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Full-scale monitoring system for structural prestress loss based on distributed brillouin sensing technique

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Abstract. Prestress loss is critical to impact the safety of prestressed structures. Unfortunately, up to date, there are no qualified techniques to handle this issue due to the fact that it is too hard for sensors to survive the harsh construction environments and the time-dependent service life of the large-span prestressed structures. This paper proposes a novel technique to monitor prestress loss in prestressed beams using Brillouin optical fiber sensors. A novel smart steel strand based on the sensing technique of full-scale Brillouin optical fiber sensors was introduced. Two kinds of prestressed structure were used to verify the concept of monitoring prestress loss using smart steel strands. The prestress loss data have been taken by Brillouin optical fiber sensors. And the monitoring results agree well with those from the conventional sensors. The monitoring data can reveal both the full-scale distribution and the time history of prestress loss during the construction stage and also in-service phrase.

1. Introduction

For the past decades, prestressed techniques were frequently used in the modern buildings to reduce the deadweight of structures and improve their durability and reliability. Typical application examples can be seen in the construction of bridges and nuclear reactor containments. It is well known that the stress of the strands is of paramount importance to ensure safety of prestressed structures. Due to production technology and material inherent character of prestressed concrete, stress of prestress stand is continually decreased during the construction stage and in-service phrase. However, owing to the influence of material feature, manufacturing process and environmental condition, it is complicated even impossible that the prestress loss is computed well and truly.

The value of prestress loss is therefore expected to be measured and monitored to ensure that the prestress level is sufficient. Accordingly, many approaches have been developed to implement the measuring task in the structures: Ahlborn et al. used acoustic emission to monitor the prestress loss under the vehicular load^[1]. Chen et al. and Di-Scalea et al. used the concept of acoustoelasticity (change in ultrasonic velocity with applied stress), coupled with the elongation effect, for the measurement of stress levels in post-tensioning rods and seven-wire strands^[2-3]. Maji et al. obtained the stress of the strands at random time using the SMA sensors ^[4]. Zhao et al. developed magnetoelastic sensors to monitor the stress in a multi-strand-cable system, then applied sensors on QianJiang No.4 Bridge to monitor the stresses of key hanger cables and post-tensioned cables is presented ^[5]. Kim et al. presented a vibration-based method to simultaneously predict prestress loss and flexural crack in PSC girder ridges ^[6]. Barr et al. monitored the behavior of five prestressed concrete girders made with high-performance concrete using vibrating-wire strain gages over a period of approximately 3 years ^{[7].}

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In recent years, optical fiber (OF) sensors have been increasingly applied to monitor prestress losses due to their distinguishing predominance, such as: corrosion resistance, high accuracy, electro magnetic resistance, distributed and absolute measurement. Watkins employed the Fabry-Perot interferometric (EFPI) sensor to measure internal strain in the main load-carrying layers ^[8]. Inaudi et al. employed the long gauge sensors to evaluate the curvature variations and calculate the horizontal and vertical displacements by double integration of the curvatures ^[9]. Idriss et al. installed long-gage (2m long total) optical fiber deformation sensors into girders of the Rio Puerco and I-10 Bridge over University in Las Cruces in order to evaluate in-situ material properties, prestress loss and cambers in the girders ^[10]. Xuan et al. presented an optical fiber sensor based monitoring technique to evaluate the prestress loss quantitatively in the steel-strand reinforced structures, and fixed 14 fiber-optic sensors on the steel-strand through the pre-designed windows on a sewage treating tank ^[11].

Despite many efforts, all sensors have a similar practical issue in their applications to monitoring of prestress loss since they must be easy to install and sufficiently rugged to sustain long-term harsh environments in field conditions. Zhou et al. integrated optical fiber sensors into fiber-reinforced polymer (FRP) rebar for their improved ruggedness, and then used the smart FRP rebar on cables and steel strands to monitor the long-term stress of steel strands in service, and the results indicated the smart rebar performed good compatibility with steel both in mechanical and sensing properties ^[12]. In this paper, a novel smart steel strand based on the technique of full-scale Brillouin optical fiber was introduced. Then two kinds of prestressed structure used to verify the concept of monitoring prestress loss using smart steel strands. The prestress loss data have been taken by Brillouin sensors and also the data are compared with those from conventional sensors embedded in the structure.

2. Smart steel strand and full-scale monitoring system for prestress loss

2.1. Configuration of the smart steel strand

A smart steel strand is defined in this study as a steel member that has sensing capability for structural condition assessment. It consists of a smart FRP rebar of 5mm in diameter, six common steel wires and copper foil around the FRP rebar (shown as figure 1). As the FRP rebar deforms together with the remaining six steel wires, the deformation of the steel strand can be directly measured by the full-scale Brillouin sensors embedded in the rebar. The distributed stress along the steel strand can be given by the BOTDA sensors.



Figure 1. Sketch of smart steel strands structure

2.2. Full-scale monitoring system for structural prestress loss and sensing principle

Fiber optic sensors have been developed for a number of years and many sensing techniques have been established for structural monitoring because of their features such as immunity to electrical noise, long-term measurement stability and resistance to corrosion. Instead of normal strand, smart steel strand was anchored in prestressed concrete structure. Then the prestress loss of the strand can be monitored by Brillouin optical fiber sensors in the smart steel strand using BOTDA demodulation. The sketch of the full-scale monitoring systeme is shown as Fig.2.

