POST FIRE GUIDANCE FOR THE CRITICAL TEMPERATURE OF PRESTRESSING STEEL

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ABSTRACT

Society depends on critical infrastructure – of which the closure due to fire can result in severe economic losses. If post-fire rehabilitation is done incorrectly, it can also result in life safety risk. A portion of global critical infrastructure is built using prestressed concrete. Prestressed concrete uses steel that has been chemically and mechanically altered in order to achieve high strength and durability properties by means of fabrication processes which are continually evolving and changing. In the event of a fire, the prestressing steel, when exposed to elevated temperature within these concrete structures, can be severely damaged through complicated material changes related to its fabrication techniques. As fabrication techniques are rapidly elaborated and refined, the steel behavior in and after fire becomes more intricate to describe. Additionally, traditional guidance for this steel, where the practitioner can base their post-fire assessment on prescriptive rules, relies on the peak temperature of the prestressing steel and does not account for the duration of time the steel may have been exposed to severe temperature. Within the case of critical prestressed concrete infrastructure, a fire can last up to eight hours or more in extreme conditions as seen in many published case studies. A conservative and contemporary quantification of the remaining strength of prestressing steel after it is exposed to high temperature is a research need to ensure safety of critical prestressed concrete infrastructure. A novel experimental program at Carleton University and the University of Edinburgh has been assessing the effect of exposure time on the post-fire residual capacity of prestressing steel. The residual strength was obtained for exposure durations of 2, 4 and 8 hours up to temperatures of 900C. These results herein have shown a profound effect indicating that conventional guidance may be non-conservative for long duration fires and new guidance may be necessary. This paper concludes with justification that the critical post-fire exposure temperature for contemporary prestressing steels be lowered from 600C to 500C.

INTRODUCTION

Prestressing steel is a key reinforcing steel material for many critical concrete prestressed structures (bridge infrastructure, iconic structures, power plants etc.). These structures offer necessary services which economies and lives depend upon. A recent study by the authors' highlighted that fires in concrete infrastructure that utilize prestressing steel can have extended time durations well beyond eight hours at severe temperatures. [1] Delaying post-fire investigations of critical infrastructure can incur severe economic costs, while errors in such investigations can potentially affect public safety. Recent examples of the potential for significant economic loss are the closures of critical bridge infrastructure to allow post-event investigation: Ambassador bridge in Michigan after the fire in 2015; and Hamilton Sky Bridge after a trucking accident in 2014. While these case studies are not prestressed concrete structures, they show the necessity for the timely post-event investigation of critical infrastructure to be performed. The post-fire investigation of prestressed concrete structures is difficult. In the event of a fire, the prestressing steel, when exposed to elevated temperature within these concrete structures, can be severely damaged due to the heat effect causing complex material changes related to its fabrication techniques. As these fabrication techniques are rapidly elaborated and refined in industry, prestressing steel as a unique material is becoming more complex and its behavior in and after elevated temperature can be difficult to quantify and understand. After high temperature exposure, where investigation ensues, there is limited guidance for the practitioner to assess this structure type of damage. There is even less guidance on how to actually non-destructively assess this structure type and defining such a method requires understanding the post-fire condition of the prestressing steel.

BACKGROUND AND MOTIVATION

The most commonly accepted guidance available for assessing prestressed concrete after fire is published by the Concrete Society [2] and is broadly referred to by others [3,4,5.] Within that guidance is a graphical definition of the residual strength of the prestressing steel as a function only of the peak temperature that the steel reaches during a fire – the severity of the fire (specifically its duration) is not taken into account. Assessment in this manner, can be user friendly when considering only the remaining strength of the prestressing steel after a fire (other factors neglected): identify the peak temperature perhaps based on concrete color, and tabulate the remaining strength of the steel from the guidance. The remaining strength can then be used to aid in the assessment of the structure's remaining ability to carry load. Of course this analysis may rely on accurately determining the concrete color conservatively which is very difficult as shown in reference [1]. More time consuming microstructural analysis can also be considered to identify the temperature at which the concrete was exposed to identify the temperature the steel was exposed too. It should be recognized that other factors beyond remaining strength of prestressing steel should be considered post-fire, however the scope of this paper is to consider this isolated strength-steel aspect. The reader is encouraged to consult other literature by this article's authors for a more complete breakdown of analyzing a prestressed concrete structure in and after fire which focuses on stress states of the steel [6].

