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Fire Induced Transient Creep Causing Stress Relaxation and Tendon Rupture in Unbonded Post-Tensioned Structures: Experiments and Modeling

John Gales[a], Luke Bisby[b], Colin MacDougall[c]
[a]Doctoral Student, University of Edinburgh, UK. j.gales@ed.ac.uk
[b]Reader & Ove Arup Foundation/Royal Academy of Engineering Senior Research Fellow in Structures in Fire, University of Edinburgh, UK. luke.bisby@ed.ac.uk
[c]Associate Professor, Queen's University, Canada. colin@civil.queensu.ca

ABSTRACT

Unbonded post-tensioned (UPT) flat plate concrete structures are widely used in multi-storey construction. They have numerous benefits, including reductions in slab thickness and excellent deflection control over large spans; their inherent fire resistance is also widely considered a key benefit compared to competing floor systems. The fire resistant design of UPT structures is typically assured largely on the basis of results from unrealistic standard fire resistance tests performed prior to 1983. However, much remains unknown about the true behavior of continuous multiple bay UPT slabs in real fires. Relatively little data exist on the effects of localized exposure to elevated temperature on cold drawn prestressing steel under realistic sustained service stress levels, and the potential consequences of the resulting thermally induced stress relaxation and/or tendon rupture remain unexamined. To aid in the fire-safe design and post-fire evaluation of real, multiple-bay, continuous UPT structures, large-scale tests and computational modeling have been performed to assess high temperature stress relaxation in unbonded prestressing steel tendons subjected to localized heating, as would be the case in a real building fire. A series of novel high temperature experiments and computational modeling on locally-heated, stressed and restrained prestressing tendons with realistic configurations is presented to shed light on the transient response of the tendons at high temperature. Reasonable agreement is achieved between observed and predicted stress variation during heating, although minor refinement of the predictive model's creep parameters appears to be required. Both the experiments and the modeling show that inherent inclusion of high temperature creep, as assumed in essentially all available fire design guidance documents and software packages globally, is unable to represent the true response of UPT tendons in realistic UPT concrete slabs. This may lead to unconservative design against, and assessment of, fire damage to UPT slabs in both full floor-plate and localized fires.

INTRODUCTION

Unbonded post-tensioned (UPT) concrete slabs are flooring systems which are prestressed internally with cold-drawn steel tendons that are free to move longitudinally within a duct. These systems have several advantages over non-prestressed reinforced concrete, most notably larger span-to-depth ratios, more efficient and sustainable construction, and excellent deflection control. Unrealistic and outdated structural fire resistance tests performed several decades ago, on single span UPT elements, are routinely invoked to demonstrate UPT slabs' adequate performance in fire; current design of UPT slabs for fire safety is based largely on such tests. In recent years additional testing has led to debate [1, 2] regarding the fire safety of these structures. The more recent tests have clearly shown that much remains unknown about the true response of UPT concrete structures in fire. In particular, localized tendon damage in one bay of a UPT structure can have consequences across the entire floor plate since UPT tendons are continuous across many bays. Loss of prestress (caused by thermally induced stress relaxation or tendon rupture during fire) can thus decrease a UPT structure's ability to resist flexural and shear effects over several bays [3].

No fire tests have ever been performed on realistic, continuous UPT flat plate slabs. In the absence of such tests, computational models are being used to study the response of UPT buildings in fire [4]. It is crucial however that these models show a proven capability to simulate all relevant structural behaviors, including tendon stress relaxation due to creep and strength degradation during (and after) heating and cooling. This paper presents novel experiments and computational modeling [5] on the effects of transient localized heating and cooling on a restrained UPT tendon.

BACKROUND & RESEARCH SIGNIFGANCE

The strength and modulus of a UPT tendon are reduced at elevated temperature. For a longitudinally restrained but unbonded tendon, high temperatures can cause thermal and creep deformations which result in irrecoverable prestress relaxation [6]. This relaxation reduces the ability of the structure to resist flexural and shear forces. Localized heating of stressed tendons can also cause the tendons to rupture if the prestress exceeds the tendons' tensile strength. A complex strength-stress-temperature-time interdependency exists in UPT structures which can influence structural response and which must be properly considered to build defensible computational models to simulate full-structure response.

