IRRECOVERABLE PRESTRESS LOSS IN UNBONDED POST-TENSIONED CONCRETE SLABS IN FIRE

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ABSTRACT

Unbonded post-tensioned (UPT) flat plate concrete slabs have seen widespread use in multi-storey office and condominium buildings since the 1960s. The popularity of these systems can be attributed to various economic and structural benefits (e.g., reduction of slab thickness, storey height, and building mass, and excellent deflection control over large spans). Further, the "inherent fire endurance" of these systems is often quoted as a key benefit as compared against competing floor systems. Such statements are apparently based on satisfactory results from large-scale fire endurance tests performed on UPT slabs during the 1960s and on experience from real fires in UPT buildings. However, much remains unknown about the true structural behaviour of continuous multiple bay UPT slabs in building fires. For instance, there is a paucity of data on the effect of elevated temperature on cold drawn prestressing steel under realistic service stress levels, particularly in terms of its high temperature stress relaxation which can lead to considerable irrecoverable prestress loss both during and after a fire, with subsequent structural consequences. To aid in the rational fire-safe design and post-fire evaluation of realistic UPT concrete structures, and to validate computational models for these types of structures which are under development by the authors, a series of novel high temperature experiments were performed on locally heated, stressed, and restrained prestressing tendons with realistic lengths (18.3m) and parabolic longitudinal profiles (typical of real UPT slabs). The results illustrate the loss of prestressing force, or in some cases tendon failure due to prestress alone, that may occur during a fire and that must therefore be carefully considered during design. A computational model is presented and used to predict prestress relaxation under the temperature conditions invoked during testing. Potential consequences for UPT structures are discussed, and future research directions are proposed.

INTRODUCTION & OBJECTIVES

Unbonded post-tensioned (UPT) concrete slabs are widely used continuous multiple bay floor assemblies. These systems enable a reduction of building weight by eliminating floor beams and reducing slab thickness, with subsequent architectural and sustainability advantages. They also allow for increased span to depth ratios and excellent deflection control over long spans, making them very attractive for multi-storey office and condominium construction. Only limited research is available on the behaviour of UPT slabs in fire [1], and to date no realistic large scale fire tests (or structural fire analyses) have been presented on multiple span continuous UPT slabs. An excellent summary of prior work in this area has been presented by Lee and Bailey [1], and furnace tests on UPT members have recently been reported by Ellobody and Bailey [2] and Kelly and Purkiss [3], although in both cases these were isolated member tests and the unbonded tendon lengths were not realistic. This is of particular concern because UPT structures contain unbonded tendons that are continuous across multiple bays, typically with two-way action within a floor plate. Tests on isolated, simply-supported, one-way members with short unbonded lengths, which fail to account for continuity, restraint, membrane actions, etc., cannot therefore be considered as wholly representative (or necessarily conservative).

Highly realistic full-scale tests on structures are rare due to their complexity and cost. Computational models can however, once suitably validated through comparison against few large-scale tests, aid in evaluating the potential structural consequences of building fires. Such computational models are currently used to perform performance-based structural design for fire safety of steel-concrete composite structures in the UK [4] for example. As an important first step toward developing the ability to rationally model the full structure response to fire of a UPT building, this paper describes experiments on locally-heated unbonded prestressing strands of realistic total length and presents data on the stress-temperature-time dependent strength and creep response.

The current paper follows from previous research by the authors in this area [5], and treats fundamental issues related to the potential loss of yield strength and effects of creep (or relaxation) at high temperature as is relevant to the behaviour of UPT strands in multiple bay concrete structures when subjected to standard fire conditions. The mechanical properties of prestressing steels are well known to degrade under high temperatures [6, 7], and under certain conditions this may result in dramatic and irrecoverable loss of prestress [5] or tendon rupture due to the prestressing force alone, with subsequent consequences for the load carrying capacity of the structure both during and after a fire. However, only limited information is available on the consequences of localized tendon heating on the global response of the tendon; this is the problem treated herein. The specific objectives of the research are:

- to experimentally study the changes in tendon stress (prestress) that may occur during heating of an unbonded tendon under representative service load stresses, as well as the amount of residual prestress remaining after heating to various temperatures and cooling to ambient conditions;
- to study the potential for tendon rupture due to prestress alone during fire, as a consequence of localized heating and the resulting reductions in yield strength, and to compare experimental evidence with yield strength reductions suggested in available design codes;
- to develop a validated computational model to numerically predict the loss of prestress with heating that could occur for an unbonded post-tensioned concrete slab during fire; and
- to understand the potential consequences of prestress loss both during and after fire on the load capacity of a UPT structure.