The most common post-fire critical temperature reported in literature for prestressing steel is 600C. Existing contemporary guidance suggests the residual strength of the prestressing steel after exposure to a maximum temperature of 600C will have a remaining strength of 50% of the original capacity – the critical temperature definition. This guidance [2] has extended jurisdictions in North America and Europe [3,4,5] and is the most convenient analysis method for the post fire damage assessment of prestressed concrete. However, as aforementioned, the method relies mostly on peak temperature exposure, and careful analysis of its origins traces it to the 1960s [7, 8, 9]. That could be a problem when considering the alterations in fabrication techniques for prestressing steel which occur today. Contemporary fabrication techniques were shown by the authors to be important for assessing in-fire exposure of prestressing steel [10]. If conservatism is not inherent within the current guidance, than we should assess the steel; perhaps, destructively. The paradox for prestressed concrete is that if a practitioner removes the steel, s/he can't go back and put in a new bar as it cannot be re-tensioned easily to provide its beneficial pre-compressive effects for load balancing. A conservative and contemporary quantification of the remaining strength in prestressing steel after it is exposed to high temperature is a research need to ensure safety of critical prestressed concrete infrastructure.

The research program conducted herein assesses the conservatism of traditional guidance providing insight into the 'time-effect' of temperature exposure on the post-fire strength of prestressing steel. A non-destructive technique and the concepts of micro-structural evaluation are also introduced in brevity involving hardness testing and microscopy. The authors' aim is to give the practitioner two options to promote discussion with respect to residual strength of prestressing steels after fire; either defensibly develop non-destructive techniques that can be done in a timely manner for prestressing steel in critical concrete infrastructure, or lower the critical temperature exposure of prestressing steel after fire by 100C to be conservative until the appropriate technology can be developed.

METHODOLOGY

In order to study the conservatism in the current strength reduction guidance, two different but equivalent prestressing steels were considered for this research: as sourced from a steel mill in the United Kingdom (4.15 mm wire diameter, grade 1860) and as sourced from a steel mill in Singapore (4.4 mm wire diameter, grade 1860). The respective steels were made in accordance to BS 5896 and

AS/NZS 4672 standards respectfully. The mechanical behavior at ambient temperature for both sample types is arguably the same; being approximately 1950 MPa in ultimate strength and having rupture engineering strains measured at approximately 7%. These steels are the same used in the study of prestressing steel at elevated temperature (creep effects being studied) provided in reference [10]. In that study it was shown that at elevated temperature the performance of AS/NZS 4672 appeared superior to that of BS 5896 (at least below exposure temperatures of 500C). Careful examination of Table 1, which details each of the materials' analyzed chemical composition, illustrates subtle differences that help support the previous discussion. That paper hypothesized that as AS/NZS contains a higher chromium and copper content it is thought to produce a prestressing steel with superior in-fire mechanical performances. [10] The effect of the chemical composition of prestressing steels has not been thoroughly studied after exposure to high temperature to the authors' knowledge.

The below sections detail the experimental methodologies used in this paper for performing the heating of the steels, tensile testing for ultimate strength of the steels, and microscopic analysis (including hardness correlations) of these steels, the intent being to introduce the reader to the authors' broader study of prestressing steels after fire (residual) exposure.

