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Assessment and restoration of bond strength of heat-damaged reinforced concrete elements

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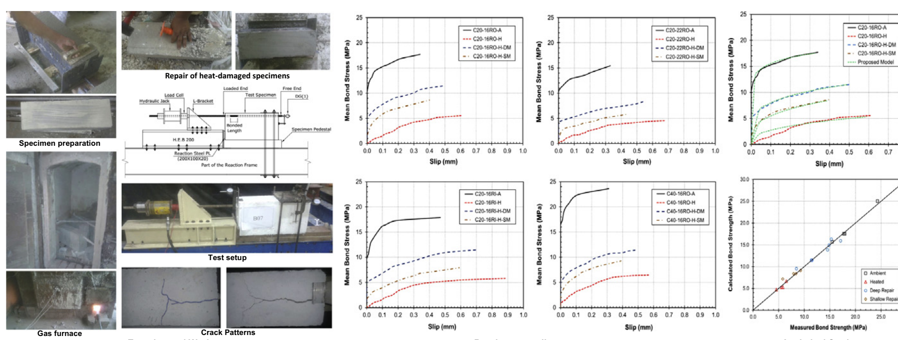
HIGHLIGHTS

- Elevated temperature dramatically decreases the ultimate bond strength.
- The beam end specimen gives reliable data while maintaining a small size.
- Deep repair is more efficient than shallow repair in restoring the bond strength.
- Commercially fiber reinforced mortar provides the highest restoring bond ability.
- The proposed relationships provide a good prediction of ultimate bond strength.

GRAPHICAL ABSTRACT



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ABSTRACT

This investigation focuses on the assessment of the residual (after cooling) bond strength between concrete and steel rebars of reinforced concrete elements after exposure to elevated temperature and how to restore the bond strength using different repairing techniques and materials. The bond test was carried out on twenty-four beam end test specimens. The test parameters considered in the current research are the exposure condition, concrete compressive strength, rebar type, rebar size, rebar location, repairing techniques, and repairing materials. The test results indicated a significant reduction in the residual bond strength for heat-damaged specimens with a dramatic change in the bond stress-slip behavior. The deep repair technique is more efficient than the shallow repair technique in restoring a large portion of the original bond strength for heat-damaged specimens. Among the different repair materials used in the current research, the commercially fiber reinforced mortar is the most efficient one. Based on the limited number of specimens considered in this study, simple relationships are proposed to predict the bond strength and characterize the bond stress – slip behavior. The proposed relationships yield good agreement with the experimental results.

1. Introduction and background

Reinforced concrete (RC) structures are vulnerable to elevated temperature during fire exposure. At elevated temperatures, the mechanical properties of concrete and reinforcing steel as well as the bond performance between concrete and steel rebars may significantly deteriorate. Many research efforts have been paid to study the mechanical properties of different concrete types at elevated temperature or to investigate the residual properties of concrete after exposure to elevated temperatures [1–14]. In general, the results showed that the mechanical properties such as compressive strength, modulus of elasticity and splitting tensile strength decreased and this resulted in structural quality

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Notation

f'_c	Cylinder concrete compressive strength	α	Parameter characterizes the ascending branch of BPE model
f'_{c800}	Cylinder concrete compressive strength after heating to 800 °C and cooling	σ_u	Tensile stress in the rebar corresponding to ultimate applied load
f_t	Average splitting tensile strength of repair materials	τ_u	Average ultimate bond strength
K_a	Slope of ascending branch of the bond stress – slip curve	τ_{u800}	Residual bond strength after heating to 800 °C and cooling
L	Bonded length	$\tau_{uD.R}$	Restored bond strength for deep repaired specimens
P_u	Ultimate applied load	$\tau_{uS.R}$	Restored bond strength for shallow repaired specimens
R_r	Relative rib area	$\varnothing$	Rebar diameter
S	Slippage		
S_u	Slippage corresponding to the ultimate bond stress		

deterioration of concrete. Moreover, It indicated a significant role of the aggregate type, the shape and size of specimen, use of additives, and whether concrete is sealed or not on the strength reduction. Consequently, the structural capacity of concrete elements is reduced and structural failure may be occurred under existed loads.

