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Beam test on bond behavior between high-grade rebar and high-strength concrete after elevated temperatures

Jianzhuang Xiao [a,*], Yizhao Hou [a], Zhanfei Huang [b]

[a] Department of Building Engineering, Tongji University, Shanghai 200092, China
[b] DTL3C3 C925A PDO, Land Transport Authority of Singapore, 1 Hampshire Road, Singapore 219428, Singapore

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ABSTRACT

In this paper, post-heating bond behavior between high-grade rebar and C80 high-strength concrete (hereafter, HSC) is studied. The high-grade rebar is HRBF500 fine grained steel with a yield strength of 500 MPa and the concrete grade C80 denotes compressive strength not lower than 80 MPa. First, the residual mechanical behavior of both high-grade rebar and HSC were tested after fire exposure. Second, the beam bond test was carried out to study the bond behavior between high-grade rebar and HSC after exposed heating at 200 °C, 400 °C, 500 °C and 600 °C, respectively. During the bond test, the influence of temperature, bond length, and some construction measurements on the bond–slip behavior were compared and evaluated. The investigation demonstrates that (1) the bond strength between high-grade rebar and HSC decreases while the peak slip increases with the elevated temperature, especially when the temperature exceeds 400 °C and (2) the confinement effect of steel wire mesh can help to improve rebar's bond behavior. Third, the bond–slip model between high-grade rebar and HSC for post-heating is proposed.

1. Introduction

With the development of high-rise buildings and underground constructions, high-strength concrete (hereafter, HSC) is becoming a widely applied material in modern civil engineering because of its high compressive strength and excellent durability. Because of various reasons, building fires caused by human or natural factors frequently occur. After Sep. 11, 2001, engineers and researchers gradually realize the importance of the anti-fire and anti-blast behavior of high-rise building. Up to date, many researchers have studied on the behavior of HSC in fire and some consensuses have been drawn.

At present, studies on the bond behavior during and post-heating mainly focus on normal-strength concrete (hereafter, NSC). Researches indicate that the tensile strength of concrete, appearance of reinforcement and degree of rust are the main factors that affect the bond behavior during and after the heating. For instance, Diederichs and Schneider [1] pointed out that the influence factors for the bond strength included test process, surface shape of reinforcement and heating temperature. Ferhat and Ruestem [2] studied the residual bond strength between steel bars and concrete after the heating. They concluded that concrete-bar bond strength increased with the concrete strength and embedment length of rebar. Zhu et al. [3] conducted pull-out tests of 40 plain and ribbed bars at room temperature and under (after) high temperatures. The results indicated that high temperature significantly influenced the bond behavior between plain bar and concrete. However, its influence on the bond behavior between ribbed bar and concrete is limited. Besides, the bond strength cannot increase again once the specimen has been cooled to room temperature. Royles [4] studied the influence of different thickness of concrete cover on bond strength under 720 °C. He pointed out that specimens with thinner concrete cover experienced a greater decrease in bond strength and the bond strength further decreased under repeated loading. Other researchers such as Zhou and Wu [5], Morley [6], Thanyawat [7] and El-Hawary [8] have also conducted similar studies.

But only a few researches were devoted to examine bond behavior of HSC under and after elevated temperature exposure. Xiao and Huang [9] undertook some preliminary study on the bond behavior between high-grade rebar and HSC with pull-out testing and put forward a simple bond–slip relationship. Sait and Turan [10] compared the post-heating mechanical properties of NSC and HSC. It is found that in terms of residual properties, HSC specimens performes better than NSC specimens for all heating cycles. Haddad and Shannis [11] investigated the post-fire bond

* Corresponding author. Tel.: +86 21 65982787; fax: +86 21 65986345.
E-mail address: jzx@tongji.edu.cn (J. Xiao).

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between HSC with natural pozzolan (hereafter, NP) and reinforcing steel. It is found out that the use of NP at a content of 25% would significantly improve the resistance against cracking without sacrificing the bond strength. As for bond recovery after post-heating recurring [12], water-recurred specimens achieved obvious strength and bond recoveries, while air-recurred specimens achieved limited strength and bond recoveries. Last but not least, Campione [13] investigated the local bond stress–slip relationship of reinforcing bars embedded in lightweight fiber reinforced concrete with expanded clay aggregates. The influences of several parameters, such as the dimension of specimens, anchorage length and so on, have been examined.

As for high-grade rebar, improved elongation and toughness as well as a higher strength are obtained by refining grain. On the basis of study on the material behavior of high-grade rebar under elevated temperatures, the authors [14] further experimentally studied the mechanical behavior of HRBF500 high-grade rebar under elevated temperatures.

