Post-fire investigations of prestressed concrete structures

Citation for published version:
Robertson, L, Gales, J, Stratford, T & Al-Merabi, A 2015, Post-fire investigations of prestressed concrete structures. in Response of structures under extreme loading: Fifth international workshop on performance, protection & strengthening of structures under extreme loading. DESTECH PUBLICATIONS, INC, pp. 747-754.

Document Version:
Peer reviewed version

Published In:
Response of structures under extreme loading

Cover page

Fifth International Workshop on Performance, Protection & Strengthening of Structures under Extreme Loading
June 28-30, 2015

Title: Post-Fire Investigations of Prestressed Concrete Structures

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Side view

Soffit view

Top view

Concrete slab after testing in fire: Note the black substance is melted polypropylene used to protect the steel embedded in the slab. The protruding wires are glass fibre temperature gauges (thermocouples)

(FIRST PAGE OF ARTICLE)

ABSTRACT

Concrete structures reinforced with prestressing steel, referred to as prestressed concrete (PSC) structures, are commonly used in bridge and tall building construction as they can easily be optimized. However, prestressing steel is well known to have complex behavior when exposed to high temperatures. To date, this structure's high temperature behavior is not fully understood and can potentially complicate post-fire structural investigations of PSC structures. After a fire, it is often difficult to guarantee stability or specify necessary repairs for this type of structure. The study herein aims to help develop guidance for investigating and assessing PSC structures (with emphasis on bridge beams) post-fire. Investigations of specific and real PSC structures after fire exposure are reviewed as case studies herein. Characteristic damage indicators and test methods for assessment are discussed. The authors characterize the residual condition of a lab-scale PSC structure previously exposed to severe temperature. Non-destructive strength analyses of prestressing steel using a calibrated hardness test procedure were carried out. Results were compared to those from destructive methods and showed satisfactory correlation. The high temperature exposed concrete was also inspected. The paper concludes with recommendations of future research required to better identify the condition of PSC structures after fires.

INTRODUCTION

Concrete is a popular construction material for both bridge and building infrastructure. In the last several decades, advances towards optimizing this type of infrastructure for long spans, reduction of materials and durability features have been made. One technology which has been used in concrete structures to meet these

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objectives uses prestressing steel. Prestressing steel is a high strength (cold-drawn) material which, when tensioned, can help concrete structures meet stringent serviceability and sustainability objectives. Bridge and tall building infrastructure are becoming increasingly reliant on this technology. However, prestressing steel (and materials like concrete) can have very complex degradation patterns and behavior when subjected to elevated and extreme temperatures as seen in fire. A recent review [1], has identified numerous fire safety concerns with building infrastructure which utilizes this technology, including: the complex interactions between prestressing steel tension and strength, and the rapid failure of prestressing steel which may be observed in the instance of concrete cover spalling. In addition a highly complex structural interaction between concrete and tensioned prestressing steel has also been identified [2-4].

Previous studies have discussed the potential economic costs associated to specific bridge failures and bridge closures [5]. An example of potential costs with bridge closure can be considered with the recent Burlington Skyway crash in 2014 in Canada. While not fire damage, the resulting four day closure of this bridge resulted in millions of dollars in economic losses (although the final figure of this has not been calculated). The fire concerns for critical infrastructure such as prestressed concrete bridges are a complex issue to resolve and are not limited to life safety alone. With prestressed concrete structures so complex to understand during and after fire, and the driver to determine whether the structure is safe to be re-opened quickly after fire, and which repairs are necessary after fire, such a topic is a worthy pursuit for further research.

The work shop of PROTECT is an excellent venue to begin discussion of this topic and the authors herein set out to provide several discussion points related to a more narrowed topic working towards developing guidance (and new technologies) for investigating and assessing PSC structures (with emphasis on bridges) post-fire. To help promote discussion, this paper reviews three real PSC structures case studies after having suffered damage from fire exposure. These studies illustrate the importance of understanding the material behavior of prestressing steel in its post-fire condition. The authors then proceed to utilize and adapt some assessment methods described in those case studies to characterize the residual condition of a lab-scale PSC structure previously exposed to severe temperature. Non-destructive strength analyses of prestressing steel using a calibrated hardness test procedure [6] were carried out. The high temperature exposed concrete was also inspected. This short study concludes with a brief list of recommendations and future research which may compliment and better identify the understanding of the condition of PSC structures after fires.