Table 1. Chemical Composition as percent

Element	BS 5896	AS/NZS 4672
C	0.88	0.79
Cr	0.01	0.29
Mn	0.61	0.59
P	0.0070	0.012
Si	0.26	0.28
S	0.019	0.008
Ni	0.02	0.03
Cu	0.01	0.14

Heating

The bulk of the prestressing steels were cut to lengths of 25 cm (in accordance to standard tensile testing methods which stipulate an appropriate gauge length for suitable strain measurement). After cutting, the samples were heated up in pairs of three to a target temperature in an annealing furnace. Samples were equally distributed in the furnace and suspended on metallic ring holders in order to assure full uniformity in heating along the entire diameter of the strands. The target temperatures were chosen at basic intervals of 100C up to and including 900C (with one exception at 727C to consider the Eutectoid strength level). Samples were heated at a rate of 10C/min to the target temperature and held for a specified duration of time. That duration of time was chosen as 2, 4, and 8 hours. Each exposure time and target temperature was its own test from start to finish with no interruption. That is to say that a separate test was done for each target temperature; and for each heating duration. For example one heating cycle for 4 hours at 800C, a second heating cycle for 8 hours at 800C. There were no interruptions in heating. The authors decided that the risk of cooling the samples during heating was too great compared to the benefits of minimizing test numbers by extracting samples while the furnace was on. Table 2 illustrates the quantity and testing configuration of specimens heated. All samples had no applied load. Samples under applied load are considered elsewhere [1].

After heating to the target temperature, the samples were carefully removed from the furnace and were allowed to cool in ambient air (again suspended in air on metallic rollers). An investigation into quenching techniques (ice bath, and naturally cooling in the furnace) was also done but showed no differences in residual strength. Other smaller samples (10 cm) were separately heated and reserved to perform later hardness testing (tensile tests were not performed to standardized lengths for those tests however).

Remarks must be considered with respect to AS/NZS samples. The limited number of AS/NZS samples is due to the limited quantity of steel available for testing, having been shipped in limited freight from colleagues at Canterbury University in New Zealand. AS/NZS steel is typically used for post-tensioned timber (see associated conference paper [9] for discussion of that infrastructure). Because of this limited quantity only selected temperature and heating durations could be considered.

To ensure accurate temperatures were being recorded all tests utilized K-type thermocouples attached to the surface of the prestressing steels. Figure 1 denotes the temperature of a sample being heated to 800C and the temperature of the furnace held for eight hours.

Figure 1
Annealing furnace temperature control in comparison to specimen

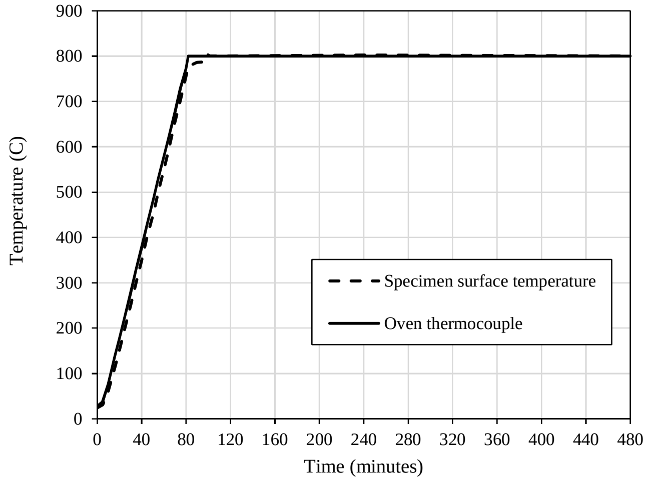


Table 2. Test heating programme

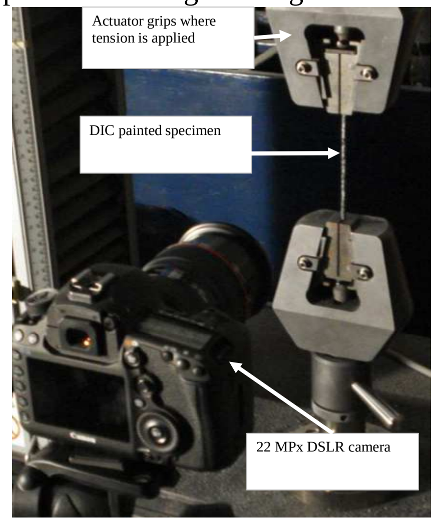
	Duration of heating			
Temperature(C)	2hr	4hr	8hr	Prestressing steel type
20	3	0	0	BS 5896
	3	0	0	AS/NZS 4672
100	3	3	3	BS 5896
200	3	3	3	BS 5896
	3	0	3	AS/NZS 4672
300	3	3	3	BS 5896
400	3	9	3	BS 5896
	3	0	3	AS/NZS 4672
500	3	3	3	BS 5896
600	6	3	3	BS 5896
	3	0	3	AS/NZS 4672
700	3	3	3	BS 5896
727	3	0	3	BS 5896
800	3	3	3	BS 5896
	3	0	3	AS/NZS 4672
900	3	3	3	BS 5896