During the last few decades, the bond behavior during and post exposure to elevated temperature have been investigated and reported by several researchers. Some researchers studied the effect of elevated temperature on the residual bond strength [15–23] and others investigated the bond-slip relationship [24–32] with respect to various parameters. The majority of these studies has conducted on pullout test specimens due to their simplicity. In the pull out test, the steel rebar is subjected to tensile stress while concrete is in compression. It should be indicated that such scenario rarely happens in the real reinforced concrete elements, and this leads to experimental bond strength greater than that in a practical situation. Therefore, there is a need to conduct more investigations to study the bond behavior after exposure to elevated temperature using a more realistic type of specimens. The beam end test specimen, adapted for this study, where the concrete is in tension offers a good alternative to study the bond behavior.

Degradation of bond strength at elevated temperature may significantly influence the load capacity of the RC elements. Recovering the structural integrity of heat-damaged RC elements requires extensive repair and rehabilitation works. The major challenge for structural engineers to develop efficient rehabilitation techniques that enable to restore the structural integrity of RC elements after exposed to elevated temperature. Very limited researches are carried out to study different techniques for repairing heat-damaged RC elements [11,13,33–38]. These techniques were conducted essentially by removing the deteriorated concrete layer and replacing them with concrete, ferrocement, and fibrous grout layers as well as fiber reinforced polymer sheets.

The assessment of the degree of deterioration of the concrete structure after exposure to elevated temperatures can help engineers to decide whether a structure can be repaired rather than required to be demolished. Furthermore, the decision to use a surface repair or deep repair technique represents another challenge to the structural engineers. To date, limited or no data exist in the literature so there is a dearth of information on restoring the bond between concrete and steel rebars for heat-damaged RC elements using either surface repair and deep repair.

To bridge the existing lack of knowledge related to the residual bond strength and how to restore it for heat-damaged RC elements, this paper presents an experimental and analytical investigation on the assessment of residual bond strength between concrete and steel rebars after exposure to elevated temperature and cooled in air to room temperature. It also discusses the effectiveness of using different repairing techniques and materials to restore the bond strength between concrete and steel rebars. The bond tests were carried out using beam end specimens. The test parameters considered in this research include: exposure condition, concrete strength, rebar type, rebar size, rebar location, repairing technique and repairing material.

2. Experimental program

The experimental program consisted of twenty four beam end specimens. Ten beam end specimens were cast to assess the post heat bond strength between concrete and steel rebars, five of them were heated, air cooled to room temperature and then tested while the other specimens were cast and tested at ambient temperature. To assess the effectiveness of using different repairing techniques and materials in restoring the bond strength, fourteen beam end specimens were cast, heated, air cooled to room temperature, repaired using different repairing techniques and materials and then tested.

2.1. Test specimens

A total of twenty four beam-end specimens with nominal dimensions of 200 mm wide, 300 mm high, and 600 mm long were tested. The beam configuration was selected to satisfy the requirements of the ASTM A 944-10 [39]. The beam end specimen was selected because it totally simulates the behavior of the bond between rebars and concrete in flexure members. Fig. 1 shows the geometry, configuration and dimensions of the test specimen used in this investigation. Each specimen was reinforced with one tested rebar in the tension side of the beam. The bottom and side concrete covers of the tested rebar were kept constant for all specimens at 50 and 100 mm, respectively. To avoid possible conical failure, the first 50 mm of the rebar from the concrete surface at the loaded end was debonded using a plastic tube, as shown in Fig. 1. The lead length was followed by the tested bonded length of 5 times the tested rebar diameter followed by a debonded length throughout the remaining portion of the specimen. Each of the tension and compression zone was reinforced with two 12 mm deformed steel rebars. Shear reinforcement consisted of 8 mm diameter stirrups at a center-to-center spacing of 125 mm was provided.

2.2. Test matrix

The test parameters considered in the current research include: exposure condition, concrete strength, rebar type, rebar size, rebar location, repairing technique and repairing material. Two different exposure conditions were applied to the specimens. In the heat exposure condition, all the heat-damaged specimens were sub-