BACKGROUND

A global literature search by the authors has identified nearly ten major and economically critical fires of PSC concrete bridges in the last decade. The authors take an international perspective by considering one case study in the United States, Canada and the United Kingdom respectively. In all cases, the PSC configuration of the fire-exposed structure was that of bonded prestressing steel. That is to say the prestressing steel is in contact with the concrete in a stressed state before the fire occurred, as opposed to unbonded, where there is no mechanical compatibility with concrete. The reason for this type of system is that prestressed concrete bridges can easily be constructed by means of pre-fabricated prestressed concrete girder sections to support bridge decks. The authors focus their attention on these girders. Within these three studies, careful consideration/attention is given to the type of fire observed, fire duration, assessment utilized, and the key conclusions as reported. Key insights follow. Primarily, the assessment of these case studies follow their respective national protocols outlined by PCI guidance in the United States [8], MTO in Canada [7] and, in the United Kingdom, following Concrete Society TR 68 guidance [9] and other documents.

Puyallup River, USA, 2002 [10]

Damage caused to Puyallup River Bridge was due to a railroad tanker collision causing what can be referred to as a hydrocarbon fire exposure (high peak temperature, rapid temperature climb), with the fire lasting for over an hour. Post-fire assessment followed protocols outlined in PCI guidance. Engineers considered concrete color, deflection behavior of the bridge spans, spalling, and the residual prestessing steel strength and remaining prestress. A variety of destructive technologies were used to meet these objectives including coring of concrete and even extraction of prestressing steel strand samples. The remaining prestress was assessed using a dial reading caliber to calculate the remaining force. The key conclusions in the engineering report suggest that the experimental data and literature capable of aiding in analyzing the effects of hydrocarbon fires under bridges is limited. They also indicated that while severe damage in the form of spalling was present, the amount of stress relaxation observed in the prestressing steel was generally small (despite indications of being heated to nearly 500C) and the steel retained its ‘original’ material properties. Replacement of the girders was favored over repair as cost was equivalent.

Don Valley Parkway, Canada, 2008 [11]

The Don Valley Parkway fire was caused by a vehicle crash on a pier which caused a fire that lasted over three hours. The post-fire assessment followed protocol outlined in aforementioned MTO guidance. Engineers noted the presence of longitudinal cracking, delamination of concrete – spalling – that exposed prestressing steel, and a pinkish hue of concrete. The available report is vague as to the extent of post-assessment of the remaining stress and strength capacity of the prestressing steel. However, the report does detail that repairs were undertaken to pour a new 200 mm thick concrete slab to reinforce badly damaged areas of the existing deck as part of an emergency response plan. A new transverse diaphragm was also cast between both ends of the new slab. The bridge was heavily instrumented after the fire by means of strain gauges and deflection transducers, and a qualitative and quantitative assessment was carried out indicating that the structure had an elastic response with full recovery with cyclic application of load. The report indicates that as there was no obvious deflection after fire, the tendons were not affected by the heat and suggests that the exposed temperature was in excess of 600C on the basis of concrete color alone. The report cautions that the bridge could experience accelerated deterioration in the future and insists upon studying the long-term effect on the bridge post-fire whilst highlighting the need to rapidly repair cracking and delaminated concrete to prevent corrosion or durability issues. The previous case study outlined similar concerns with regards to potential corrosion implications to prestressing steel if concrete was not repaired appropriately.