*- note that additional tests were performed for microspy and hardness analysis not included in this table

Tensile Testing

After heating, the steel samples were tested to tensile failure using a uniaxial tensile testing actuator. For deformation measurement, each test used Digital Image Correlation (DIC) to track and record the strain, true stress and ductility of the prestressing steel at fracture using the GeoPIV 8 software [12]. All specimens were painted using a mixture of black and white paints before testing so that accurate measurements could be made. The deformation measurement method involves using a stationary camera to track pixels between successive images. The pixel movement can be converted into a strain, or to track deformation such as cross sectional area reductions and fracture at high resolution. Previous studies have shown the accuracy of this method to enable novel qualitative and quantitative insights into both the elongation of the specimens throughout the test as well as the steel's diameter reduction [10,13,14]. The method utilized herein can be found as described in references [10, 13, 14]. Figure 2 illustrates the typical loading actuator apparatus complete with specimen and image correlation technique camera system (not shown was the halogen lighting system used). A Canon 5D Mark 3 was used for all imaging. Strains were measured at 0.2 Hz - every 5 seconds. Samples were loaded using a loading rate of 2 mm/min. Samples were tested in accordance with best practice methods for image correlation (see reference [14]).

Figure 2
Loading apparatus with Digital Image Correlation (DIC)



Hardness Testing and Microstructure

Hardness values were obtained by means of Vickers Hardness testing, providing the Diamond Pyramid Hardness (DPH) of several post-fire exposed samples. These samples were heated prior to the tensile study and have previously been reported by the authors (see reference [1]) with correlations made using the same stock of BS 5896 as for tensile testing. These are therefore relevant to the discussion herein. The hardness analysis also provided a strength-hardness correlation, but is limited only to one heating duration time.

Microstructural imaging was also performed in conjunction with hardness testing to investigate the changes in grain structure. This microscopy was used to support this study and others [8]. In brevity, this imagery will be used herein to explain the authors' results. Microscopy was performed for both transverse and longitudinal sections of the prestressing steel samples using a Zeiss Axioscope light microscope. Two 10 mm long sections were cut from each sample and mounted in EpoxiCure resin. These were ground using gradually finer grit paper and then polished with cloths and diamond paste, to obtain a flat, scratch-free surface. The samples were etched with 2% Nital to expose the grain structure.

EXPERIMENTAL RESULTS

Mechanical stress-strain observations as taken from tensile tests

The use of DIC to study deformation has unique advantages over traditional instrumentation for high temperature testing as discussed previously by the authors. Figure 3 illustrates stress-strain diagrams of tensile tests of BS 5896 which also include an analysis of true stress. True stress was calculated by measuring the cross sectional area reduction as the specimen was loaded. It is essentially the recorded load (in Newtons) divided by the new area (in mm^2). To the knowledge of the authors, there is limited data in existence which investigates the strain at failure of prestressing steel post-fire, as well as attempting to quantify the true stress of the material under loading. This information is useful for practitioners with an interest in fracture mechanics and strain hardening behaviour. The information also provides insight into the overall failure characteristics of the steel post fire, should the prestressing steel not be replaced in a fire-exposed structure. Figure 4 illustrates imagery taken at failure for each specimen. Note in Figure 4 that the classical cup and cone failure profile disappears at 700C. This, with the stress-strain diagrams in Figure 3, confirms that the area reduction would be quite small. The true stress can help the practitioner understand ductility concepts which are quite essential in the post-fire usage of these steels. For example, even if remaining strength is present when the temperature in these cases exceeds 700C, there could be much less warning before strength failure of the prestressing steels if they were used in the future. This is particularly why it is essential to limit the temperature exposures and durations to cases where the prestressing steel experiences no more than 50% its losses. The strength gain from extreme temperature exposure afterwards is unreliable from an engineering perspective and cannot be counted upon.

