Study on bond behaviour exposed to fire using beam specimen

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Abstract

The composite action of concrete and steel in a reinforced concrete structure depends upon the bond between them. Bond behaviour is studied in terms of bond-slip relationship. The bond between them depends upon mechanical properties of concrete and steel. In an event of fire these mechanical properties degrades and hence the bond behaviour changes. Some researches were performed to study the effect of temperature on the bond-slip relationship which are based on pull out specimens. Generally these relationships are obtained using pull out specimen which over estimates the bond properties. In this study beam specimens were used which is recommended by Rilem. These specimens were exposed to elevated temperatures up to 650 °C and there bond-slip behaviour were studied. The study shows that bond strength decreases while peak slip increases with increases in temperature. Also an equation proposed was proposed which can predict the bond strength between concrete and steel exposed up to the temperature of 650 °C.

1. Introduction

In reinforced concrete members the stress transfer from steel to concrete is due to bond. The bond between concrete and steel is due to three basic mechanisms: adhesion, friction and mechanical interlocking between ribs and the mortar matrix. The adhesion between steel and concrete is due to the chemical action between them. This part of the bond is the weakest one and the first interface between the duos which can be overcome at very nominal stress in the bar. Soon as bar starts moving the friction comes in to picture because of the rouge surfaces in contact to each other however both the above contributions are almost negligible and vanishes at very early stage of loading. Later the mechanical interlocking becomes the only cause of bond between concrete and steel. Further upon loading the ribs in steel causes some crushing of concrete in front of them and bearing causes hoop stresses in concrete surrounding the stressed steel. Sometime these hoop stresses exceeds the tensile strength of the concrete (when the cover around steel is lesser) which causes the splitting of the surrounding concrete. However when they does not exceed the tensile strength of the concrete no splitting was observed rather the lug crushes the concrete in front of them resulting in a more ductile failure often called as pull-out failure.

When RC elements exposed to fire or elevated temperatures the first thing that is influenced is the interface between steel and concrete (since cover is exposed). During the fire exposure the temperature of the section increases and achieved its maximum temperature during cooling phase. The mechanical properties of concrete and reinforcing steel degrades as the temperature increases [1]. In this way the splitting of the same concrete occurs very early in comparison to concrete at ambient temperature. Also the same applies to the pull out failure.

Studies have been carried out in past to understand the behaviour of bond in RC elements when they are exposed to elevated temperatures [2]. Generally the specimens used are pull-out specimens which are not the representative of the true state of bond because during testing the concrete remains in compression while steel is in tension hence in the process the bond strength is overestimated. This study...
was carried out on beam specimen to understand the bond behaviour more accurately since the steel and concrete both are in tension while testing.

2. Experimental program

2.1 Specimen details

The specimen was similar to Rilem beam specimen for the assessment of bond behaviour at ambient temperature. Since the diameter of the bar was 12 mm the beam specimen type I was used also the development length was kept ten times the diameter of the bar. The details of the Rilem beam specimens [3] are shown in the figure.1

![Figure 1. (a) Loading arrangement and cross sectional details (b) auxiliary reinforcement and position of thermocouples.](image)

2.2 Instrumentation and casting

The specimen was instrumented with K type Chromal-Alumal thermocouples in the middle of each halves of the specimens at the three locations as shown in figure 1(b) in order to ensure steady state during heating. The main reinforcing bar under study was 12 mm nominal diameter of yield strength 500 MPa. However the auxiliary bars provided were having a yield strength of 250 MPa. The concrete was proportioned with OPC 43 grade cement and carbonate aggregate conforming to IS 8112 [4]. It had a consistency of 30% and Blaine fineness of 355 m²/kg. River sand with a specific gravity of 2.64 and fineness modulus of 2.90 was used as the fine aggregate; while natural crushed coarse aggregate of specific gravity 2.69 was used as coarse aggregate. Third generation carboxylic ether based superplasticizer was used to obtain the desired workability. The Indian standard IS: 10262-2009 [5] was used
for proportioning of M35, the cement content was 390 kg/m³ bearing a ratio of 1:3:1.75 with course aggregate and fine aggregates respectively and the water to cement ratio was 0.42. The cubic compressive strength of concrete after 28 days was found to be 38.6 MPa.