An explicit computational creep model (coded in FORTRAN) was previously developed and validated by the authors [5] to predict stress relaxation for a restrained tendon under various heating and cooling scenarios. The model considers the reduction of tendon stress due to reversible restrained thermal expansion [7] and (depending on the current stress level, temperature, and duration of heating) irreversible transient creep (essentially based on the Harmathy creep model [8, 9]). The model is capable of treating any transient heating and cooling regime for any tendon length, heated length, tendon profile, and initial prestress level (see [5, 10] for full details of model development and validation). The authors' model *explicitly* accounts for transient creep deformation in computing the prestress relaxation on heating. Conversely, available structural fire design parameters and procedures purport to *implicitly* include creep at elevated temperature by using stress-strain curves developed from stress relaxation tests performed under (and strictly valid only for) prescribed heating rates. Such an *implicit* approach was apparently used, for instance, in determining the strength and modulus reduction factors for steel that are specified in the Eurocodes [7].

EXPERIMENTAL PROCEDURE

Creep of prestressing tendons is negligible for most UPT structures under ambient conditions. However, at temperatures above 250°C [6], irrecoverable creep can accelerate and cause relaxation of prestress. In a localized heating scenario (e.g. an isolated fire, localized cover spalling, or variable cover due to parabolic tendon profile) UPT tendons may rupture due to a combination of accelerating creep strains and loss of tensile strength. To investigate the strength-stress-temperature-time dependency of locally heated, stressed, unbonded and restrained tendons of realistic length and parabolic tendon profile, eleven transient high temperature stress relaxation tests were conducted using a bespoke "strongback" testing frame.

Tendons with a length of 18.3m were stressed against the strongback frame (Figure 1). The strongback frame was specifically designed to simulate the tendon conditions found in typical UPT concrete slabs. A custom fabricated tube furnace was installed in the strongback to locally heat the tendon at mid-length. The tendon was mounted in a guide channel which was attached to parabolic profile plates welded to the top flange of the strongback beam. Bearing plates were added at both ends to accommodate end anchorages, load cells, and jacking of the tendon.

Individual seven-wire 12.7mm Ø Grade 1860 low relaxation prestressing tendons were stressed to $0.5f_{pu}$~$0.6f_{pu}$ along the strongback frame (a typical stress for a UPT structure after time dependent prestress losses have accumulated [11]). The tendons were then locally heated with a 3% heated length ratio following a prescribed heating and cooling regime (see Table 1 for testing details).

Each test comprised three phases: (1) an increasing temperature ramp at 10°C/min to a predefined temperature set point between 200°C and 700°C (the ramp rate was chosen to be consistent with previous experimentation by MacLean [5, 12]); (2) a soak time of 90mins at constant temperature (selected to be representative of typical North American fire resistance ratings for restrained UPT floor systems with 20mm of concrete cover); this allowed observation of the steady-state temperature dependency of creep deformation; and (3) slow cooling to ambient temperature, which enabled investigation of residual prestress after heating. These experiments were similar to those performed previously by MacLean [5, 12] although they used a more realistic (longer) total tendon length and (smaller) heated length ratio. MacLean's tests had an 11% heated length ratio and a total tendon length of only 5.4m. These two sets of data with different heated length ratios allow a better understanding of the effects of localized heating on prestress relaxation. Heated length ratios in available furnace tests of isolated UPT flexural elements range from 70% to 85% [2, 13, 14]. This may not be representative of real fires, particularly in open plan UPT buildings with travelling or localized fires [15].

In reality, thermal deformations (elongation of the slab, thermal bowing), continuity, restraint, and membrane action (both compressive and tensile) may influence the response of continuous multiple-bay UPT structures in fire [9]. Future research will attempt to address these additional issues.

