Construction and Building Materials 128 (2016) 12–23

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Analysis of the bond behaviour between prestressed strands and concrete in fire

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HIGHLIGHTS

- Develop a robust model for modelling the bond-slip between concrete and strands for prestressed concrete structures in fire.
- Incorporate the bond-slip model into the 3D finite element analysis of prestressed concrete structures in fire.
- The model has been validated against previous test results and good agreements are achieved.

ARTICLE INFO

Article history:
Received 15 August 2016
Received in revised form 5 October 2016
Accepted 6 October 2016

Keywords:
Bond-slip
Prestressed concrete
Strands
Fire conditions

ABSTRACT

In this paper a robust model has been developed to predict the average bond stress-slip relationship between the strands and concrete of prestressed concrete structural members. Two bond-slip curves have been proposed to represent the bond-slip characteristics for the three-wire and seven-wire strands. This model considers the variation of concrete properties, strands' geometries and the type of strand surface, smooth or indented. The degradation of materials and bond characteristic at elevated temperatures are also included in the model. The proposed model has been validated against previous experimental results at both ambient and elevated temperatures.

1. Introduction

Prestressed concrete (PC) construction has obtained wide popularity in current building construction. PC members can be constructed by utilizing unbonded or bonded strands. For bonded PC members, the bond is essential for the success of prestressing system. The bond in PC members may be categorized as transfer bond and flexural bond. During PC manufacture, strands are initially prestressed by using jacks at the ends abutments. The concrete is cast and cured then the strands are cut. Initial tensioning of the strands causes a reduction of the strands diameter due to Poisson's effect. After concrete reaches sufficient strength, the strands are released from the abutments, and the stress in the strands at the free ends of the members returns to zero. With this reduction of the strand stresses, the diameter of the strand expands along the transfer length and wedging action caused by lateral expansion (called Hoyer effect) results in improved bond performance over the transfer bond length [1]. From the literatures, to determine the bond for the flexural bond length, pull-out tests had been conducted by cast the concrete surround the strand then; the strand is pulled from the concrete with measuring the pull-out force versus the slip. However, the bond for the transfer bond length can be obtained by applying initial prestress on the strand, and then casting the concrete until the time of test, then releasing the stress from the strand gradually with recording of stress released versus the slip [1,2].

For the bonded PC structural members, the force is transferred from strands to concrete through end anchors, together with the bond between strand and concrete. Therefore bonded PC beams are more robust structural members at ambient temperature. However, previous research indicated that compared to normal reinforcing steel, prestressed steel wires are more sensitive to elevated temperatures due to the stress level in prestressing wires is very high [3]. Structural fire safety is one of the most important considerations in building applications. The conventional approach of evaluating fire resistance through fire tests is expensive, time consuming and limited to study different parameters. An alternative to fire testing is the use of numerical modelling for evaluating fire resistance of PC structural members. Numerical methodology allows incorporation of various parameters in an efficient and cost-effective way [4].

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http://dx.doi.org/10.1016/j.conbuildmat.2016.10.016
0950-0618/

Nomenclature

V_c	shear force resistance of the concrete in front of strand ridges
v_c	shear strength of the shear keys in the concrete mass
A_{sh}	shear area of the cracked surface
d_w	diameter of the outer wires
l_w	length of the wires
d_s	nominal strand diameter
F	force along the length of the wires
C	cohesion between the concrete and steel
μ	coefficient of friction
θ	pitch angle of the outer wires
τ	peak shear strength ($v_c = \tau$)
f'_c	concrete compressive strength
f_t	concrete tensile strength
σ_n	normal stress perpendicular to the strand axes
P_1	initial tension force on the strand usually equal to 0.75 f_u (0.75 ultimate stress)
P_2	force after the stress released from the strand
A_s	nominal area of the strand
E_s	modulus of elasticity of the strand
v	Poisson ratio of the steel equal to 0.3
ε_{s1}	first strain of the strand at P_1
ε_{s2}	second strain of the strand at P_2
ε_c	strain of the concrete due to the lateral pressure of strand.
T_b	maximum bond force in the direction of strand
τ	average bond stress
$\tau_{\max}$	maximum bond stress
S	slip between strand and concrete.
A_b	contact area between the strand and concrete
τ_T	bond stress at elevated temperatures
$\tau_{\max,T}$	maximum bond stress at elevated temperatures