Figure 3
Selected Stress Strain Relations at 2 hours for BS 5896

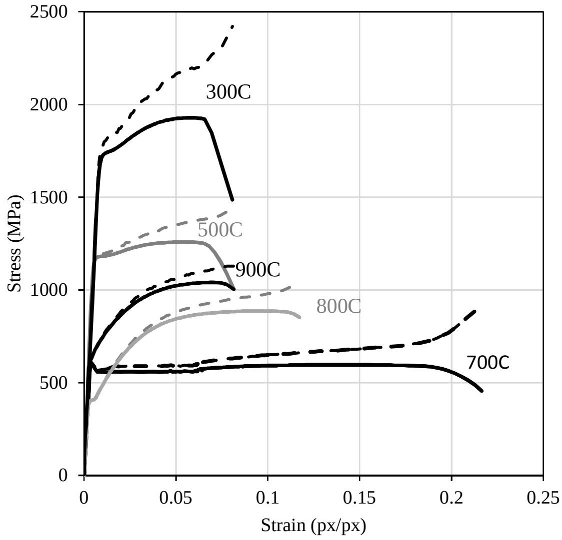
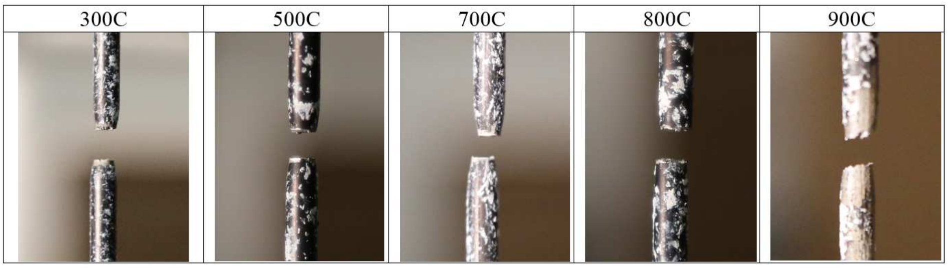


Figure 4
Selected Fracture planes at heating duration of 2 hours for BS 5896



Mechanical strength observations as taken from tensile tests

Varying the duration of temperature exposure time illustrates a large effect on the residual strength of the specimens. For example the duration of heating caused a 5 to 10% reduction in strength between the 2 hour and 8 hour prestressing steel samples for all of the temperatures tested. For all tests, the residual strength decreased as the heating duration increased, with the exception of BS 5896 samples exposed to 800C. For BS 5896 exposed to 800C, the opposite was observed with the residual strength actually increasing with the heating duration. This behaviour can be observed in Figures 3 and 5. Shown also in Figure 5 is a good demonstration of the typical test repeatability observed in this research program. Note that the failure strain observed is dependent on where the fracture of the steel occurs (near grip) relative to the measurement gauge length of the DIC method – this explains why some samples have less apparent ductility. Fracture mechanics suggests that once steel begins to neck, the strain effects will be localised in that region; outside that region, straining stops (the dip in the stress strain curve for example). These effects normally cannot be observed unless high speed and high resolution photography are used.

The unique behaviour at 800C is hypothesized to be due to the change in grain structure which occurs in the prestressing steel as it is exposed to high temperatures. In the manufacturing of prestressing steel, the grain structure is specifically altered to increase the strength. Exposing the steel to high temperatures undoes these alterations and returns the grain structure back to one not dissimilar to that of mild steel when exposed to temperatures above circa 727C. The longer exposure duration gives the recrystallization process more time to proceed to completion. This may help explain why the extended exposure time results in a decrease in residual strength at lower temperatures and can also account for the strength gain at 800C.