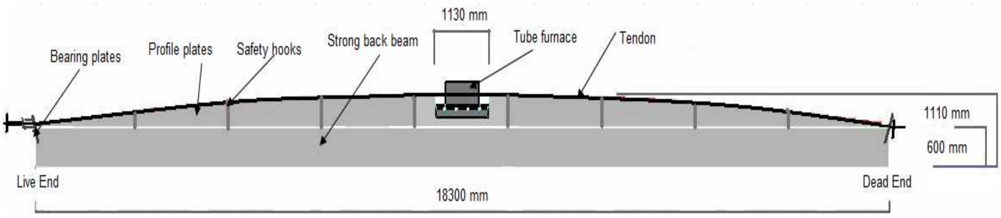


Figure 1: Strongback frame and custom tube furnace configuration.

TABLE I. TEST PROGRAMME, TEST DATA, AND MODEL PREDICTIONS

	Test set up				Experimental		% Difference	
Test #	Initial stress (MPa)	Soak temp (ºC)*	Soak time (mins)	Ramp rate (ºC/min)	Hot stress (MPa)	Residual stress (MPa)	Soak period (%)	Residual period (%)
1	974	200	90	10	961	972	<1	<1
2	971	300	90	10	941	948	<1	1
3	973	400	90	10	808	831	17	17
4	1009	400	90	10	807	831	18	17
5	600	400	90	10	549	569	3	2
6	997	400	5	10	882	897	8	6
7	1015	400	45	10	815	824	15	13
8	1007	400	90	2	805	814	20	18
9	1015	400	90	30	769	786	19	17
10	983	700	0	10	Rupture	Rupture	Rupture	Rupture
11	997	500	2	10	477	Rupture	21	Rupture

* Note: the prescribed soak temperature indicates the specified set point, actual temperature for Test 10 was 524ºC and for Test 11 was 501 ºC.

EXPERIMENTAL RESULTS

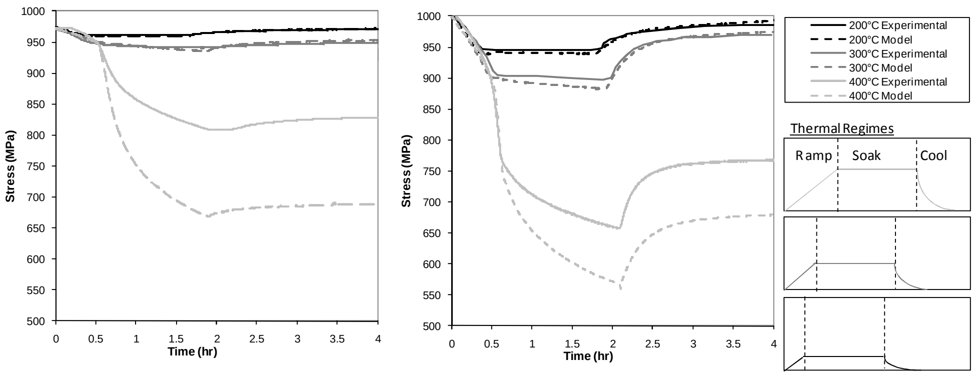
Several testing regimes were used to assess the tendon's performance during heating and cooling; these are summarized in Table 1. Tests 1 to 4, 10, and 11 considered different target set point temperatures (200ºC to 700ºC) but were otherwise identical. This allowed experimental investigation of the effect of creep/relaxation at different temperatures and also provided a comparison against MacLean's tests [5, 12]. It should be noted that Tests 10 and 11 both resulted in tendon rupture either at or before the target soak temperature was reached.

Available creep parameters that are used in the authors' predictive creep model are extrapolated beyond the stress range for which they were originally generated (up to 690MPa) and may therefore require updating [5]. Test 5 therefore considered a lower initial prestress level which lay within the limits of available high temperature creep data. Tests 6 and 7 varied the soak phase duration (5min and 45min) and Tests 8 and 9 explored the effect of different heating ramp rates (2ºC/min and 30ºC/min).

Figure 2 shows the predicted and observed stress versus time plots for Tests 1 to 3, with a heated length ratio of 3%, along with otherwise identical tests performed by MacLean [12] with an 11% heated length ratio. Upon cooling from a soak temperature of 200°C (Test 1) a small amount of irrecoverable tendon stress loss (about 2MPa) was observed. After cooling from soak temperatures of 300°C or more, greater irrecoverable losses were observed; 23MPa for Test 2 at 300°C and 142MPa for Test 3 at 400°C. This clearly illustrates the irrecoverable stress relaxation that occurs due to transient creep at high temperatures.