At present, investigations of the bond behavior between rebar and concrete after elevated temperatures mainly adopt the pull-out test. In a central pull-out test, rebar is subjected to tensile force while concrete is in compression. It should be pointed out that seldom does such a scenario occur in the actual engineering practices. This is because the thickness of concrete cover in the test is generally several times greater than that in a real concrete structure, and this leads to experimental bond strength being often greater than that in a practical situation. On the other hand, beam test where the concrete is in tension (so that the weakness of central pull-out test can be overcome) [15] offers a good alternative to examine the post-heating bond behavior. The latter is adopted in this study.

2. Significance of research

After a fire event, the degradation of mechanical properties of HSC leads to the deterioration of safety, integrity and durability of a structure. Examination of the post-heating bond behavior between high-grade rebar and HSC can promote the application of high-performance materials as well as establish certain theoretical basis for strengthening a fire-attacked reinforced concrete (RC) structure and determining the changed behavior of rebar—this is essential for evaluating the structure after a fire attack. In this paper, beam tests were conducted to study (1) how bond behavior between high-grade rebar and HSC changes after exposed to different heating temperatures, (2) how bond length affects the bond–slip behavior, and (3) how steel wire mesh affects the bond performance after a fire attack.

Table 1
Mechanical property of high-grade rebar at room temperature.

Diameter (mm)	Yield strength (MPa)	Yield strain (%)	Ultimate strength (MPa)	Ultimate strain (%)	Elastic modulus ($\times 10^5$ MPa)
12	555	0.27	721	12.15	2.06

Table 2
Mixture ratio of C80 HSC.

Mixture ratio (kg/m^3)						Slump (mm)
Cement	Slag	Sand	Crushed stone (5–20 mm)	Water	Water reducing agent	
406	174	619	1151	162	30	200

3. Experimental program

3.1. Experiment materials

HRBF500 high-grade ∅12 rebar was selected in this investigation, its main mechanical properties are listed in Table 1. For the C80 HSC, the cement was Grade 52.5 ordinary Portland cement, the slag was high-performance grounded furnace slag, the water was tap water, the fine aggregates were medium sand, the coarse aggregates were continuous grading calcareous crushed stone with a diameter of 5–20 mm and the water reducing agent was polycarboxylates high-performance water-reducing admixture. The mixture ratio is listed in Table 2.

3.2. Design of specimen

Specimens were designed and cast according to the *Standard Methods for Testing of Concrete Structures* [16] and RILEM-FIP-CEB's recommendation [15] on beam bond test. In total, there were 21 test beams with a typical size of 100 mm × 180 mm × 680 mm. Detailed dimensions of specimens are shown in Fig. 1 and listed in Table 3. In Fig. 1, the PVC pipe was used to eliminate the influence of the transverse force at the support and mid-span and l_a denotes bond length of the high-grade rebar. Concrete cover for the bottom bar was 50 mm and the stirrup was HPB235 Φ4@40. Due to fire exposure, the steel hinge in the middle of beam was replaced by concrete.

Six standard 100 mm concrete cubes were cast for examining the residual compressive strength of concrete. Another six more cubes were also prepared to serve as standbys (in case that cubes spalled during or after the heating). Specimens were cast in the moulds and cured at ambient condition for 28 days after the moulds were removed. Before the testing, the specimens were moved to a dry room with good ventilation for one-month natural drying.

4. Fire test under elevated temperature

4.1. Heating program

A 36 kW DRX-36 high-temperature test furnace was used for this study. The furnace is able to achieve a maximum operating

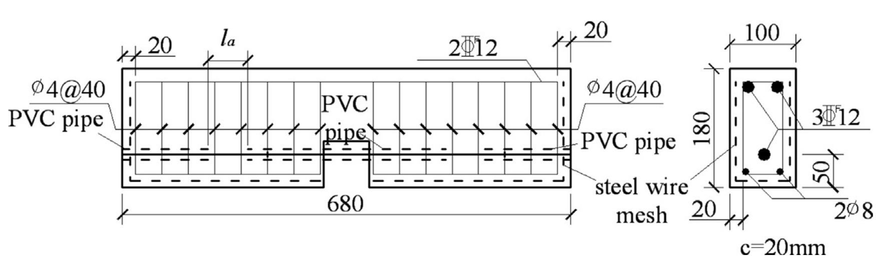

Fig. 1. Details of a beam specimen.