Deans Brook Viaduct, United Kingdom, 2011 [12]

Deans Brook Viaduct fire is said to have started in an alley and scrapyard near the bridge. Fire brigade reports suggested that the fire achieved temperatures as high as 800°C beneath the bridge and spalling was observed up to 3 hours after the fire started. A variety of guidance was utilized to assess the condition of the bridge, including TR 68 and the use of knowledge in various Highway Agency reports implying that there is ‘proof’ that prestressed concrete beams retain much of their initial prestress after exposure to a five hour fire (even though the severity of that fire is not mentioned and presetress is inferred from dated standard fire tests- see reference [1]). An initial assessment hypothesized that the bottom layer of prestressing steel had no strength as it was exposed due to spalling, whereas the upper layer of prestressing steel in the beams had 75% remaining strength. The post-fire assessment conducted included hammer tests to assess delamination, destructive material testing giving consideration to the color discoloration of the aggregates, and microscopic analysis for concrete micro-cracking. After extraction of a portion of prestressing steel from the beam, hardness and tensile strength tests of that steel were conducted. The key conclusions were that they were able to show confidence in existing TR 68 guidance while noting that, where concrete cover remained, it was sufficient to prevent significant tension losses in the prestressing steel (< 15%). However, where the concrete cover had been completely lost, exposing the steel losses were significant (> 60%). The engineering reports also highlight a need for a standardized test procedure which could determine the remaining tension in wires after a fire. Current methods rely on destructive testing of the wires by cutting and measuring relaxation, or by vibration analysis.

Insights from Case Studies

When dealing with critical infrastructure, time is the most pressing issue. Being able to quickly assess the structure and determine the severity of fire damage is essential. Several days of closure at key times can amount to millions in economic damages. The majority of assessments utilized in these studies demonstrate a variety of destructive and time consuming test procedures. The lack of standardized procedures for considering prestressed concrete bridges is apparent. However, the differences between each approach are a worthy investigation to pursue but remain beyond the scope of this paper. However, recent efforts by Rush et al., [13] have been undertaken to look into the subject of assessing concrete structures post-fire from an international and cumulative perspective. However, such approaches still necessitate that the fire condition be well understood. For the above case studies, the length and severity of fire demonstrate that prestressed concrete bridge structures can experience a diverse range of potential fires and potential damage indicators. Development of that style of framework would benefit from analyzing prestressed concrete structures post-fire (whether they be bridges or buildings). Interestingly, despite lower severity fires in some case studies, spalling beneath the prestressing steel appears to be always prevalent - thereby indicating severe localization and potential localized damage to the prestressing steel. The condition of the bridge is therefore highly dependent on the remaining capacity of the prestressing steel and each case study has commonality in being able to assess these appropriately.

EXPERIMENTAL PROGRAM

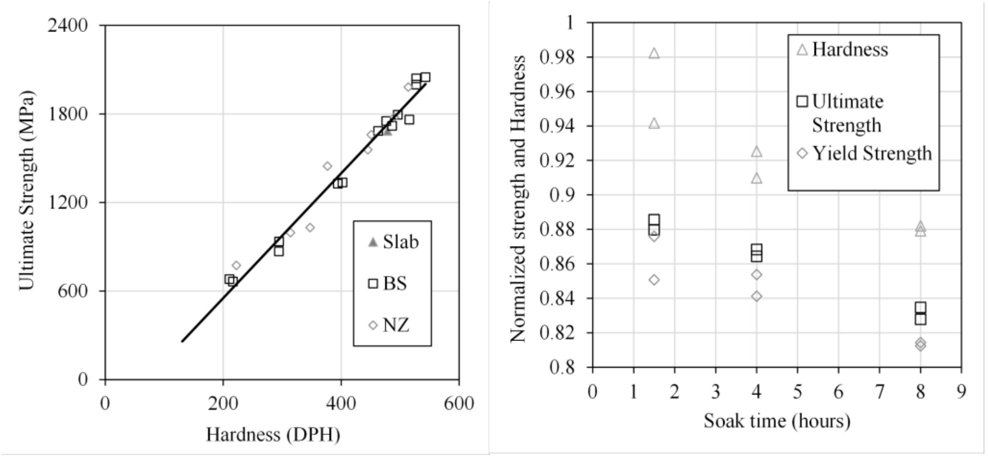
The preceding sections indicate trends towards destructive and what can be considered time consuming post-fire assessment. While we may be confident in our ability to determine the extent of fire exposure on a concrete structure, assessing prestressing steel post-fire is not simple. For instance, even on the basis of color change, there is a belief that heat in the prestressing steel can be conducted away (longitudinally) from the fire source indicating less temperature in the steel than the surrounding concrete [5]. Recent experiments with temperature measurement have indicated that 'non-pink' concrete may experience temperatures which can be assumed critical for prestressing steel [4]. There is also a recent manufacturing trend in the prestressing steel industry to manufacture strands to a strength nearly 10% higher than the quoted grade (this makes it conceivable that no strength was lost after fire in some analyses). The authors herein explore some considerations with respect to post-fire prestressing steel strength, while a multitude of other factors could easily be considered. This paper refers to tests that were part of the University of Edinburgh research program into prestressed concrete in fire, involving the participation of the principal authors and others (see acknowledgements). Two tests of relevancy for this paper's discussion include a multi-span post-tensioned slab test and a suite of non-destructive hardness tests on various prestressing steels sourced internationally. Among the last deliverables of that research program was a post-fire assessment of the aforementioned concrete slab: non-destructive hardness tests were directly compared to destructive tensile tests of the prestressing steel strand extracted from the fire exposed slab. There is a driver to develop portable non-destructive hardness testing capabilities which would result in a fast approximation of remaining tendon strength after fire. Confidence in the test procedure is the scope and objective of this paper. In addition, the authors discuss various crack and color changes which were observed in the slab. The intent is to instigate further research and discussion in this topic.

