to fluctuating temperature, such as the elevating–heating–cooling procedure, involves temperature fluctuation as a function of exposure time. This study focuses on developing a process for using the whole temperature–time history to predict the residual bond strength of rebars in concrete following exposure to fluctuating high temperatures.

2. Experimental procedure

Concrete specimens (15 × 15 × 20 cm) were chosen for pullout testing to evaluate rebar bond strength. Two #3

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rebars were embedded vertically into each specimen from both ends, with embedded lengths of 6 and 8 cm, respectively (Fig. 1). Type I cement was used. The fineness moduli of the fine and coarse aggregates were 2.10 and 7.14, respectively. Meanwhile, the weight ratio of cement/water/fine aggregate (dry)/coarse aggregate (dry) of the concrete was 1:0.5:2:3. The specimens were water cured for 28 days after initial construction, and their average compressive strength was 502 kg/cm^2 (49.2 MPa). Additional details can be found in previous investigations [4,5]. After water curing, the specimens were air-dried for a week and then exposed to elevated temperatures in an electrical oven to simulate fire exposure. Three stages were programmed for the oven temperature. In the first stage, the program raised the temperature from room temperature, T_r (25 °C), to a specific temperature, T_c (240, 320, 400, 500, or 550 °C), with the rate of increase being 30 °C/min. During the second stage, the temperature was maintained at a constant level for a specific exposure time (30, 60, 90, 120, 150, or 180 min). Finally, the third stage was a cooling stage, with the cooling function being $T = T_c - 345 \log_{10}(8t_c + 1)$, where T denotes the temperature and t_c represents the cooling time. One day after the temperature reached room temperature, the specimens were removed from the oven and vertically mounted on a universal testing machine. Both rebars were griped and then pulled slowly, with a pulling rate of 1 cm/min. The maximum pullout force was recorded to represent the bond strength. Because the embedded lengths of the two rebars differed, the rebar with the shorter embedded length (6 cm) was always pulled out. Three specimens were tested for each temperature–time setting. Each time specimens were made, unheated specimens were prepared and tested to obtain the original value of the bond strength as a reference. The residual bond strength measured from all the heated specimens was divided by the original bond strength of the reference specimens, thus obtaining the residual bond strength ratio. A substantial decrease in bond strength occurred if the exposure temperature exceeded 200 °C. Fig. 2 displays the results of these postfiring pullout tests

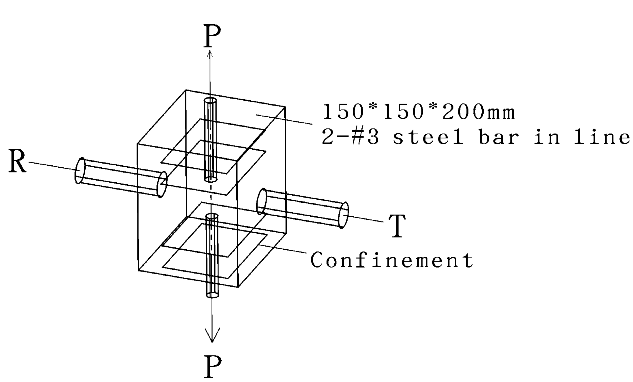

Fig. 1. Specimen configuration for pullout testing.

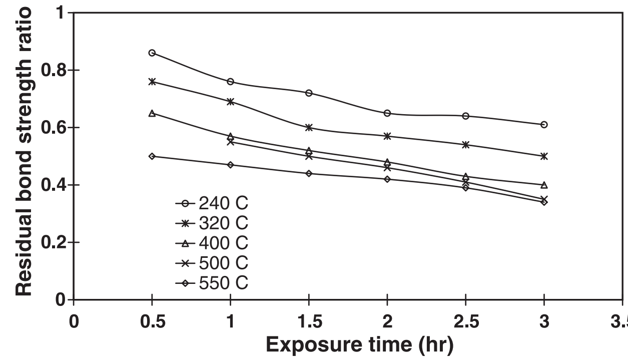

Fig. 2. Results of postfiring pullout tests.

(similar to the pullout test stated by ASTM C234). Some similar experimental studies on residual bond strength have also been published [6–8].