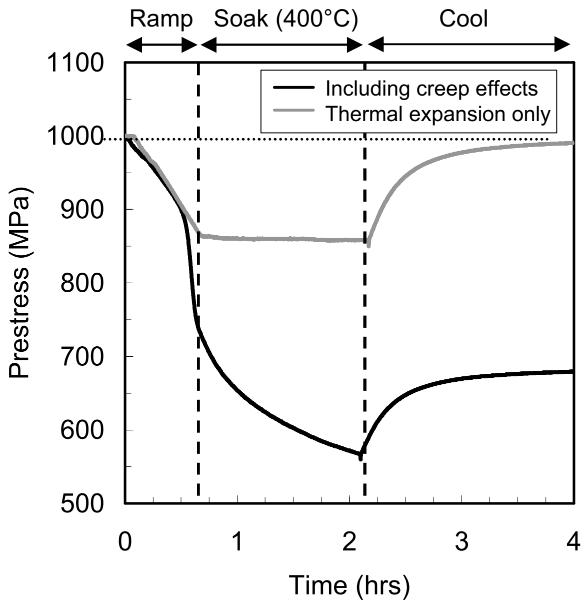
BACKGROUND AND MOTIVATION

When an unbonded (but restrained and stressed) prestressing tendon is heated, the stress will decrease due to a combination of a gradual, *reversible* reduction of prestressing force resulting from restrained thermal expansion, and, depending on the stress level and temperature, a more severe, *irreversible* reduction resulting from creep (or relaxation) under stress at high temperatures. When a stressed tendon is heated locally, because creep is a time-stress-temperature dependent process, a complex interaction exists between stress levels and temperature history for a tendon which undergoes a heating and cooling cycle. Figure 1 shows the predictions of a computational model (described below) for prestress loss in a restrained prestressing tendon, stressed to 1000 MPa and then heated over approximately 10% of its length to 400°C (with a ramp rate of 10°C/min); the importance of properly capturing the creep (relaxation) component of prestress loss is clear, and the ability to predict this transient variation in tendon stress levels is thus crucial in accurately modelling the response of UPT structures both during and after a fire. This figure also illustrates the *recoverability* of thermal strains and the *irrecoverability* of creep strains, an issue which must be considered in the post-fire evaluation of even locally fire damaged UPT slabs.

Under ambient conditions for most in-service structures, creep of the prestressing steel is so small as to be negligible. Under stress and high temperatures however, irrecoverable creep will accelerate and may cause a dramatic relaxation of prestress. In cases of extreme localized heating, as may occur due to cover spalling for instance, the tendons may rupture due to a combination of accelerating creep and loss of ultimate tensile strength. Clearly, prestress loss or tendon rupture will affect the capacity of UPT flat plate slabs in both flexure and punching shear, both of which are functions of the prestressing force.

It is important to highlight that only the prestressing tendons are considered in the current paper. The surrounding structure is ignored completely at this stage, so that the tendon behaviour can first be understood and accurately modelled. In reality, thermal deformations (e.g., thermal elongation of the slab and/or thermal bowing), continuity, membrane action, concrete spalling and splitting, and restraint are all known to play important roles influencing the response of multiple bay continuous structures to fire [8]. The purpose of this paper is to demonstrate the stress-temperature-time dependency in a locally heated unbonded tendon, to verify the creep model outlined in the paper for treating this very specific transient problem, and to highlight some key potential impacts of the observed/predicted tendon behaviour for UPT structures in fire.

Figure 1: Stress variation in a restrained prestressing tendon due to localized heating (based on test data presented by MacLean et al. [5])



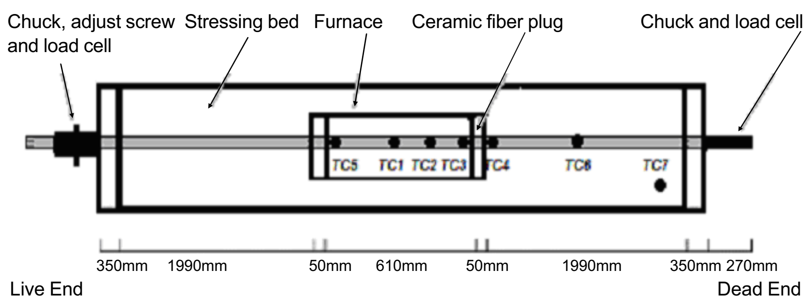
METHODOLOGY

To accomplish the aforementioned objectives, a computational model was developed and validated against observations from a series of novel high temperature experiments on locally heated, stressed, and restrained prestressing tendons with realistic lengths and parabolic longitudinal profile. Both the experimental and computational aspects are described below.