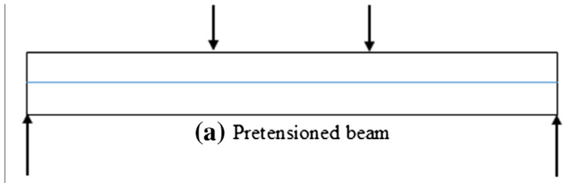
Previous research indicated that concrete structures begin losing strength rabidly when temperature reaches higher than 300 °C. The reduction of the concrete strength at elevated temperatures is commonly attributed to the degradation of the calcium silicate hydrate (C–S–H) as it begins to lose structural water along with dehydration of other hydrates like calcium hydroxide and ettringite. This dehydration leads to initiate internal thermal stress gradients especially with high density and low porosity of cement past. When temperature increases the water vapour inside the concrete is unable to escape causing pressure that builds up in the pores of concrete. This results in concrete cracking and potential damage to the concrete elements, also initiation of thermal incompatibility between aggregates and cement paste which leads to decompose of concrete [5]. On the other hand, exposer of concrete structures to high temperatures leads to significant losses in yield strength of the steel bars. This reduction can reach to half at temperature 550 °C. For the prestress steel, the loss of strength occurs at lower temperatures compared to normal steel rebar. A considerable reduction can occur in prestress steel strength at temperatures 300–400 °C [6]. The steel bar as a polycrystalline material has an ordered microstructure consisting of iso-oriented crystalline regions or grains. Some defects and imperfections at the atomic scale called as "dislocations" can be found in the crystalline structure. The creation, multiplication and interaction among the dislocations together with grain size explain why high dislocation densities and small-size grains improve yield strength of a material. At high temperatures the unstable microstructure undergoes a rearrangement of the dislocations leading to a final smaller dislocation density. The smaller dislocation density together with the formation of new grains which are larger than the original grains explains the observed sensitivity of the mechanical properties of the rebar to high temperature [7].

At present, a number of investigations has been conducted to study the bond behaviour between prestressed strands and concrete at ambient temperature [1,8–11]. However, there are very limited researches conducted for investigating the bond-slip characteristic between prestressed strands and concrete at elevated temperatures. Hence, the main objectives of this paper are:

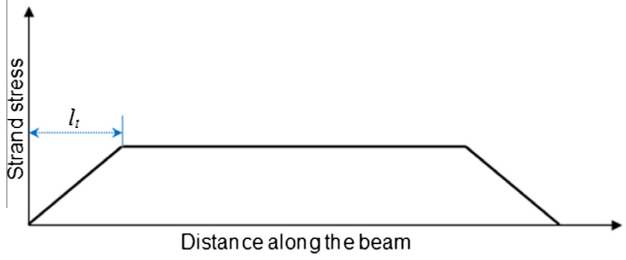
- To develop a robust model for modelling the bond-slip between concrete and strands for prestressed concrete structures in fire. This model can be used to predict the bond stress-slip for three-wire and seven-wire strands with smooth or indented surface at elevated temperatures.
- Incorporate the bond-slip model into the 3D finite element analysis [12] for prestressed concrete structures under fire conditions.
- To validate the model against previous test results.

2. Analytical model

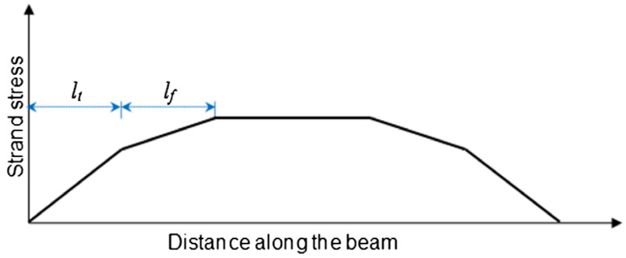
For pretensioned concrete members, there are two distinct regions with different bond characteristics: the transfer bond length region and the flexural bond length region. Figs. 1 (a) and (b) show the variation of stresses in the pretensioned strand along an unloaded beam after the prestress is released from



(a) Pretensioned beam



(b) Variation of stress in the strand after release the stress before loading



(c) Variation of stress in the strand after loading

Fig. 1. Transfer bond length and flexural bond length before and after loading.