Hardness Tests (2011) [6]

Research undertaken by Robertson et al. provides a correlation between hardness and strength of (various) prestressing steels (BS, NZ) after having been submitted to temperatures up to 800C for various soak times (1.5, 4, and 8 hours). The hardness values were obtained by means of Vickers Hardness testing to provide Diamond Pyramid Hardness (DPH). The surface of the prestressing steel was first ground to obtain a small flat area at least 3 mm wide to avoid edge effects which would give false readings. Four readings were taken for each sample and averaged to obtain a final value. A correlation between strength and hardness is expressed in Figure 1a. The best fit correlation is expressed with the below relation:

$$Ultimate\ strength = 4.336\ (Hardness\ value\ in\ DPH) - 309.6$$

Investigation [6] indicated that the hardness provides an estimate of the residual strength with an accuracy of +/-10%. For exposure temperatures of 600C and over, the ability of hardness to be used as an indicator for the yield strength of the prestressing steel is more tenuous due to material properties. However, with regards to ultimate strength, derivation via hardness values maintains its accuracy. Although reference [6] considered prestressing steel from one mill, further research in this test program indicated that the behavior of other prestressing steels from different mills in general was similar. Therefore the same hardness-strength correlation could be used.

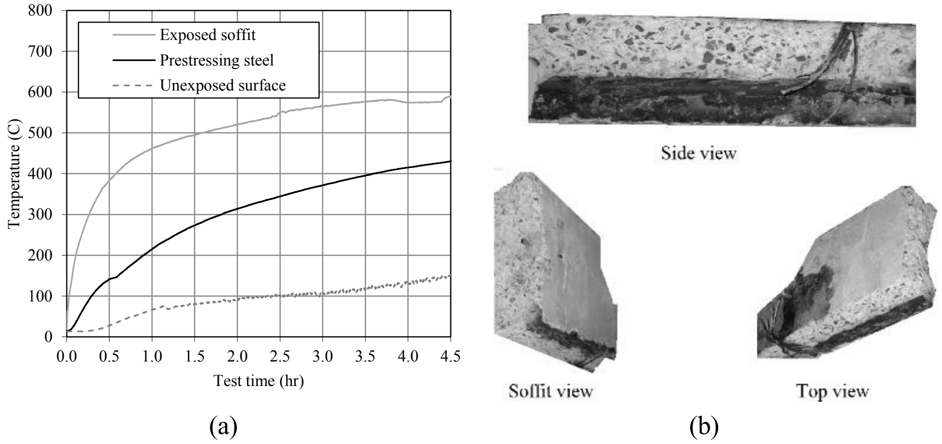


(a) (b)

Figure 1. (a) Variation of Hardness with Ultimate Strength (b) Variation of Hardness with Soak time at 400C

Slab Tests (2013) [2]

Several one-way continuous mono-strand slabs, fixed to four partially rigid connections and loaded with weights to simulate real-life loadings were conducted in 2013. The tests were heated with a non-standard fire exposure and full results and schematics can be found elsewhere. While post-fire studies were conducted for each slab, of importance herein are the results for the last tested slab. The time and temperature isotherms of this test's most severely heated location is provided below.