Experiments on Locally-Heated Tendons

Before presenting the tests on 18.3 m long tendons performed for the current paper, it is useful to summarize a series of smaller scale tests performed previously by MacLean [9] to experimentally characterize the effects of localized heating on a straight unbonded prestressing strand by monitoring prestress loss due to creep and thermal expansion. Eight transient high temperature experiments were conducted to quantify the effects of creep and relaxation on 13 mm diameter Grade 1860 ASTM A416-03 low relaxation 7 wire strands, pre-stressed to about 55% of their room temperature ultimate strength. This prestress level is typical of service conditions for a UPT slab after both short and long-term loses have accumulated in a real structure [10]. Individual 6.3 m long prestressing strands were stressed in a prestressing bed, incorporating load cells at both their dead and live ends, to measure the variation in tendon stress with heating. A custom-built electric tube furnace was used to heat the strand at its mid-length over a distance of 610 mm to predetermined temperatures. A schematic of the test setup is shown in Figure 2. Temperature set points of 200, 300, 400, 500, and 700°C were used with a heating ramp rate of 10°C/min followed by a constant temperature soak of either 5, 45, or 90 minutes, and a slow cooling period in which the tendon was allowed to cool naturally to ambient conditions. Temperatures were recorded along the strand during heating and to obtain experimental time-temperature histories at selected locations. These were then used to generate spatial and temporal temperature profiles for the tendon by linear interpolation between thermocouples. MacLean's tests [9] confirmed the importance of creep at high temperature for locally heated tendons and also highlighted the complex interactions that exist between stress, temperature, time, and (significantly for the current paper) the ratio of the heated length to the overall tendon length (heated length ratio). The data obtained also showed that available creep data could be used to reasonably predict the observed variations in tendon stress.

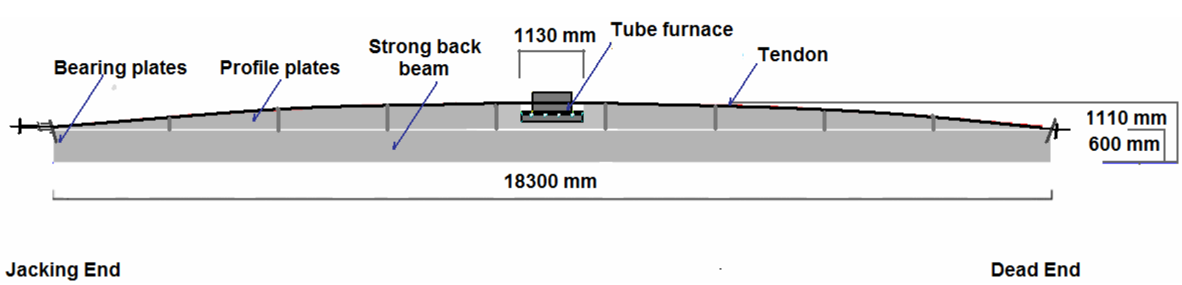
Figure 2: Plan view schematic of the experimental set-up used by MacLean [11]



More recently, a second series of high temperature tests were carried out on tendons of more realistic overall length using a modified "strong-back" beam apparatus shown in Figures 3 and 4 and initially developed by MacDougall [12] for studying the effects of individual wire breaks in seven-wire prestressing strands. The strong-back beam was designed to simulate the boundary and restraint conditions found in typical unbonded post tensioned concrete slabs, with an overall length of 18.3 m and a parabolic profile. The tendon specimen was mounted in a guide channel that is attached to parabolically profiled plates of varying height along the beam. These profile plates were welded to the top flange of the strong back beam. The maximum tendon drape (500mm at mid-span) was selected to simulate the external load balancing forces typical of post-tensioned concrete slab design [12]. Bearing plates were added to accommodate anchorage and jacking of the tendon at the ends of the beam. Plastic sheathing was installed over the length of the guide channel to simulate the frictional effects to which the tendons would be exposed in service.

The profile plates at the strong-back's mid-span were modified to allow the installation of the same electric tube furnace as used by MacLean [9], which was again used to locally heat the strand under various ramp-soak-cool temperature regimes. For these tests, a heated length of 610mm was again used centered on the tendon's mid-point and using temperature set points of 200°C, 400°C, and 600°C. A ramp rate of 10°C/minute was chosen to be representative of the heating rates which could be expected for post-tensioned tendons protected by concrete cover and exposed to a standard fire. A soak time of 90 minutes was selected to be representative of typical fire endurance ratings required for restrained UPT floor systems with 20mm of concrete cover to the prestressed reinforcement. Two identical tests were performed at 400°C to verify the repeatability of the testing method.

Figure 3: Strong-back beam details and selected dimensions



Each test used a single 13 mm diameter Grade 1860 ASTM A416-03 low relaxation seven-wire strand jacked to a prestress level of 50 to 60% of its ultimate room temperature tensile strength ($0.5f_{pu}$ to $0.6f_{pu}$). Load cells were placed at live and dead ends to monitor prestress levels. Prestress levels were verified using total elongation readings. Nine K-type thermocouples were used to monitor tendon temperatures at various locations during heating, as shown in Figure 5. One additional thermocouple was used to monitor the ambient temperature 2 m from the oven. Electrical resistance foil strain gauges were mounted on the tendon 0.5 m from the live end anchorage and 0.5 m from the face of the tube furnace to monitor frictional effects (if present) and to verify prestress readings from the load cells. To verify the calibration of the strain gauges against potential changes in gauge temperature, a thermocouple was also placed at each strain gauge location.