3. Analysis of residual bond strength

The ratio of residual bond strength, denoted as R, should initially be 1 prior to exposure to high temperature. Experimental results show that R usually decreases as exposure time increases and finally approaches a specific value asymptotically. However, R may increase in some cases shortly after the initial heating starts and temperature is moderate. To simulate the trend of experimental observation, an empirical function, Eq. (1), is assumed to prescribe the relationship between the ratio of residual bond strength, temperature, and exposure time.

$$R = \frac{(R_m - R_\infty)(1 - R_\infty)}{(R_m - 1)\left(\dfrac{t}{t_m} - 1\right)^{2n} + (1 - R_\infty)} + R_\infty \tag{1}$$

where R_m represents the maximum value of R, R_∞ is the limiting value or steady-state value at infinite exposure time, t denotes the exposure time, and t_m represents the exposure time corresponding to R_m. R_∞, R_m, t_m and n are assumed to be functions of temperature only. The above equation satisfies the following conditions.

$$R = 1 \text{ at } t = 0; \quad R = R_\infty \text{ at } t \to \infty; \quad R = R_m \text{ at } t = t_m \tag{2}$$

When $t_m \geq 0$, R will increase at the very beginning and then decrease to approach the final value. On the other hand, R will decrease monotonically all the way to approach the final value if $t_m \leq 0$. To simplify the analysis, temperature is defined as a constant herein, and the exposure time is only considered to include the time at which the temperature is constant. However, it is impossible to avoid periods of temperature increase and cooling in real experiments. To consider the effects of these two steps, one more unknown,

Table 1
Parameters for Eq. (3) determined by the experimental data

Parameters	Temperature (°C)				
	240	320	400	500	550
R_m	1.20	1.20	1.07	1.07	5.00
R_∞	0.58	0.45	0.40	0.33	0.34
t_m	42.00	39.00	38.00	40.00	50.00
n	1.10	1.10	1.50	1.50	1.01
t_0	77.00	77.00	90.00	90.00	100.00

t_0, was added to Eq. (1). Consequently, the temperature raising and cooling steps in the experiment results in equivalent exposure time, t_0. Eq. (1) thus becomes:

$$R = \frac{(R_m - R_\infty)(1 - R_\infty)}{(R_m - 1)\left(\dfrac{t + t_0}{t_m} - 1\right)^{2n} + (1 - R_\infty)} + R_\infty \qquad (3)$$

R_∞, R_m, t_m, t_0, and n are unknowns that need to be determined by least square curve fitting based on the experimental data from the pullout test (Table 1). All the parameters in Table 1 are temperature dependent. If a specific temperature is not shown in the table, inner interpolation can be used to calculate the proper parameter values for that temperature.

The changing rate of R can be obtained from Eq. (3) and given as

$$\frac{dR}{dt} = -\frac{2n}{t_m}\frac{(R_m - 1)}{(R_m - R_\infty)(1 - R_\infty)}\left[\frac{(R_m - R)(1 - R_\infty)}{(R_m - 1)(R - R_\infty)}\right]^{\frac{2n-1}{2n}} \times (R - R_\infty)^2 \qquad (4)$$

R_∞, R_m, t_m, and n in Eq. (4) can be obtained via Table 1 provided the temperature, T, is known. Prediction of the changing rate of R for different R and T can thus be calculated using Eq. (4).

4. Predicting the residual bond strength

When exposing a specimen to elevated temperatures, it is impossible to keep the temperature constant throughout the experiment. To predict final residual bond strength, the temperature history of exposure should first be mathematically cut into numerous, short time intervals. The accuracy of final residual bond strength prediction increases with the number of intervals. In the first time interval, the initial value of R should be 1 because the sample is unheated, and the temperature, T, is the average temperature of the interval. Table 1 lists all required parameters at this temperature, and the dR/dt can easily be calculated from Eq. (4). The change of R, dR, due to the temperature exposure of this time interval equals the product of dR/dt and the length of this interval, dt. The final R of the second interval equals the initial R plus dR, while the final R of the first interval equals the initial R of the second interval. The calculation procedure can be repeated to obtain the final R of the second interval and the remaining intervals. In any interval, if the initial R is already lower than its R_∞ at its average temperature, then this interval of exposure will not damage the specimen further, and thus can be skipped. This phenomenon is frequently encountered in the cooling step. Finally, the final R of the whole exposure history can be obtained. Four tests of high-temperature exposure have been conducted based on temperature histories of different exposure times. Table 2 presents an example of calculations using the above procedure, while Table 3 compares predictions of residual bond strength ratio and the experimental datum.

