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Transient high-temperature stress relaxation of prestressing tendons in unbonded construction

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ABSTRACT

Unbonded post-tensioned (UPT) flat plate concrete slabs are popular for modern continuous multiple bay floor assemblies due to economic and sustainability benefits (reductions in slab thickness and building self-weight) and structural advantages (decreased deflections over larger spans). Only limited research has been conducted on the performance of UPT flat plate slabs under fire conditions, yet the inherent fire endurance of these systems is sometimes quoted as a benefit of this type of construction. One concern for these structures in fire is that high-temperature stress relaxation of the unbonded prestressed reinforcement may cause considerable and irrecoverable prestress loss, with subsequent structural consequences. This paper uses a computational model which has been developed to predict the transient high-temperature stress relaxation (i.e., prestress loss) for typical UPT multiple span flat plate slabs in fire, to study the potential prestress relaxation behaviour under various plausible temperature conditions as might occur during exposure to a standard fire. The model is validated using experimental data from relaxation tests performed on locally heated unbonded seven-wire prestressing stand. The initial prestress level, concrete cover to the prestressed reinforcement, and ratio of heated length to overall tendon length are varied to investigate the potential implications for prestress loss, and subsequently for flexural and punching shear capacity. The results highlight the need for particular care in the construction of UPT slabs to ensure adequate concrete cover for structural fire safety.

1. Introduction and objectives

Unbonded post-tensioned (UPT) flat plate slabs are favoured in modern continuous multiple bay floor assemblies due to economic and sustainability benefits (reduction of building weight by eliminating floor beams and reducing slab thickness) and structural advantages (increased span to depth ratios and excellent deflection control). However, only very limited research has been performed on the behaviour of realistic UPT slabs in fire. Of particular interest in the current paper is the potentially problematic high-temperature creep (or relaxation) behaviour of UPT strands in multiple bay structures when subjected to standard fire conditions. The mechanical properties of prestressing steels are well known to degrade under high temperatures, and under certain conditions this may result in dramatic and irrecoverable loss of prestress [1], with subsequent consequences for the load-carrying capacity of the structure.

Expanding on prior experimental research aimed at studying the high-temperature stress relaxation of prestressing strands locally exposed to elevated temperatures [2]; a simple computational model was developed to provide a rational prediction of prestress loss (or tendon stress variation) both during and after fire in UPT flat plate concrete structures. The model is used herein to perform parametric studies on the effects of various key parameters on prestress loss during exposure to a standard fire, and to highlight potential concerns and areas where additional study is warranted. It should be noted at the outset that only the prestressing tendons are considered in the current study, and the surrounding structure is assumed not to deform due to the fire. Clearly, this is a dramatic over simplification of reality—one which will be remedied in future work—since thermal deformations (e.g., thermal bowing), continuity, membrane action, and restraint are all known to play significant roles in the fire performance of real, multiple bay continuous concrete slabs. Furthermore, fire tests on bonded prestressed concrete double tee beams [3] have shown that tendon stress increases up to 250 MPa may occur due to thermal bowing in the early stages of a fire; these potential tendon stress increases during the initial stages of fire have also been ignored in the current analysis.