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Figure 2. Sketch of Full-scale monitoring system

3. Experimental setup

3.1. Calibration test for the smart steel strand

In order to test the sensing properties of the smart steel strand, it was fixed on a reaction frame. The length of the specimen is 3m. The load is given by oil pressure jack, and the frequency shift of the optic fiber is monitored by DiTeSt BOTDA provided by OMNI Inc in Switzerland. The test load has been divided by ten grades. The total load was 30kN. The two loading and unloading cycles was repeated. The data of load and frequency shift of the optic fiber sensor were recorded simultaneously. The photo of the calibration experiment are given as Fig.3



Figure 3. Setups of calibration test

3.2. Full-scale prestress monitoring experiment for the concrete beam

In this experiment, the concrete beam is a post-tensioning system with bonded strands, and its span is 4m and the dimension of its cross-section is $200\text{mm}\times400\text{mm}$. The materials are concrete (graded as C40), five smart strands (graded as 1660 MPa) with diameter of 15.24mm (same as the test one), one lined steel bellows with aperture of 60mm and six common steel wires (graded as HRB335) with diameter of 12mm. After the casting of the concrete, it was cured for 28 days under the normal temperature. The experimental process was same as the test one, except that the controlling stress of the test was $\sigma \text{con=}0.75$ fptk, i.e. the max value of the tension load is 180KN. The photos of the experiment setup were as Fig.4.



Figure 4. Photos of experimental setup

4. Experimental results and discussions

4.1. Calibration results for the smart steel strand

The results of the calibration test, as shown in Fig.5, show that smart steel strands can be installed as traditional strands, the full-scale strain distribution of the strand can be obtained, and the linearity and the repeatability of the BOTDA sensors in the smart steel strands were good, the linearly dependent coefficient n=99.954%.



4.2. Full-scale prestress of the concrete beam

All the sensors started to take data as some referenced points during the process of construction and in-service. The referenced points in the process of construction were chosen at the increasing and releasing tension for analyzing the instantaneous losses, and the time interval of collection data was enlarged as the monitoring times in the service. The data in the service were chosen to analyze the time-dependent loss. The distribution of the instantaneous losses along the strand is presented in Fig.6. Then, the instantaneous losses measured by force sensor and the BOTDA sensor in the same location of the smart steel strand and the error ration are listed in Table 1.



Figure 6. Strain distribution along the strand measured by BOTDA sensor

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The BOTDA measurements were made with a minimum spatial resolution of 1m and a measurement interval of 10cm to obtain detailed strain data. In Fig.6, the distribution of strain is conspicuously depicted along the steel strand. It agrees well with the rule of instantaneous prestress loss change. The entire strain distribution of strand is quite even, but the prestress loss at left site is larger than the right.

Load(kN)	Smart strand (MPa)	Force sensor (MPa)	Error ratio (%)
120	62	64	3.2
150	83	82	1.2
180	122	122	0

Table 1. Results of the instantaneous loss for concrete beam with smart strands .

It can be observed from Table 1 that instantaneous loss is increasing with controlling force. And the monitoring results of the smart steel strand and the data of the force sensor were close. The error ratio was less than 3.2%.

According to the data of Brillouin optic fiber sensors in the smart steel strands within 30 days after tension, the contrastive graph of the time-dependent prestress loss with BOTDA sensors can be obtained as Fig.7. In Fig.7, three-dimensional time-dependent prestress loss is depicted. The X axis shows the time after tension, the unit is hours; the Y axis shows the position of sensors in the smart steel strand, the unit is meter; and the Z axis is the time-dependent prestress loss of the strand, the unit is MPa. From Fig.7, it can be seen that values of the prestress loss along the strand is almost same, and the time-dependent loss increases with the increasing time, and losing rate of pre-stress will decrease with the increasing service time.



Figure 7. Time-dependent prestress loss measured by smart steel strand

5. Conclusions

In this paper, based on the sensing technique of the Brillouin optical fiber, a novel smart steel strand was introduced. Two kinds of prestressed structure were used to verify the concept of monitoring of prestress loss using smart steel strands. The prestress loss data have been taken by Brillouin sensors in the smart steel strand. Then the data are compared with those from conventional sensors. Based on the test results obtained from this experimental work, the following conclusions can be drawn:

1. The smart steel strands are easy to install and sufficiently rugged to sustain long-term harsh environments in field conditions.

2. The distributed instantaneous loss of the prestressed concrete beam along the steel strand can be measured by BOTDA sensors in the smart steel strand. The instantaneous loss monitored by BOTDA sensor and the force sensor are close. The error ratio is less than 3.2%. Three-dimensional time-dependent prestress loss along both the position of the strand and duration time is depicted by the monitoring data of the BOTDA sensors. The time-dependent losses of monitored by BOTDA sensors agree well with the evolution rule of the prestress loss. The novel smart steel strand can be suitable for monitoring prestress loss in the prestressed concrete beams during the process of construction and inservice.

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