Figure 5
Stress Strain Relations at 800C for BS 5896 with Repeat Testing Shown

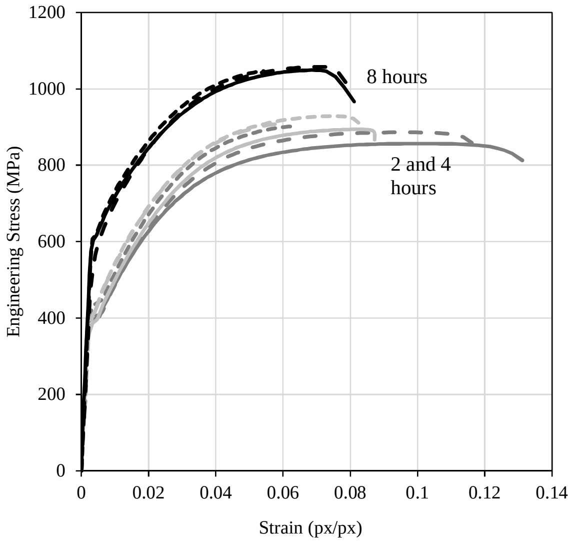
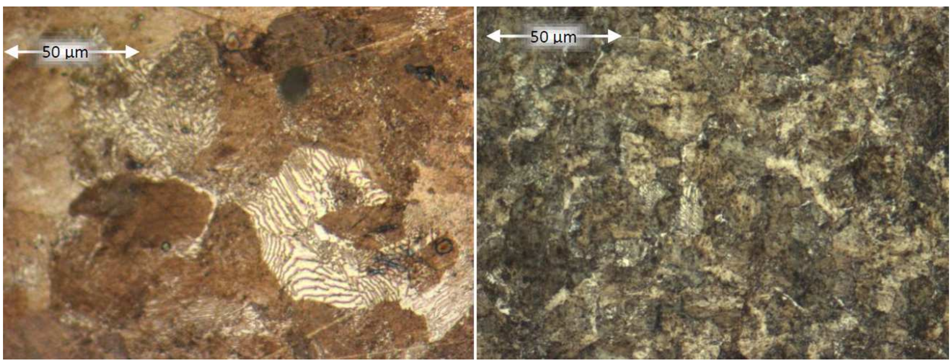


Figure 6 illustrates the microstructure of both BS 5896 and AS/NZS 4672 after exposure to 800C. Lower grain sizes are indicative of higher yield strength and comparison of tensile tests and microscopy of both BS and NZS correlate with this 'rule'. However, the discussion of post-fire yield stresses is outwith the discussion here and will be treated in more detail in future articles.

Figure 6
Microstructure after exposure to 800C for BS 5896 (left) and AS/AZS 4672 (right)

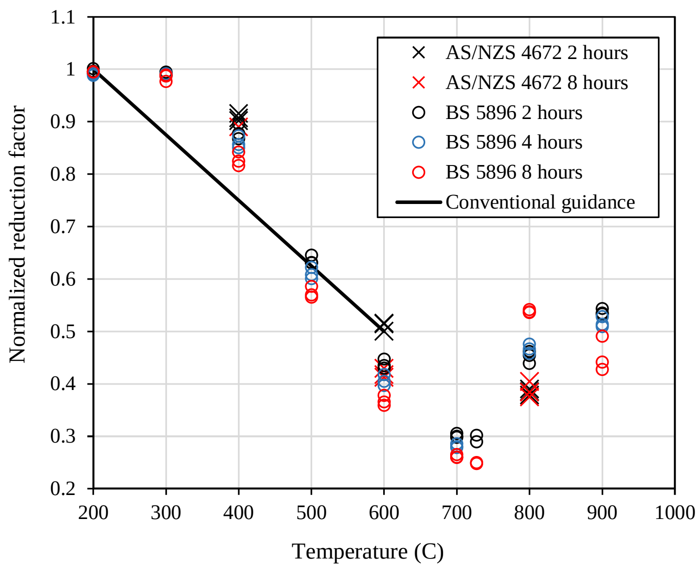


The lower strengths observed for AS/NZS at higher temperatures above 500C than there BS 5896 counterparts is a unique response. This is unique because the addition of chromium is thought to aid in the fire performance of PS steels. The higher amounts in PS steel appears to have no effect beyond certain temperatures.