The residual prestress levels for Tests 3 and 4 (both at 400°C) differ by less than 1MPa, indicating good test repeatability. Figure 2 compares Tests 1 through 3 to MacLean's tests with a larger heated length ratio [12]. The larger heated length ratio is seen to result in more prestress loss on heating and the smaller heated length ratio shows proportionally less prestress recovery on cooling. Both of these observations are due to the proportionally greater recoverable effects of thermal expansion for the larger heated length ratio. The shorter heated length ratio maintains a higher overall stress level, which leads to greater irrecoverable creep losses in the heated region for the same soak time.

Tendon failure was observed in Tests 10 and 11 between 500ºC and 525ºC. However, tendon failure was not observed in any of MacLean's tests [12], in some cases up to 700ºC. This highlights the complex interplay between stress, time, and temperature for the tendon.



(a) (b)

Figure 2: Stress versus time for (a) 11% heated length ratio and (b) 3% heated length ratio.

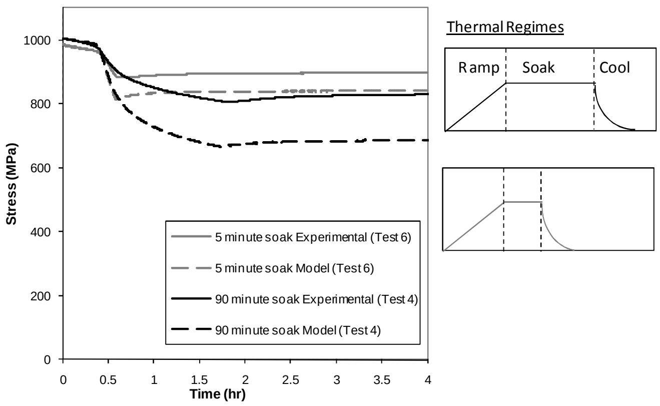


Figure 3: Effects of varying soak time.

Predictions were made for each of the tests using a computational explicit creep model developed previously [5]. The model used temperature input values from actual thermocouple readings collected on the tendons during the strongback tests, and imposed the actual initial prestress levels recorded by the load cells. The predictions are given in Figure 2 and Table 1. For the strongback tests, the model shows reasonable agreement at 200°C and 300°C (a maximum difference of less than 1%). At 400°C the error is considerably larger at about 18%. This is expected since the model is known to calculate creep in a conservative manner [5]. It should also be reiterated that the creep parameters used in the model are based on steady-state creep tests up to stress levels of only 690MPa, whereas the initial prestress levels in the current experiments were about 1000MPa.

For Test 5, which had a lower initial prestress of 600MPa, the computational model predicts slightly more prestress loss than observed in the experiment, with differences of only 3% (16 MPa) during the soak phase and 2% (13 MPa) on cooling. This is in comparison to Test 3 (initial prestress of 1000MPa but otherwise identical) where the difference was 18%. This confirms that the creep is modeled more accurately at lower stress levels using the available creep parameters.

Tests 6 and 7 had soak times of 5mins and 45mins and were compared against Test 3 with a soak time of 90 minutes, all at a soak temperature of 400°C. As expected, Figure 3 shows that the amount of creep after a 5min soak at 400°C (115 MPa) is less than after a 90mins soak at the same temperature (202 MPa). The accuracy of the model increases with shorter soak times since creep is a function of time and thus lower creep losses occur with smaller soak periods. As already noted, the model conservatively over-predicts the amount of creep so that longer soak times lead to greater errors in prediction.

To the knowledge of the authors no information is available on the effects of varying heating rates on the mechanical response of prestressing steel. Different heating rates can be considered akin to tendons placed with different depths of concrete cover in a real UPT structure; a parabolic tendon in a real UPT slab will always experience different heating rates at different locations along its length. Figure 4 shows the effect of heating rate on the response of the tendons used in the strongback tests with a temperature set point of 400ºC (Tests 4, 8, and 9).

