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Effect of temperature induced bond degradation on fire response of reinforced concrete beams

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ABSTRACT

The influence of temperature induced bond degradation on response of reinforced concrete (RC) beams exposed to fire is presented. A finite element based numerical model is developed in ABAQUS for tracing the response of reinforced concrete beams exposed to fire. Temperature induced interfacial bond degradation between concrete and reinforcing steel is specifically taken into account using bond-link element approach. The effect of temperature dependent local bond stress-slip relations on fire resistance of both normal strength and high strength reinforced concrete beams is investigated. A comparison of numerical model predictions with response parameters measured in fire tests clearly indicate that interfacial bond between reinforcing steel and concrete can influence extent of strength degradation and deflections in RC beams exposed to fire leading to relatively lower fire resistance in the beams. Hence, the current approach of assuming a perfect bond between rebar and concrete in fire resistance analysis of reinforced concrete structures may be un-conservative in certain scenarios, especially for RC beams reinforced with smooth rebars and when rebar temperature exceeds 400 °C.

1. Introduction

Reinforced concrete (RC) structural members, when exposed to elevated temperatures, as in the case of fire, experience loss of structural capacity as a result of temperature induced degradation in mechanical properties of reinforcing steel and concrete [1]. Of the various properties, bond between concrete and rebar is critical in facilitating load transfer between concrete and rebar along the longitudinal direction of reinforcement. Temperature induced bond deterioration can lower the extent of tensile stresses transfer from concrete to rebar, and thus influence the stiffness or the moment capacity of RC members exposed to fire. Previous studies indicate loss of bond to be about 60% of its room temperature value when temperatures at the interface of rebar and concrete exceed 500 °C and this can significantly reduce the load-bearing capacity of RC members under service loads [2]. It is worth mentioning that, for an un-bonded post-tensioned RC beam exposed to fire, the bond between steel and concrete in the anchorage zones is a critical issue since sudden structural failure may occur due to the loss of anchorage bond [3].

Under fire conditions, temperature induced bond degradation influences crack propagation in concrete, and has an effect on the integrity of the beam. Furthermore, such localized damage (cracking) can be a significant factor when carrying out post-fire repair using a layer of externally bonded dissimilar material (such as FRP) on the fire exposed surface of the beam. Indeed, the failure mode (de-bonding) in FRP-strengthened beams is strongly influenced by cracking patterns and crack widths that occur in concrete [4].

In current practice, the effect of temperature induced bond degradation is not specifically taken into consideration in evaluating response of fire exposed RC members. This is largely due to the fact that there are no reliable guidelines for incorporating temperature induced bond degradation in fire resistance analysis of RC beams. Furthermore, only a limited number of publications have appeared on this problem [3,4]; and a fundamental understanding of the relationship between bond and temperature is still lacking. This is due to the complex nature of the problem and lack of experimental and numerical data on bond degradation in RC members under fire conditions. Moreover, the effect of bond degradation on both the global response as well as local response in terms of bond-slip and stress distribution within rebar under elevated temperature exposure is not well established.

With these considerations, this paper presents a numerical model accounting explicitly for fire induced bond degradation in

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tracing response of RC beams under fire conditions. Both normal strength concrete (NSC) and high strength concrete (HSC) beams are considered in the present study to evaluate the effect of concrete strength. Also, in addition to proposed relations for bond behavior at elevated temperatures in numerical models [1,5], a generalized material model, based on experimental data generated from residual bond tests [6] is incorporated in the finite element model for comparison. Furthermore, the validated model is utilized to examine the localized behavior at rebar-concrete interface in fire exposed RC beams to illustrate the effect of bond degradation on fire resistance of RC beams.

2. State-of-the-art on temperature induced bond degradation

There are limited studies in the literature on the problem of temperature induced bond degradation between reinforcing (or pre-stressing) steel and concrete in fire exposed RC members. While the temperature induced deterioration in strength and stiffness properties of concrete and reinforcing steel is studied extensively and codified [7–11], only very limited investigations focused on bond degradation at elevated temperatures. Current design codes for RC structures under fire conditions assume a perfect bond between concrete and reinforcing steel throughout the temperature range encountered in a fire. Moreover, there are no clearly established principles or methods in current design standards or codes for incorporating deterioration of bond between reinforcing steel and concrete in evaluating fire resistance of RC structures. Some of the notable experimental and numerical studies pertaining to temperature induced bond degradation are reviewed here.