The experimental results clearly show that traditional strength reduction guidance may not be conservative for the two prestressing steels considered herein. The results obtained by the 2 hour tests for BS 5896 showed that at 600C, where the guidance suggests 50% strength should remain, only 44% of the original strength actually remained based on three samples. That is without considering extended durations of heating time. When extended exposure is considered, BS 5896 specimens were seen having only 36% the original strength, far below traditional guidance.

Even for 500C most tests showed less strength remaining than what guidance would indicate. Figure 7 illustrates reduction factors for both steel types (BS 5896 and AS/NZS 4672) with respect to heating time and conventional graphical guidance after 200C (strength remains similar to ambient temperature before that point). Strength reduction factors were developed by considering their post high temperature exposure stress as divided by their average ambient temperature strength value. As a remark, it should be noted that at 600C both steels (BS and AS/NZS) at 8 hours are below the traditional guidance, and that strength appears to be gaining even over 800C. The dip in strength is considered based on Eutectoid level of Prestressing steel which occurs at circa 727C. The authors tested that temperature as well but no significant added insights were obtained, other than the strength values at 2 and 8 hours were similar to the behavior at 700C (and definitely not the same value to one another). The transition point the where the steel begins to gain strength is not known without more testing, but apart from being a curiosity, seems to have little short term benefit for a practitioner to study to describe strength loss; the critical temperature happens well before this point.

Figure 7
Ultimate strength reduction factors for BS 5896 and AS/AZS 4672 with conventional guidance after 200C



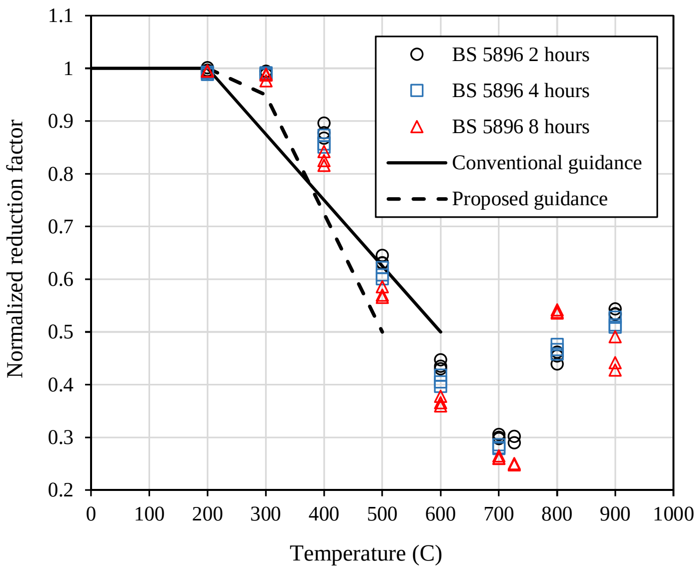
DISCUSSION

In order for current strength reduction guidance for prestressing steel to be conservative and account for the possibility of long duration and severe fires, The authors believe conventional guidance which relies solely on temperature and omits the duration of heating is in need to be updated if it is to be considered conservative.

Any conservative guidance should consider the following aspects. First it is not practical to provide the practitioner with several sets of strength reduction curves/isotherms that have had different heating times as this is because in a real fire there will not be a constant and consistent temperature, but highly variable fluctuations in peak temperature and in duration. If practitioners want defensible guidance based on graphs and prescriptive rules for quick analysis, they must also consider both the duration (time dependent) and the temperature peak. In that way guidance is always conservative. Of course it must be acknowledged that identifying the peak temperature brings uncertainty with current methods. To move to a situation where the time and temperature history of the real fire is known is not feasible with today's infrastructure (smart sensoring isn't there yet economically), so a practitioner must prescriptively still assume a peak temperature and duration on a conservative basis. The second issue revolves around where to terminate strength reduction guidance, traditionally this is done at 600C, where the steel was said to have 50% strength reduction from ambient temperature. However it is shown herein that the lowest threshold can potentially occur under certain circumstances at 500C not 600C. Neither the 800C strength gain with duration of heating, nor the small increases in strength after 900C can be relied on.