Table 2
Example calculation based on the time–temperature analysis

Interval	T (°C), average temperature	R_i, initial value	R_∞	dR/dt, 1/min	t (min)	dR	$R_{i+1} = R_i + dR$
1	130.0	1.000	0.900	– 0.013	4	– 0.054	0.946
2	235.0	0.946	0.875	– 0.009	4	– 0.036	0.911
3	340.0	0.911	0.854	– 0.010	4	– 0.041	0.870
4	445.0	0.870	0.766	– 0.015	4	– 0.061	0.809
5	550.0	0.809	0.501	– 0.027	4	– 0.108	0.702
6	550.0	0.702	0.501	– 0.026	4	– 0.105	0.597
7	550.0	0.597	0.501	– 0.025	4	– 0.101	0.495
8	550.0	0.495	0.501	–	4	–	0.495
9	550.0	0.495	0.501	–	4	–	0.495
10	550.0	0.495	0.501	–	4	–	0.495
11	550.0	0.495	0.501	–	4	–	0.495
12	550.0	0.495	0.501	–	4	–	0.495
13	550.0	0.495	0.501	–	4	–	0.495
14	550.0	0.495	0.501	–	4	–	0.495
15	550.0	0.495	0.501	–	4	–	0.495
16	550.0	0.495	0.501	–	4	–	0.495
17	550.0	0.495	0.501	–	4	–	0.495
18	550.0	0.495	0.501	–	4	–	0.495
19	550.0	0.495	0.501	–	4	–	0.495
20	550.0	0.495	0.501	–	4	–	0.495
21	550.0	0.495	0.501	–	4	–	0.495
22	550.0	0.495	0.501	–	4	–	0.495
23	368.7	0.495	0.938	–	4	–	0.495
24	247.1	0.495	0.962	–	4	–	0.495
25	165.7	0.495	0.793	–	4	–	0.495
26	111.0	0.495	0.651	–	4	–	0.495
27	74.4	0.495	0.558	–	4	–	0.495
28	49.9	0.495	0.500	–	4	–	0.495
29	33.4	0.495	0.464	–	4	–	0.495
30	22.4	0.495	0.440	–	4	–	0.495

Table 3
Comparison between experimental results and time–temperature analyses

Exposure temperature (°C)	550	550	550	550
Exposure time (h)	0.5	1.0	1.5	2.0
Time–temperature analyses, R'	0.50	0.50	0.46	0.40
Experimental, R	0.50	0.47	0.44	0.42
1 – (R'/R) (%)	0.02	– 6.38	– 4.55	4.76

5. Conclusions

Determining whether a fire-damaged reinforced concrete (RC) structure should be abandoned or reinforced for reuse is very important, and deciding how much a fired-damaged RC structure should be reinforced is even more significant. Furthermore, predicting the service life of RC structures exposed to high-temperature environments is also important. All these problems arise from the difficulty of quantifying the damage caused by elevated temperatures and the lack of efficient analysis. The effects of high temperatures on the bond strength of a rebar in concrete do not depend solely on the exposure temperature, or the maximum temperature during exposure, and exposure time is also important. Exposure with fluctuating temperatures makes analysis both theoretically and experimentally difficult. This study presented and experimentally verified a general mathematical process for accumulating damage to RC structure arising from high temperature. The experimental results indicate that the effects of high temperature on RC structures can be mathematically characterized. Damage to concrete due to high-temperature effects in an arbitrary temperature history can be quantified for further damage assessment.

Experiments confirmed that the bond strength of a rebar embedded in concrete usually decreases if the RC structure is exposed to high temperature. The proposed procedure allows final residual bond strength to be accurately predicted. The assumptions regarding empirical functions for bond strength herein are very subjective. However, it must fit the initial conditions and follow the trend of the experimental data closely. This work makes two contributions to the prediction of temperature-induced damage to concrete structures. The first contribution is experimentally and numerically relating the ratio of residual bond strength, R, to temperature, T, and exposure time, t. The second contribution is developing a procedure for integrating changes in bond strength due to temperature fluctuations to predict final residual bond strength. Experimental results agreed closely with the predictions obtained by the proposed procedure. The same procedure can also be used to forecast the effects of high temperature on other properties of concrete, such as its compressive strength.

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