Figure 4: Strong-back beam with the prestressing tendon passing through the tube furnace at mid-span

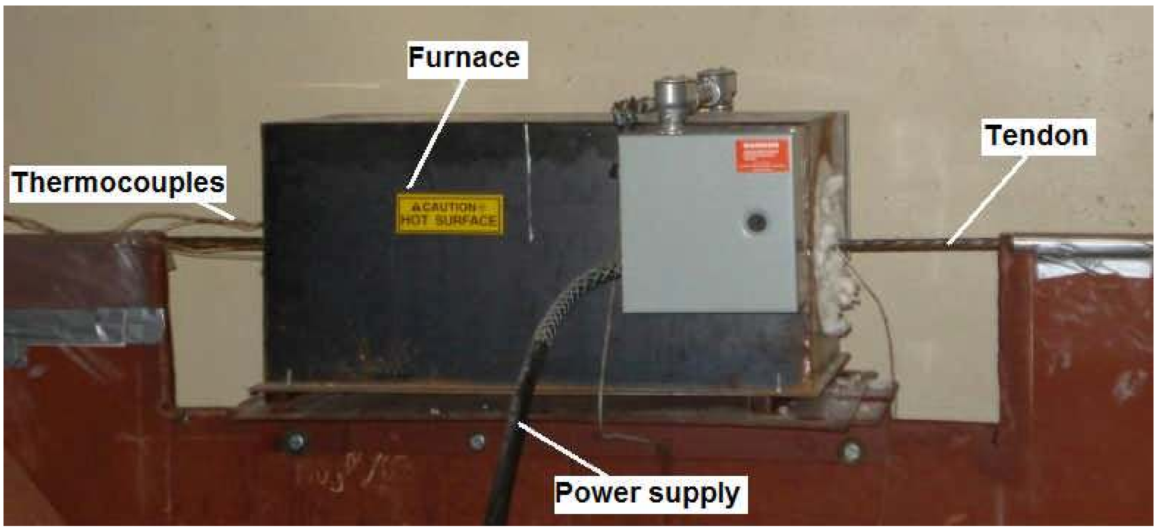
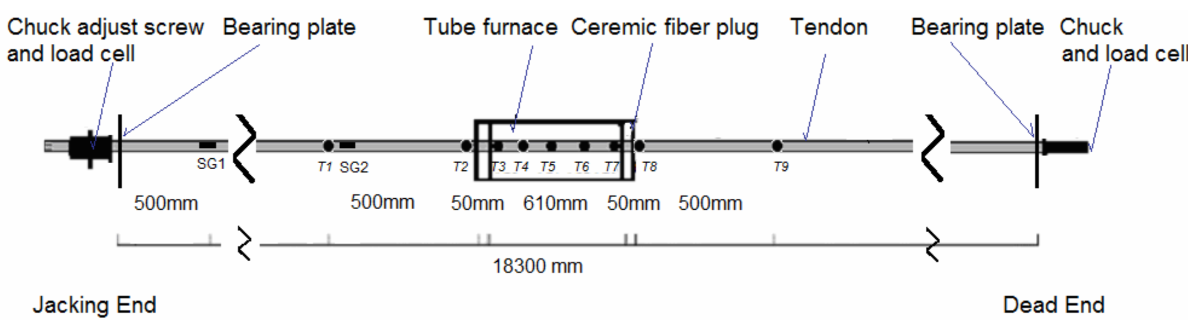


Figure 5: Plan view of thermocouple layout used in strong-back beam tendon heating tests



Computational Model for Transient Tendon Stress Variation

The changes in tendon stress (prestress loss) experienced by the tendons in the tests described above can be computationally predicted using a model developed previously by the authors [11]. Only a brief description of this is presented here, and the relevant equations are presented in Table 1. The model is based on available high temperature creep data and accounts for transient thermal creep and stress relaxation in a locally-heated, restrained tendon by subdividing the tendon into constant temperature *thermal regions* along its length, and applying a forward difference algorithm to update prestress levels as time advances under any heating and cooling regime. Because the tendon is unbonded over its entire length, the overall relaxation of stress for the tendon in any given time step is calculated by summing the relaxation contributions arising from each of the thermal regions during that time interval. The temperature in each thermal region is assumed constant during each time step, so that the precision of the analysis improves with shorter thermal regions and smaller time steps. The change in strain in each thermal region directly affects the change in overall prestress level through the invocation of a temperature-dependent modulus of elasticity (based on data found in Anderberg [13]).

For a given time interval and thermal region, the stress loss behaviour for each region is treated following the algorithm shown in Figure 6, which is described in complete detail by Gales et al. [11] and which incorporates analytical models and creep coefficients taken from several prior studies to formulate a transient stress relaxation model. The change in total strain in a given thermal region, $\Delta\varepsilon_{Total}$, is the summation of the change in thermal strains, $\Delta\varepsilon_T(T)$, creep strains, $\Delta\varepsilon_{cr}(\sigma,T,t)$, and strains causing mechanical stress, $\Delta\varepsilon_\sigma(\sigma)$. If the ends of the tendon are fixed, the change in total strain is zero and:

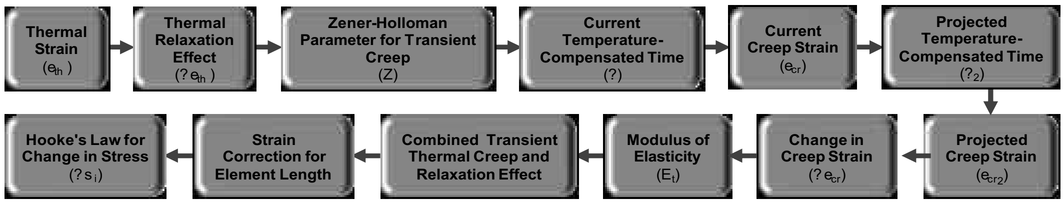
$$\Delta\varepsilon_\sigma(\sigma) = -\left(\Delta\varepsilon_T(T) + \Delta\varepsilon_{cr}(\sigma,T,t)\right) \qquad [1]$$

The thermal strain of prestressing steel, $\Delta\varepsilon_T(T)$, is based on Eurocode recommendations [6]. Creep strains in various grades of steel at high temperature can be approximated using Harmathy's pioneering research in this area [14, 15], along with guidance from additional sources [6, 13-19]. The Zener-Hollomen parameter, shown in Figure 6 and used in the creep strain calculations, must be invoked with caution since it has only been determined experimentally up to stress levels of 690 MPa for Grade 1720 prestressing steel, whereas the tests presented herein used Grade 1860 prestressing steel under initial stresses of about 1000 MPa.

Table 1: Equations invoked in the transient high temperature creep (relaxation) model (refer to Figure 6)

Equation	Range	Reference(s)
$\varepsilon_T = -2.016\times10^{-4} + 1.0\times10^{-5}T + 0.4\times10^{-8}T^2$	$20°C < T < 1200°C$	CEN [6]
$\varepsilon_{cr} = \frac{\varepsilon_{cr,0}}{\ln 2}\cosh^{-1}(2^{Z\theta/\varepsilon_{cr,0}})$	Current *s*	Harmathy [14, 15]
$\Delta\varepsilon_{Total} = 0 = \Delta\varepsilon_\sigma(\sigma) + \Delta\varepsilon_T(T) + \Delta\varepsilon_{cr}(\sigma,T,t)$	Assuming constant total length	Anderberg [19]
$\theta = te^{\frac{-\Delta H}{RT'}}$	*? H/R* = 30556 K	Harmathy and Stanzak [15]
$Z = 195.27\times10^6\sigma^3$ $Z = 8.21\times10^{13}e^{0.0145\sigma}$ $\varepsilon_{cr,0} = 9.262\times10^{-5}\sigma^{0.67}$	*s* = 172 MPa 172 < *s* = 690 MPa Current *s*	Harmathy and Stanzak [15]
$\frac{E_T}{E_{20°C}} = -2\times10^{-6}T^2 + 0.2\times10^{-6}T + 0.987$	$20°C < T < 700°C$	Anderberg [13]

Figure 6: Schematic of algorithm for transient thermal creep and stress relaxation model for a constant temperature region during a single time interval (refer to Table 1)



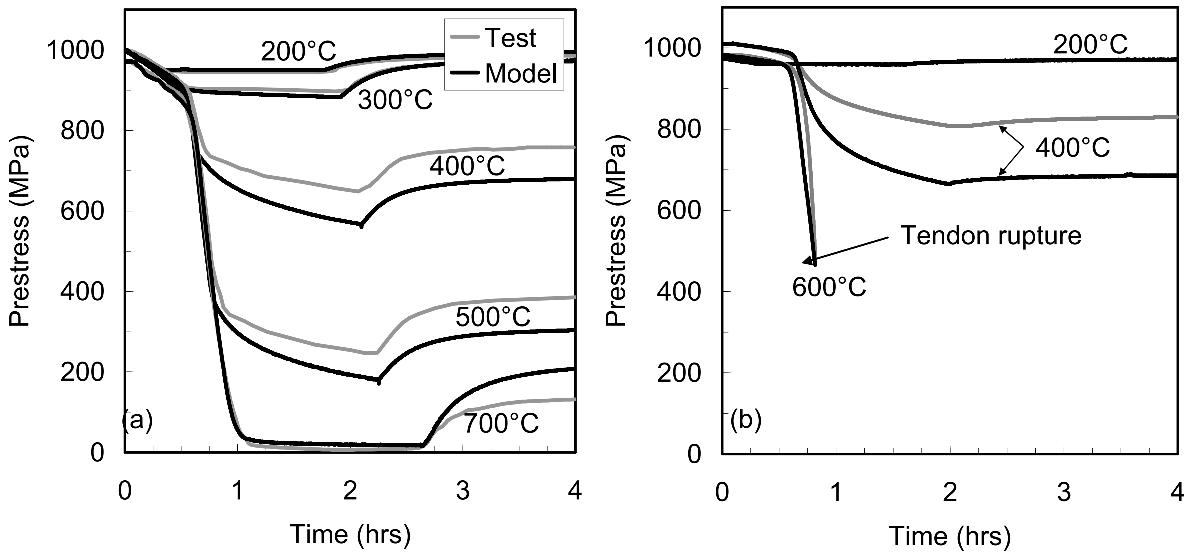
Following the computation of both the transient thermal creep and thermal relaxation during a given time step, the total strain change for each thermal region can be assessed in accordance to Equation 2, meaning that any increase in creep and thermal strain will be proportionally followed by a decrease in strain to cause stress. This strain is converted into a change in prestress using a temperature dependent modulus of elasticity for prestressing steel. Stress changes from each thermal region are then summed over the length of the tendon, and an overall average stress relaxation is applied to the tendon's prestress at the beginning of the next time step, such that the tendon's overall length remains unchanged. The time is then incremented forward and the process is repeated using the same thermal regions. This implies that the prestressing tendon physically moves through the heated regions as it locally expands and contracts during the analysis, whereas the heated regions remain stationary. The computational model incorporates checks for each thermal region to ensure that the stress in the thermal region at any given temperature does not exceed the yield strength of the prestressing steel at that temperature [7]. The model also checks for modulus values approaching zero in each element, which would also indicate tendon rupture due to unrealistically large axial strains.