The authors' recommendation is that strength reduction guidance consider that residual strength begins to decrease after 200C, being conservatively 95% of the ultimate strength at 300C, and linearly tapering to 500C where only 50% of the original strength remains. This decreases conservatism at 300C (which is shown valid to consider) and increases conservatism by lowering the critical temperature from 600C to 500C (also shown valid). Regardless of time durations, the current traditional strength reduction guidance is not conservative. The new graphical guidance as proposed by the authors is shown relative to BS 5896 strength reductions in Figure 8.

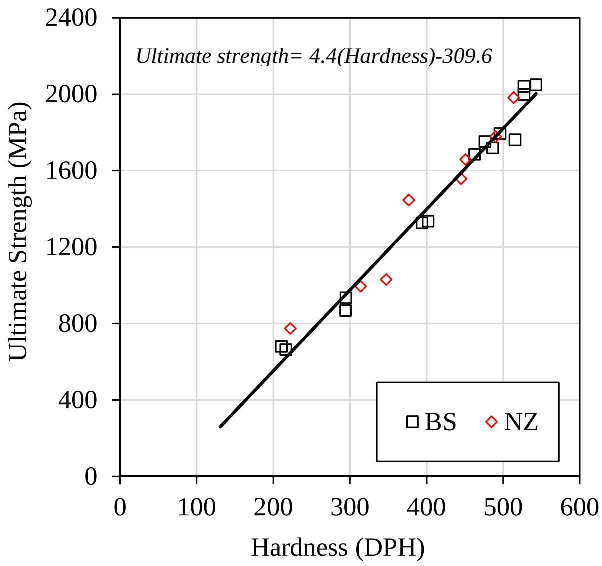
Figure 8
Contemporary strength reduction guidance



Obviously this may have repercussions on the industry's manufacturers and practitioners. The authors maintain however and suitably defend that if the practitioner continues to take a traditional treatment of the subject strength reduction by largely a graphical and prescriptive rule basis, it should be based upon a conservative approach. It is the authors' opinion that rather than perform what could be considered unreliable tabulated checks which consider concrete color change or time consuming microstructural analysis (concrete doesn't change color for some mixes as discussed in reference [1]) to estimate the remaining strength with obvious uncertainties, that non-destructive testing methods should be improved and explored further with continuing research. Exploring hardness testing procedures for prestressing steel may help the practitioner without damaging the steel assess the remaining strength. Figure 9 illustrates a typical hardness strength relationship for this stock of BS

5896 steel as developed by the authors. Of course in this method, it is not possible to predict the peak temperature (say over 700C where the steel begins to increase in strength again), and that has resulting implications on the prestressing steel's remaining ductility.

Figure 9
Hardness- strength correlations for BS 5896



While efforts have been made to be comprehensive with the data utilized within this paper, it must be realized that the data obtained through the use of DIC permits additional insights to be realized beyond true stress and strain. For example, discussion involving yield and plastic strain hardening effects, behavior after heating for samples that were loaded, stress relaxation, deflections of the members, concrete behavior, and comparison to in-fire temperature behavior as reported by the authors earlier this year [10]. These are currently beyond the scope of the authors' discussion for this paper but will be addressed in time by the authors if not in existing publications elsewhere.[6]

This study's primary goal is to illustrate a critical need for updating conventional strength reduction guidance first with a new conservative post-fire critical temperature for prestressing steel – lowering it to 500C from 600C.

CONCLUSIONS

The ability to determine the residual strength of prestressing steel is an essential tool for the assessment and rehabilitation of critical structures after fire. The predictability of a fire is debatable so it is necessary to account for every possible situation when creating conservative recommendations to be used in practice. The current method for obtaining the strength as suggested by traditional graphical and prescriptive rule guidance is in need of revision and further research to support alternative and quick analyses post-fire. This study provides a valuable convention to the contemporary strength reduction guidance which also takes into consideration extended exposure times likely to occur in a real fire. This should be considered until a defensible performance based approach and technology development can be considered for the assessment of modern prestressed concrete infrastructure after fire.

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