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Analysis of bond-slip between concrete and steel bar in fire

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ABSTRACT

This paper presents a robust model for predicting the bond-slip between the concrete and steel reinforced bar at elevated temperatures. The model is established based on a partly cracked thick-wall cylinder theory and the smeared cracking approach is adopted to consider the softening behaviour of concrete in tension. The model is able to consider a number of parameters: such as different concrete properties and covers; different steel bar diameters and geometries. The proposed model has been incorporated into the *Vulcan* program for 3D analysis of reinforced concrete structures in fire. The model has been validated against previous test results.

1. Introduction

Exposure of concrete structures to high temperatures leads to significant losses in mechanical and physical properties of concrete and steel reinforcement as well as the bond characteristics between them. Degradation of bond properties in fire may significantly influence the load capacity or flexibility of the concrete structures. Therefore the bond behaviours need to be considered for the structural fire engineering design of reinforced concrete structures. At present, the information about the material degradations of concrete and reinforcing steel bars at elevated temperatures are generally available. However, the research on the response of the bond characteristic between concrete and reinforcing steel bar at elevated temperatures is still limited [1,2].

Previous researchers indicated that when the reinforced concrete members are loaded, the stresses in the interface between concrete and steel bar increase. The capacity of the interface to transmit stress starts to deteriorate at the particular load level, and this deterioration becomes worse at elevated temperatures. The damage at the interface of the bond gradually spreads to the surrounding concretes. The development of this process results in a slip between the steel and concrete. The mechanism to transfer stresses between concrete and rebar can be represented by adhesion, mechanical interlock and friction. Adhesion can be defined as the chemical bonds which are developed during the curing process of concrete. This bond is very small and can be lost in the early stages of loading or during exposure to fire. Hence, this kind of the bond can be ignored in the modelling of bond characteristics in fire. In the case when deformed bars are used, stresses are transferred mainly by mechanical interaction between the rebar's ribs and the adjacent concretes. Also, the friction does not occur until there is a slip between the steel bars and concrete [3–6].

For the mechanical interaction of the bond, there are two types of bond failure which can take place. The first one is pull out failure (shear off) due to the cover of concrete is very large and under high confinement. In this case, concretes are shearing off by the wedging action of ribs, and then concretes between the ribs are crushed gradually resulting in a pull-out failure. The second type of failure is splitting failure due to the cracks of the concrete cover surrounding the steel bar start to propagate radially. This type of failure is more common for pull-out tests of reinforced steel bars in the real structures [2–4].

During the past decades, numerous models have been developed to calculate bond stress at ambient temperature [3–8]. The majority of these models is empirical and based on a statistical methodology. Thus, these models are highly dependent on the test data, which may limit their validity in the different situations [3]. Currently there are a limited number of numerical models available for modelling bond characteristics at elevated temperatures. Huang [9] adopted the CEB-FIP bond-slip model at ambient temperature [10] and considered the degradation of bond strength at elevated temperatures by using the experimental results generated by Bazant and Kaplan [11]. Hence, the Huang's model is the first order approximation of the bond characteristics in fire. Pothisiri and Panedpojaman [2] have proposed a mechanical bond-slip model at elevated temperatures based on the theory of thick-wall cylinder and smeared crack of concrete in tension. The model has taken into account the variation of concrete properties with temperatures and the differential thermal expansion of rebar and

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Nomenclature

Notation

σ_r	radial stress
$\sigma_{t,T}$	tangential stress at elevated temperatures
P_T^i	total radial pressure at elevated temperatures
$P_{i,T}$	pressure resistance of the elastic outer zone at elevated temperatures
r	radius from the centre of the rebar
R_s	radius of the steel bar
R_c	radius of concrete cylinder = R_s + the least thickness of concrete cover
R_i	radius of the uncracked inner face
$\varepsilon_{u,T}$	smeared strain of concrete at elevated temperatures when tensile stress equal to zero
$\varepsilon_{t,0}$	smeared tangential strain at the rebar interface
f_{ct}	tensile strength of concrete at ambient temperature
$E_{0,T}$	initial elastic modulus of concrete at elevated temperatures
τ_T^i	bond stress at elevated temperatures
α	effective face angle
$f_{ct,T}$	degradation of the concrete tensile strength at elevated temperatures
C	concrete cover
S_{max}	maximum slip at the maximum bond stress point τ_{max}
$F_{T,x}^i$	bonding force between the concrete and the steel bar
A	the contact area between the concrete and the reinforcing steel bar
U	perimeter of the steel bar
L	length of the steel bar which contributes to the node connected by the bond element
$\mathbf{\Delta F}$	nodal force increment vector
$\mathbf{\Delta u}$	nodal displacement increment vector
k_1^i	tangent stiffness coefficients of the bond connector
l_b	embedded length of the rebar inside the specimens
d_b	diameter of the rebar

concrete. However, the model was established to calculate the bond-slip based on the correlation between the experimental slip obtained from previous researches.