Early tests to study deterioration of bond with temperature were conducted by Diederichs and Schneider [12] through concentric pull out tests on NSC specimens in 20 °C–800 °C temperature range under both steady state and transient thermal conditions. They concluded that shape of the rebar (ribbed or smooth) has significant influence on bond strength besides temperature itself. Also, the rate of temperature induced bond strength degradation was found to be higher than the rate of degradation of respective strengths in concrete and reinforcement with temperature [12].

Morley and Royles [13] studied bond behavior through concentric pull out tests on NSC specimens under four different test conditions, namely, stressed during heating and loaded to failure when hot; stressed during heating and loaded to failure when cooled; no applied stress during heating and then loaded to failure under hot state; and finally no applied stress during heating and loaded to failure after cooling. The concrete cover to the reinforcement was also varied during tests. Based on test results, the authors pointed out that bond in specimens stressed during heating was higher than those that were not stressed. Higher concrete cover led to relatively larger slip indicating a pull-through type of failure. Also, crushing of concrete immediately beneath the ribs in rebars was the primary mode of bond failure in these tests. Similar to previous study by Diederichs and Schneider [12], the reduction in bond strength with temperature was found to be higher than the corresponding reduction in the compressive strength of concrete [13].

In a relatively recent study, Haddad et al. [14] studied the effect of elevated temperature on the bond between steel reinforcement and fiber reinforced concrete members through double pull-out tension tests for temperatures ranging from 350 °C to 700 °C. The specimens were heated to a target temperature without any applied loading during heating, and then cooled down to room temperature before loading to failure. The authors concluded that significant reduction in bond strength between concrete-rebar occurs when temperatures at the interface exceed 400 °C.

Besides the aforementioned tests at the material level, limited numerical and analytical studies are reported on modeling temperature induced bond degradation between rebar and concrete. Pothisiri and Panedpojaman [15] developed a mechanical model for predicting bond strength between rebar and concrete at elevated temperatures by incorporating smear crack theory. Based on a parametric study conducted using the developed model, the authors concluded that bond strength predictions using empirical models developed using experimental data to be un-conservative when concrete cover thickness to rebar diameter ratio is less than two.

At the structural level, very few studies are carried out to study the effect of temperature induced bond degradation on fire response of RC members. Various numerical models have been developed in the last few decades to trace the response of fire exposed RC structures [1,5,16–21]. These models take into consideration load level, boundary conditions, as well as deteriorating stress-strain characteristics of concrete and reinforcing steel at elevated temperatures. However, in most of these numerical models, a perfect bond is assumed between rebar and concrete throughout the temperature range of 20 °C–800 °C.

The variation of temperature induced bond between rebar and concrete was specifically considered only in three different studies by Huang [1], Gao et al. [5] and Panedpojaman and Pothisiri [18]. In these three studies, the authors incorporated the influence of bond degradation utilizing zero thickness bond-link (spring) elements in evaluating response of RC beams under fire. The authors illustrated that assuming a perfect bond between rebar and concrete at elevated temperatures may lead to un-conservative predictions of fire resistance in RC beams in certain scenarios. The extent of influence of temperature induced bond degradation on overall fire resistance predictions varied depending on the assumptions used in analysis. However, the effect of rate of temperature induced bond degradation or the influence of different concrete strengths on fire resistance was not quantified in these studies.

The above literature review indicates that the bond behavior at concrete-rebar interface at elevated temperatures is complex and can depend on numerous factors including rebar surface characteristics, concrete properties, heating conditions and other characteristics. Very few studies are reported to incorporate temperature induced bond degradation in evaluating fire resistance of RC structural members. Further, these limited studies focused mainly on NSC members and no studies are reported for concretes of higher strength. In addition, the effect of different local bond models on global response and localized rebar stresses or bond-slip of fire exposed RC beams is not studied exclusively. The present study is aimed at incorporating bond degradation in evaluating response of fire exposed RC members.

3. Interfacial bond at elevated temperatures

Concrete at material level, exhibits linear elastic response up to almost 80% of its tensile strength; followed by marginal post-peak softening due to micro-cracking in the cement-matrix, as well as cement-matrix-aggregate interface. This steep descending branch in concrete under tension is a consequence of aggregate interlock across the crack plane, as well as discontinuous nature of microcracks which can coalesce only when further deformation occurs in the specimen [22]. This ‘softening’ behavior gets enhanced at elevated temperatures due to reduction in tensile strength and almost no reduction in fracture energy, leading to a softening branch with a lower slope (larger ultimate tensile strain) [5].

At structural level the tensile behavior of concrete in an RC member is even more complicated due to bond interaction at concrete-reinforcing steel interface. In particular, when tensile cracking occurs in RC beams, undamaged concrete present between cracks has the ability to carry tensile stresses and provide stiffness. This phenomenon, referred to as tension stiffening, is