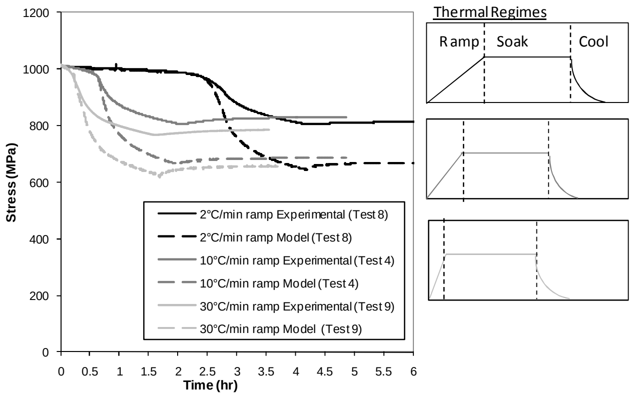


Figure 4: Varied Heating rates.

Tests 4, 8, and 9 all tend toward the same residual prestress level (within about 50 MPa of each other). Test 4 (10°C/min) displayed less residual prestress loss (178 MPa) than either Test 8 (2°C/min, 193 MPa) or Test 9 (30°C/min, 229 MPa), indicating no significant trend due to heating rate. The model predicted the experimentally observed trends but differed by up to 30MPa between the three tests.

DISCUSSION

With various countries currently in the process of adopting performance based structural fire design codes, it is a necessity to better understand various aspects of the real behavior of UPT concrete flat plates (and other types of structures) when subjected to elevated temperatures. A rational first step in this direction for UPT slabs involves accurately evaluating the response of the cold-drawn steel prestressing tendons under transient high temperature conditions. It is clear that available high temperature mechanical property reduction models for prestressing steel which *implicitly* account for creep cannot possibly capture the time-dependency of creep under transient heating conditions as would occur in a real fire. The consequences of this inability for computational structural modeling in support of performance based structural fire engineering remain unknown.

The interactions between strength, stress, time, and temperature at high temperatures in prestressing tendons of realistic length with localized heating have, until now, gone largely unexamined. Creep data currently do not exist for realistic in-service tendon stress levels; such data are needed as inputs for computational models and are currently being elucidated by the authors.

CONCLUSIONS AND RECOMMEDATIONS

A series of eleven transient high temperature stress relaxation tests on locally heated prestressing tendons have been performed and are compared herein to a previously developed [5] explicit creep model. Soak temperature, initial prestress level, soak duration, and heating ramp rate were all studied, both experimentally and computationally, leading to the following conclusions:

- Irrecoverable (pre)stress losses resulting from transient creep deformations increased with higher soak temperatures periods and became noticeable above 300°C.
- Small heated length ratios (3%) resulted in tendon rupture at soak temperatures above 500°C, confirming that localized heating of a tendon, which is reasonably likely for a real fire in a UPT building, may result in tendon rupture. No ruptures were observed up to 700°C for a larger heated length ratio of 11%.
- The authors' explicit creep model [5] predicts the correct trends in tendon response subject to transient localized heating, although in general it over-predicts creep relaxation. This is thought to be due to the fact that the creep parameters used in the model are based on tests performed at stress levels below 690MPa. Additional testing is needed to develop creep parameters appropriate for realistic in-service stress levels of 1000MPa or more.
- An important time dependency for creep relaxation was observed at elevated temperatures below the critical temperatures commonly assumed for prestressing steel [16]. Thus, thermal exposures in the range of minutes may become important for structural response at these tendon temperatures.
- Stress relaxation was observed to be unaffected by different heating ramp rates between 2ºC/min and 30ºC/min up to a soak temperature of 400ºC.

The consequences of prestress relaxation and tendon rupture for the global structural performance of UPT concrete structures in fire should be evaluated, both through detailed finite element modeling of full-structure response to fire, and through large scale non-standard fire tests on UPT multi-bay model structures.

The authors' creep model is currently limited to consider only the behavior of the prestressing tendon. A more complete understanding of the performance of a UPT slab in fire can be made by studying the tendon's interaction with concrete and associated structural actions in fire such as thermal bowing, global thermal expansion, restraint, in-service concrete stresses, and compressive or tensile membrane action. Consideration must also be given to spalling during fire, since this would obviously cause localized heating of the tendons and is likely to occur in a real structure. 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.

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