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Evaluating the early-age behaviour of full-scale prestressed concrete beams using distributed and discrete fibre optic sensors

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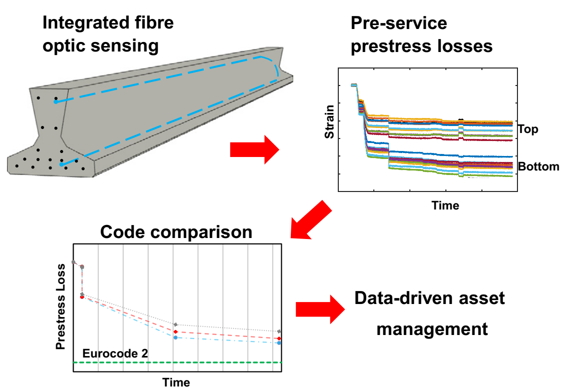
HIGHLIGHTS

- Distributed and discrete fibre optic sensors were installed in prestressed beams.
- Strain data were recorded during beam manufacturing and over the first 6 months.
- Results highlight the effect of beam production on early age prestress losses.
- Measured prestress losses were up to 79% of Eurocode 2 predicted ultimate losses.
- Strain-derived camber at detensioning underestimated theoretical 6 month cambers.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper evaluates the results of a monitoring study that captures the early age behaviour of four 11.9 m prestressed concrete bridge beams utilising both distributed and discrete fibre optic sensor (FOS) arrays. The performance of the beams is evaluated before they are placed in-service as part of new concrete railway bridges in the Midlands in the UK. Two types of prestressed beams were monitored, two TY7 internal beams and two TYE7 edge beams. The beams incorporated high strength (up to 90.7 MPa) self-consolidating concrete. The entire manufacturing process which included early-age curing and the detensioning process was captured in great detail using the installed FOS system. An analysis of the curing strains within the beams revealed the significant effect that ambient temperature, curing duration, and formwork restraint has on the development of prestress losses prior to detensioning. Based on the distributed FOS readings, it was observed that the strain remained uniform along the length of the beams during the various beam monitoring stages. The measured strain data was then used to calculate prestress losses in the first six months after casting (prior to casting of the in-situ concrete bridge deck). The TY7 and TYE7 beams experienced losses that were 79% and 72% of the ultimate losses predicted using Eurocode 2 equations, respectively. Distributed strain measurements were used to provide estimates of the change in beam camber with time. The pre-camber values calculated using the recorded FOS strain data at the time of detensioning closely match the theoretically calculated values. However, camber values increased by up to 1.7 times in the first six months compared with the post-detensioning values and deviated significantly from the theoretically calculated values. The future aim of this research is to establish integrated FOS systems as viable tools for monitoring strain evolution in concrete bridges in

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order to establish comprehensive baselines to facilitate long term data-driven bridge monitoring programmes.

1. Introduction and Background

During recent decades, fibre optic sensors (FOS) have been used increasingly to monitor the changing condition of a variety of infrastructure assets around the world. In many cases, the assets are instrumented because they are critical or landmark structures (i.e., dams, landmark bridge structures, power plants, etc.) or because their existing and/or remaining capacity has been called into question (i.e., old bridges, deteriorating buildings, historically valuable assets, etc.). As a result, the use of FOS technology has primarily been limited to one-off type applications and often times is not installed during the construction phases of a structure. There is however, a greater potential to impact the entire life cycle of an infrastructure asset through the widespread installation of FOS networks in new structural components. These components could be manufactured either on or off-site and would consist of primary load-bearing elements such as piles, footings, columns, slabs or beams. Permanently integrating FOS into one or more of these critical elements before they are placed in service allows the entire load history of these elements to be captured over time. In the case of modular structural components, invaluable information can be gathered to help manufacturers optimise their processes. Therefore, engineers and researchers can assess design assumptions against measurements of real behaviour and asset managers can more confidently address future questions about an assets' existing and/or remaining capacity and its potential for reuse in other structures. In particular, prestressed concrete beams are ideal candidates for being converted into 'self-sensing' structural elements as they are often produced in controlled conditions in which sensor instrumentation could be added to the manufacturing process; and, because their behaviour changes significantly with time, having a means to measure these changes accurately is invaluable.