(a) (b)

Figure 2. (a) Measured temperatures for slab test [4] (b) Excavated slab [4]

The slab was subjected to localized heating under the mid-span until the prestressing steel temperature reached critical at 426C. The slab was then allowed to cool. Of importance for discussion is that this slab was unbonded. That means the tendon was installed in a sheathed and greased configuration. The aforementioned bridge studies relied on a pre-cast bond between the tendon and the slab. The structural consequences of the slab tests are therefore not applicable for comparison with the previous discussion; however the indicators such as concrete color and temperature exposure of the prestressing steel (measured by two thermocouples) are applicable to instill confidence in the hardness test calibration procedure.

Post-fire Investigation

After heating, the slab was cooled naturally. The prestressing steel was de-stressed and a section from the heated area was extracted to analyze its residual properties and the concrete in the heated zone was inspected for color changes. The tendon extracted from the slab was tested for residual strength and hardness: hardness was obtained as previously described and translated to a strength value of 1691 MPa by the above equation. The central strand of the tendon underwent destructive tensile testing and failed at a stress of 1685 MPa (a 16% drop in strength from original stress of 2000 MPa, but only a 9% drop on grade strength). With this negligible difference from the value predicted by the hardness, there appears to be support that hardness testing can be used as an accurate indication of strength post-fire. However, this result should be treated with a moderate caution. Hardness correlations depicted in Figure 1a are based on a soak time of 1.5 hours. If the soak time is extended however, the strength will further decrease due to continual metallurgical changes however this effect can be considered less than 10% for temperatures up to 400C. This relation is illustrated above in Figure 1b. Further research beyond this temperature is encouraged as there may be important consequences in the case of a prolonged and highly severe fire.

When exposed to fires, concrete will spall, crack and change color depending on the temperature reached. The slabs tested exhibited small transverse cracks along the soffit on the side not exposed to heating. On the underside of the slabs, exposed to heating, longitudinal and transverse cracks were respectively located directly below the prestressing steel, at the center and on each side of the heated zone. The concrete color can be used as an additional indicator for post-fire investigation as concrete changes color depending on the temperatures reached. However, this only provides a very general estimation. The afore-mentioned laboratory tested slab, exhibited an area of pink concrete extending only 10 mm into the slab on the side exposed to heat. This typically occurs at temperatures above 300C and the prestressing steel was heated to critical. Figure 2b illustrates a portion of the slab. Of interest is the black concrete. This was caused by the sheathing melting during the test and seeping out of the concrete.

CONCLUSIONS

The hardness technique shows good accuracy for assessing a prestressing steel post-fire for remaining strength. However the hardness test correlations are valid for temperatures below 700C after which microstructural changes will cause recrystallization thereby removing the effects of high strength cold-drawing.

Recrystallization of the prestressing steel should be expected in severe fires where the steel is exposed to fire due to spalling. Color change is of obvious use, however the concrete immediately parallel to the slab experiment considered was not of pink hue despite being at critical temperatures. Assessing the remaining prestress is a very important parameter as this considers the bridges ability to maintain serviceability. In the example shown, the slab was of unbonded configuration. From that perspective one can easily deduce the remaining prestress level non-destructively and correlate well to existing tension relaxation models. In the bonded case, there is a need as implied earlier for a quick and accurate standard measure to assess this remaining prestress. While the paper did not explicitly deal with buildings per say, many of the observations and research needs applicability extend to them as well.

ACKNOWLEDGEMENTS

The authors thank the previous contributions of Zuzana Dudorova, Jane Blackford and Luke Bisby.

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