RESULTS AND DISCUSSION

A summary of the experimental results and the accompanying predictions from the computational analysis for both Maclean's tests and the more recent Strong back beam tests is provided in Figures 7a and 7b. These figures compare the measured and predicted prestress variation for a 90 minute soak time at various set point temperatures from 200°C to 700°C, and clearly show that heating above 300°C causes considerable (and irrecoverable) prestress loss. It is clear from these figures that the model provides reasonable but generally conservative predictions of the prestress variation recorded during all tests performed to date. In the case of MacLean's tests, the predictions of the computational model differ from experimental results in each run by a maximum of 1% for 200 and 300°C, 14% for 400°C, 21% for 500°C, and 57% for 700°C (although the large variance at 700°C is experienced during the cooling phase). In general, the model captures the observed trends in this set of tests, although comparison with the test data indicates that refinement of the model may be necessary. This is likely due to the initial tendon stress levels of approximately 1000 MPa that were used in the tests. While this represents a realistic service stress for a UPT slab, it is considerably higher than the stress levels for which the high temperature creep parameters used in the model were derived by previous authors (only up to 690 MPa) [14, 15]. This necessitated a significant extrapolation of available experimental creep data, which may or may not be appropriate. Additional high temperature creep tests on prestressing wire are needed (and are planned by the authors) to obtain the relevant high temperature creep parameters for initial stress levels up to or exceeding 1000 MPa.

The agreement between model and test is not as good in the case of the more recent tests on longer tendons. At a soak temperature of 200°C (where thermal expansion is easily accounted for and dominates the response) the agreement is excellent, again with less than 2% difference between model and prediction. However, at 400°C the model over-predicts prestress loss by more than 20%. This is thought to be due to the shorter heated length ratio in the longer tendons, which has the effect of reducing the proportion of prestress loss due to thermal expansion, thus maintaining high levels of tendon stress in the locally heated region, and an amplification of the inaccuracies of the creep model. This further supports the need for tests to determine high temperature creep parameters at stress levels above 690 MPa.

Figure 7: Summary of both the experimental results and the accompanying predictions from the computational analysis for variation in prestress with exposure time for both (a) Maclean's tests [9, 11], and (b) the more recent tests described herein



The Strong-back beam test at a soak temperature of 600°C (data shown in Figure 7b) is particularly interesting. In this test, the ultimate tensile strength (failure stress) of the tendon was apparently exceeded within the heated region of the locally heated tendon, and this loss in strength resulted in tendon failure during the heating ramp phase at a temperature of 524°C, *before* sufficient creep (relaxation) had occurred to reduce the tendon stress to a value less than its strength. Total loss of strength, causing tendon rupture under the action of prestress alone, is therefore also a realistic concern for locally-heated unbonded strands; the extreme analogue of this is the process of torch cutting used to release prestressing tendons in a precast plant. The reader will note that MacLean's test at 700°C, which had a larger heated length ratio, did not experience tendon rupture. Clearly, this is because the longer heated length ratio in this test meant that thermal expansion caused a proportionately larger decrease in stress upon heating, reducing the tendon stress sufficiently to avoid failure. The fact that the computational model (which includes checks for tendon failure using easily adaptable material strength parameters found in Hertz [7]) failed to predict the observed tendon failure is a further indication that the complex interactions that exist between stress, time, temperature, and heated length ratio remain incompletely understood. This will be an important consideration in the future analysis of full UPT structures' response to fire.

As a final comment on Figure 7, comparison of the 400°C experimental traces in each of parts (a) and (b) seems to suggest that the longer heated length ratio (Figure 7a) was the more severe of the two thermal exposure cases (larger maximum prestress reduction and lower residual prestress for the larger heated length ratio). However, the tendon with the larger heated length ratio actually survived the 700°C exposure in Figure 7a, while the one with the smaller heated length ratio failed in tension before reaching 600°C in Figure 7b (with a smaller heated length ratio). Therefore, the most critical thermal exposure for a given unbonded post-tensioned structure might be a highly localized fire with relatively low temperatures, rather than the more commonly considered large, fully developed standard fire over the full floor plate; this is a very important insight given current discussions within the structural fire engineering community regarding the relevance of standard fire testing [20].