2.3. Heating-Cooling
The specimens were heated in an electric beam furnace at a rate of 5 °C/min until the desired temperature was reached as shown in figure 2 (a) and then a soaking period of two hour were kept so that the beam specimen should achieve steady state. After soaking the specimens were cooled to room temperature in furnace as shown in figure 2 (b).

3. Testing
Soon after cooling to room temperature the beam specimens were tested under four point bending as per as shown in the figure 3 (a) at a loading rate of 30 N/mm²/min. The figure 3 (b) shows the placement of LVDT's on the concrete surface and attached to the reinforcing bars so as to capture the relative displacement of steel and concrete. Displacement was monitored till both the sides attained a slip of 4 mm which is greater than the rib distance of the reinforcing bar.

Figure 2. (a) Time temperature curve of beam specimen (b) Specimen after cooling in the furnace

Figure 3. (a) Testing set up for the Rilem beam specimen (b) Arrangement of LVDT for the measurement of displacement.
4. Results and Discussions

All the specimens were failed in pull out mode and the load-slip curve from both halves of the beams were obtained and an average load-slip curve was produced. The bond stress along the length was assumed to be constant for this development length L and can be calculated from the stress in the bar.

The stress in the bar was calculated from the mechanics based equation as \[ \sigma = \frac{1.25P}{A} \] where P is the load applied, d is the diameter and A is the cross-sectional area of the reinforcing bar. Hence the bond stress \( \tau_b \) at any load can be calculated by assuming the force in the bar being fully transferred to the surrounding concrete as

\[
\begin{align*}
\tau_b \pi d L &= A \sigma \\
\tau_b &= \frac{A \sigma}{\pi d L} \\
\tau_b &= \frac{\sigma \pi d^2}{4 \pi d L} \\
\tau_b &= \frac{\sigma}{40}
\end{align*}
\]

The figure 4 (a) shows the bond stress vs slip for three temperatures viz ambient, 350 °C and 650 °C. In all the three curves the bond stress first increases with slip and then decreases. However some differences were observed. The peak bond stress or bond strength decreases with increases in temperature. This behaviour can be attributed to the fact that the previous studies [6-8] shows bond strength as a function of concrete compressive strength and the concrete compressive strength decreases with increase in temperature hence the strength reduction can be explained. The peak slip increases with exposure to elevated temperature however shows no significant difference when the temperature is increases from 350 °C to 650 °C figure 4 (b), this can be explained on the basis that the slip is not dependent on the strength of the concrete rather depends on the reinforcing surface properties and the reinforcing surface is same for all the specimens.

![Figure 4](image)

**Figure 4:** (a) Bond stress vs slip (b) Slip vs temperature (c) Comparison of experimental to predicted bond strength (d) normalised bond strength with temperature
The experimental bond strength was compared to the bond strength expression proposed by FIB model code 2010 [9] considering the degraded compressive strength model as per Eurocode 4 [10] figure 4 (c). It was observed that the bond strength at elevated temperature was being overestimated which may be since the FIB model code expression was based on the pull out specimens. These pull out specimens over estimates the bond strength because during pull out the concrete is in compression but steel remains in tension. The figure 4 (d) shows the linear relationship of normalised bond strength degradation with temperature. This equation can predict the bond strength up to 650 °C and can be expressed as

$$\tau_f/f_{ck} = -0.0003(T) + 0.3715 \quad (3)$$

5. Conclusions

The study however is not extensive but gives an insight that how the bond behaves using beam specimens. Firstly the bond strength decreases with increase in temperature. Also the peak slip increases with increase temperature. The mode of failure however does not change with increase in temperature. The model available at ambient over estimates the bond strength hence not recommended. An equation for prediction is proposed also more extensive study is needed to establish the accuracy of the equation.

Example: The bond strength of fck 40 MPa after exposure to 400 °C can be calculated using equation

$$\tau_{400} = (-0.0003*400 + 0.3715)*40$$

$$= 10 \text{ MPa}$$

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