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Notation

a	depth of the compressive stress block of concrete (mm)
A_c	cross-sectional area of concrete (mm^2)
A_s	area of mild steel reinforcement (mm^2)
A_p	area of prestressing steel (mm^2)
α_1	ratio of average stress in a rectangular compression block
α_s	shape factor coefficient for interior columns
β_1	compressive stress block factor
β_p	shape factor for punching shear resistance
b	design strip width of the slab (mm)
b_o	effective perimeter of the slab (mm)
c_y	depth of the neutral axis assuming f_{pr} equals f_{pu} (mm)
d_p	depth from the extreme compression fibre to the centroid of the prestressing steel (mm)
d	average depth of the slab (mm)
$\Delta H/R$	activation energy of creep divided by the universal gas constant (K)
ε	strain, theoretical creep strain
ε_{cr}	creep strain
$\varepsilon_{cr,0}$	dimensionless creep parameter
ε_σ	strain due to applied loading and prestress
ε_T	strain due to thermal elongation
E	elastic modulus (MPa)
E_T	elastic modulus at temperature T (MPa)
$E_{20\,^\circ C}$	elastic modulus at room temperature (MPa)
f'_c	compressive strength of concrete (MPa)
f_s	degraded yield stress of mild reinforcement due to elevated temperature (MPa)
f_y	yield stress of mild reinforcement (MPa)
f_{cp}	compressive stress in concrete at the centroid of the cross-section (MPa)
f_{pe}	tensile strength of prestressing strand/wire after losses (MPa)
f_{pr}	stress in prestressing strand/wire at factored resistance (MPa)
f_{pu}	tensile strength of prestressing strand/wire (MPa)
l_o	anchor-to-anchor length of tendon (mm)
κ_1	relative concrete compressive strength reduction factor
κ_2	relative ultimate prestressing strength reduction factor
σ	stress (MPa)
P_e	applied prestressing force after losses (N)
t	time (h)
T	temperature (°C or K)
T_c	average elevated temperature of concrete compressive zone (°C)
T_{mr}	elevated temperature of reinforcing steel (°C)
T_p	average elevated temperature of prestressing strand (°C)
TC_i	thermocouple temperature (°C)
T_i	thermal region temperature (°C)
V_c	punching shear resistance (force)
M_r	flexural resistance (kN m)
n	number of plastic hinges
θ	temperature compensated time (h)
ϕ_c	material resistance factor for concrete
ϕ_p	material resistance factor for prestressing reinforcement
ϕ_s	material resistance factor for mild reinforcement
Z	Zener–Hollomon parameter (h^{-1})

2. Research significance and background

Two significant effects of fire can cause a reduction of prestress force in an UPT tendon; namely a gradual, recoverable reduction of prestressing force resulting from restrained thermal expansion, and a more severe, irrecoverable reduction resulting from creep (or relaxation) under stress at high temperatures. Because creep is a time–stress–temperature-dependent process, a complex interaction exists between prestress levels and temperature history for a tendon which undergoes a localized heating and cooling cycle. Creep is typically so small as to be negligible for prestressing steel under ambient service conditions. However, under stress and at temperatures specific to cold drawn prestressing strand, irrecoverable creep will accelerate and cause a relaxation of prestress. This will affect the capacity of UPT flat plate slabs in both flexure and punching shear, both of which are functions of the slab geometry, concrete strength, amounts of mild and prestressed steel reinforcement, and prestressing force.

Realistic large-scale tests on structures in fire are rarely feasible, which necessitates the use of computational models to aid in the evaluation of the structural effects of a severe building fire. Indeed, in some forward-looking jurisdictions complex numerical models are currently used to perform performance-based structural design for fire safety. However, only limited research, experimental or computational, is available on the capacities of UPT flat plate slabs either during or after fire. An excellent summary of prior work in this area has been presented previously by Lee and Bailey [4], and additional recent furnace tests have also been reported by Ellobody and Bailey [5] and Kelly and Purkiss [6], although in both cases these have been isolated member tests and the unbonded tendon lengths were therefore unrealistic. This paper represents the first attempt to consider the potential consequences of localized heating of unbonded prestressing strands in fire; an important first step towards rationally modelling the complex behaviour of real UPT flat plate structures in fire.

3. Modelling transient thermal creep and stress relaxation at high temperature

A simple computational model for predicting prestress loss in UPT tendons in concrete flat slab structures during fire (accounting for transient thermal creep and stress relaxation) was programmed in Fortran. Fundamentally, the model focuses on the calculation of the transient high-temperature thermal creep strain increment over a chosen length of tendon at constant temperature (i.e., a predefined thermal region) during a given time interval, and then on determining the overall relaxation of stress for an unbonded tendon over its total length by summing the contributions from the various thermal regions along the length of the tendon; these regions may be at different temperatures. The change in strain in each thermal region thus directly affects the change in overall prestress level through the invocation of a temperature-dependent modulus of elasticity, which also varies along the length of the locally heated tendon.

Two main input data files are required; namely discretized heated coordinates along the tendon's length (i.e., a numerical description of the tendon's geometry and depth profile within the concrete slab), and the corresponding time–temperature histories