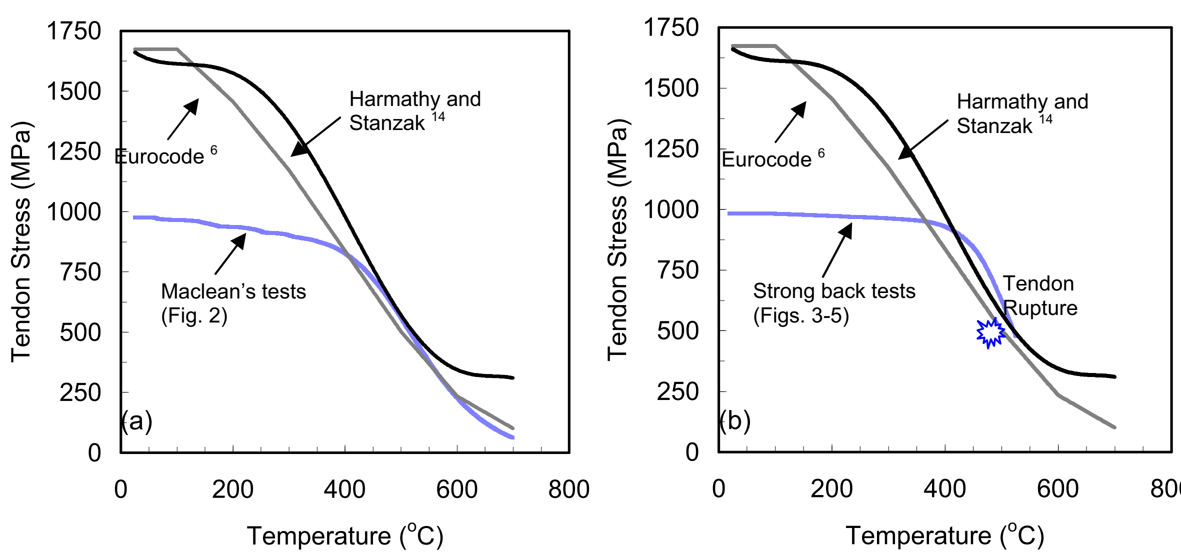
Loss of Strength at High Temperature

Several national or international building codes (e.g., Eurocode [6]) currently provide equations that can be used to approximate the reduction in mechanical properties (e.g., yield strength, ultimate strength, and elastic modulus) of prestressing steel under exposure to elevated temperatures. These equations are typically said to *inherently* account for the effects of creep at elevated temperatures. However, strength is both temperature *and* load-rate dependent (even at room temperature, but much more so at high temperature). At high temperature, creep effects become significant and should be included, particularly for UPT construction.

Figure 8 shows the Eurocode [6] relationship for loss of ultimate strength of Class A cold-drawn prestressing strand with temperature. Also included in this figure is a similar "upper bound" strength loss curve for cold drawn prestressing steel presented by Harmathy and Stanzak [15] as well as the data obtained during the heating ramp phases of the tests performed by MacLean up to 700°C and using the Strong back apparatus up to 524°C.

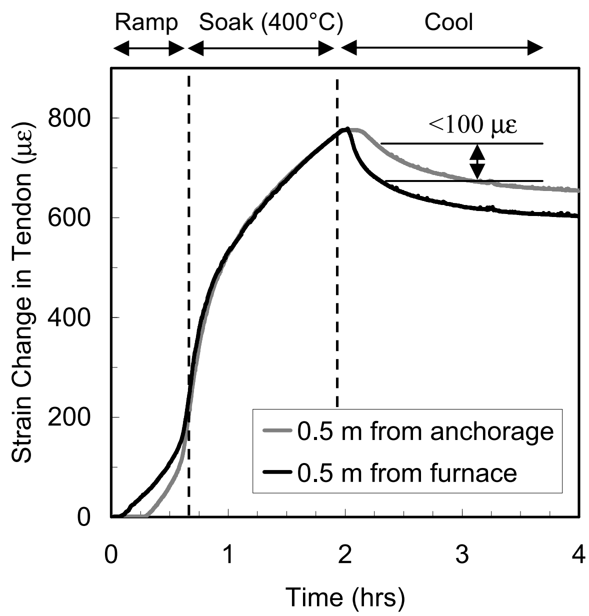
These figures clearly show the strong influence of creep as the yield strength of the prestressing steel is approached at high temperature. Note that tendon rupture was not observed in any of MacLean's tests, whereas the Eurocode curve predicts that rupture should have occurred in the tests at 400, 500, and 700°C with this heated length ratio. In the more recent Strong back apparatus tests, the Eurocode equations predict rupture at temperatures above 360°C, although none was observed at 400°C (a test which was repeated twice). Even the upper bound expression suggested by Harmathy and Stanzak [15] predicts failure in cases where none was observed. Therefore, while it does not seem possible, given the strong stress-time-temperature dependency of creep, for the Eurocode [6] equations (or others which claim to implicitly include creep) to rationally treat the situation of localized heating of prestressed reinforcement for the unbonded case, the equations appear to be conservative on the basis of the limited testing presented in the current paper (i.e., they predict failure in the one case where it was observed and also in many cases where it was not).