Research into the time-dependent behaviour of precast prestressed concrete beams has been ongoing for several decades. Prestressed concrete offers many advantages over reinforced concrete in terms of controlling cracking and minimising long-term deflections. In addition, by using high strength self-consolidating concrete (SCC) mixtures, the overall constructability and quality of the finished product can be greatly improved. The use of high strength concrete in bridge beams offers economic advantages over traditional mixes due to increased stiffness and reduced deflections, permitting longer spans and smaller section sizes. However, accurate prediction of the prestress losses in high-strength concrete, in particular at an early age, is required for design. An underestimation of the prestress losses may lead to cracking under service conditions and an associated reduction in section efficiency which can lead to long term durability issues. In contrast, overestimating prestress losses in a beam can lead to excessive camber and unnecessary additional elastic shortening. Therefore, it is important to provide accurate prestress loss predictions to ensure that the remaining prestressing force is adequate to control deflections of prestressed members under permanent load. Guidance in current European (EN 1992-1-1:2004) [1] and American (AASHTO-LRFD) [2] standards pertaining specifically to high strength concrete is limited and has been identified as an area requiring further investigation [3]. Calculating reasonable estimates of early age prestress losses in prestressed beams that use high strength SCC before they are made composite with the concrete bridge deck has also not been studied extensively. There have been several experimental studies that have investigated quantifying early age time-dependent behaviour in prestressed concrete beams. A large study was conducted by Garber et al. [4] on 30 full-scale precast prestressed bridge beams with the aim of measuring prestress losses for up to three years. The beams were 13.9 m long AASHTO Type C I-beams of two different depths, 1016 mm and 1168 mm. Vibrating wire strain gauges were used to validate a flexural service load testing method for estimating long-term prestress losses. Examining the prestress losses that occurred during the first year, it was found that 90% of the 1 year prestress loss took place within the first 4 months and that the prestress losses were highly influenced by the concrete stiffness properties. Porco et al. [5] attached SOFO (*Surveillance d'Ouvrages par Fibres Optiques*) sensors directly to the prestressing strands of eight prestressed concrete beams that formed the superstructure of a simply supported bridge viaduct in Bari, Italy. The prestress in the strands were monitored during several stages of construction including after detensioning of the strands, after casting of the concrete deck slab, and after the permanent dead loads were in place. It was found that the measured prestress losses were 4–24% lower that the losses predicted using Eurocode 2 [1]. Lin et al. [6] conducted laboratory testing of post-tensioned concrete beams with embedded fibre Bragg grating (FBG) fibre optic sensors. The thermal strains due to concrete curing and the mechanical strains induced during the post-tensioning process were measured. In addition, a method for detecting crack locations and depths when the beams were subjected to four-point bending stresses was established. Khayat and Mitchell [7] investigated the structural performance of four full-scale AASHTO Type II precast pretensioned beams constructed using SCC. Using embedded vibrating wire strain gauges, it was identified that the SCC mixtures developed higher autogenous shrinkage in the first 28 days and higher drying shrinkage and creep strains in the first 300 days compared to the control beams. The authors concluded that due to the greater drying shrinkage values, SCC beams may experience higher prestress losses and smaller camber values.

In reviewing a broad range of studies in field monitoring of prestressed concrete beams, to the Authors current knowledge, there have been no studies that have integrated both distributed and discrete fibre optic sensors at the time of manufacture to measure the early age behaviour of prestressed concrete beams. In addition, there appears to be a need to compare field measured values of early-age prestress losses to those predicted based on the Eurocode 2 equations. Depending on the age of the beams when they are placed in service (i.e., installed on the bridge abutments and after the concrete deck is cast), this could have a significant effect on their prestress losses and subsequent in-service behaviour because of the differential creep and shrinkage that occurs within the beams and in-situ concrete deck.

This study investigates the pre-service behaviour (i.e., prior to casting compositely with the concrete bridge deck) of four newly constructed prestressed concrete beams that form part of the superstructure of a new 11.2 m concrete railway bridge near Stafford UK. The construction of this bridge is part of a large rail infrastructure upgrade and redevelopment scheme known as the Stafford Area Improvements Programme [8].

This study is significant as it presents an integrated FOS system for mass-produced prestressed concrete beams. Both discrete fibre Bragg grating based sensors that can measure dynamic strain and distributed fibre optic sensors based on Brillouin Optical Time Domain Reflectometry that measure strain along a prestressing