As indicated in Ref. [9], due to the lack of robust models for considering the influence of the bond characteristics between the concrete and steel bar at elevated temperatures, the majority of the numerical models developed for predicting the behaviour of reinforced concrete structures in fire was based on the full bond interaction. Hence, the main objective of this paper is to develop a robust numerical model for predicting the bond-slip between concrete and steel bar under fire conditions. The model presented in this paper is mainly based on the partly cracked thick-wall cylinder theory and the smeared cracking approach is adopted to simulate the splitting failure of the concrete cover. In this numerical model, the calculation of the bond slip relationship is based on the constitutive equations of concrete and geometric properties of the rebar and concrete cover. The developed mode can generate the bond stress–slip curve at elevated temperatures. The model can be used to calculate the bond radial pressure, bond stress versus slip. Also, this numerical model has been incorporated into the *Vulcan* software [12] for 3D modelling reinforced concrete structures under fire conditions.

2. Analytical model

The mechanical action between the rebar's ribs and the surrounding concretes is explained in Fig. 1. The transfer of the load between the reinforced bar and concrete is achieved by the bearing of the ribs on the concrete. The resultant forces acting on the ribs are compressive forces which are generated due to the restraint of the surrounding concrete. The compressive forces acting on the ribs resulted from the pull out load are decomposed into two directions, parallel and perpendicular to the reinforced steel bar. The reaction forces acting on the concrete, due to the perpendicular components of the compressive forces acting on the ribs, create circumferential tension stresses in the concretes surrounding the steel bar. If these tensile stresses exceed the tensile strength of concrete, splitting failure occurs [5]. Wang and Liu [5] have established a model based on the theory of thick wall cylinder [4] by taking into account the strain-softening of concrete in tension to calculate the maximum radial stress and maximum bond stress.

As mentioned above the bond-slip model developed in this paper is mainly based on the partly cracked thick-wall cylinder theory with the aid of a smeared cracking approach and average stress–strain of concrete in tension [4,5]. As shown in Fig. 2, the magnitude of the pressure acting on the steel rebar, P_T^i, increases when pull-out force acting on the rebar increases. When P_T^i reaches to the maximum value, which is the capacity of the bond, then the bond will fail and P_T^i starts to reduce with increasing bond slip until R_i reaching to R_c, in which R_i is radius of the uncracked inner face and R_c is the radius of concrete cover (see Fig. 2).

In the partly cracked thick-wall cylinder theory there are three stages: the first stage is the uncracked stage; the second stage is the partly cracked stage and the third stage is the entirely cracked stage [4,6].

2.1. Uncracked stage

As shown in Fig. 2a, for uncracked outer part of the concrete cover, the linear elastic behaviour of the concrete cylinder is assumed. Based on the theory of elasticity the pressure at inner surface of uncracked outer part $P_{i,T}$, compressive radial stress σ_r and the tensile tangential stress $\sigma_{t,T}$ are represented as [13]:

$$\sigma_r = \frac{R_i^2 P_{i,T}}{R_c^2 - R_i^2}\left[1 - \frac{R_c^2}{r^2}\right] \tag{1}$$

$$\sigma_{t,T} = \frac{R_i^2 P_{i,T}}{R_c^2 - R_i^2}\left[1 + \frac{R_c^2}{r^2}\right] \tag{2}$$

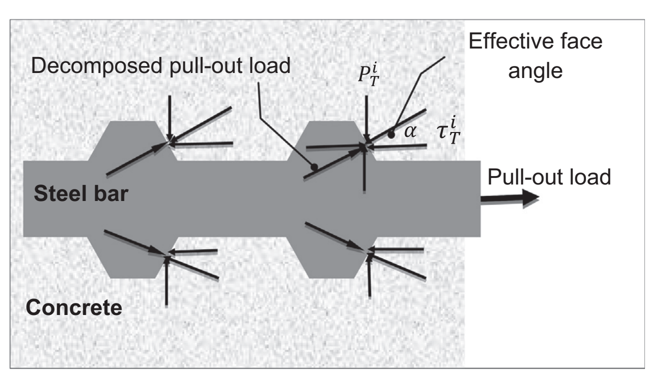

Fig. 1. Mechanical action between the steel bar and concrete.