Figure 8: Comparison of stress versus temperature histories recorded during the heating ramp phase for tests performed (a) by MacLean up to 700°C, and (b) using the Strong back apparatus up to 524°C against tendon strength envelopes suggested by the Eurocodes [6] and Harmathyand Stanzak [15].



For the sake of interest, Figure 9 shows the strains recorded on the prestressing tendon in the Strong back beam test to 400°C and gives an indication of the frictional effects that were present in influencing the prestress changes recorded at the anchorage as opposed to those occurring in the furnace at midspan. The friction effects are mild but present with a maximum difference of less than 100 με between the furnace and the anchor (during the cooling phase). This corresponds to a maximum stress differential of less than 20MPa between the furnace and the anchor, which is not considered significant in influencing the agreement between experiment (where friction exists) and model (where friction is currently ignored).

Figure 9: Recorded changes in tendon strain



POTENTIAL CONSEQUENCES

Loss of prestressing (due to fire) has potentially serious consequences for the load carrying capacity of a UPT flat plate structure. In particular, both the flexural and the punching shear capacity may be reduced as prestressing force is lost (all other factors equal). The magnitudes of the likely reductions remains unknown given other factors at play during a fire, and a detailed analysis (likely using advanced finite element modelling) is required. It must be reiterated that thermal bowing, global thermal expansion, restraint, and compressive or tensile membrane action of the concrete slab, and frictional effects on the unbonded prestressing tendons have been ignored in the current paper. Additional research is needed to refine the evaluation of prestress losses within the computational model and to understand the influence interactions with the concrete (and potentially frictional effects) on tendon stress over multiple bays from compartmentalized or highly localized fires. The reader should note that, depending on the boundary conditions of a fire exposed bay, the load capacity of a UPT slab may be considerably increased by the development of membrane in-plane forces [21]; these factors should be considered in future studies to arrive at a more rational treatment of the structural fire safety of UPT members and structural systems in modern concrete buildings.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be drawn on the basis of the experimental testing and computational analysis presented in this paper:

- Based on previous research by others, a computational model has been developed that can be used to study the consequences of transient localized heating (and cooling) of an unbonded post-tensioned cold-drawn prestressing tendon. The model provides reasonable but generally conservative predictions of the prestress variation recorded during all tests performed to date, although comparison with the test data indicates that refinement of the model may be necessary and that research is needed to determine creep parameters for prestressing steels under realistic service stresses (i.e., > 690 MPa).

- Both the testing and the analysis indicate that total loss of strength, causing tendon rupture under the action of prestress alone, is a realistic concern for locally-heated unbonded strands. However, the complex interactions that exist between stress, time, temperature, and heated length ratio for locally heated UPT tendons remain incompletely understood; this will be an important consideration in the future analysis of full UPT structures' response to fire.
- Tests performed to date indicate that the most critical thermal exposure for a given unbonded post-tensioned structure might be a highly localized fire with relatively low temperatures, rather than the more commonly considered large, fully developed standard fire over the full floor plate. This is in contrast to current thinking and represents an important insight for these types of structures.
- While it does not seem possible for simplified equations such as those presented in the Eurocode [6] to rationally treat the situation of localized heating of prestressed reinforcement for the unbonded case, these equations appear to be conservative on the basis of the limited testing presented in the current paper.

Additional research is needed to refine the evaluation of prestress losses within the computational model and to understand the influence interactions with the concrete on tendon stress over multiple bays from compartmentalized or highly localized fires. The consequences for global structural performance in fire should be evaluated, both through detailed finite element modelling of full-structure UBT response to fire, and through full scale non-standard fire tests on two-way UBT multi-bay structures.

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NOTATION

E	= elastic modulus (MPa)
E_T	= elastic modulus at temperature T (MPa)
$E_{20°C}$	= elastic modulus at room temperature (MPa)
f_{py}	= yeild strength of prestressing strand/wire (MPa)
f_{pu}	= tensile strength of prestressing strand/wire (MPa)
t	= time (hrs)
T	= temperature (°C)
T'	= temperature (°K)
T_c	= average elevated temperature of concrete compressive zone (°C)
Z	= Zener-Hollomon Parameter (hrs^{-1})
? H/R	= activation energy of creep divided by the Universal Gas Constant (°K)
?	= temperature compensated time (hrs)
e	= strain, theoretical creep strain
e_{cr}	= creep strain
$e_{cr,0}$	= dimensionless creep parameter
e_s	= strain due to applied loading and prestress
e_T	= strain due to thermal elongation
s	= stress (MPa)

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