Optical Fiber Sensors for Monitoring Post-Tensioning Strands: Next-Generation Technology

by Dr. Krista M. Brown

The use of nondestructive methods to monitor, evaluate, and assess the structural health of a bridge is vital to achieve the structure's design service life. Toward that goal, the ability to perform ongoing, long-term monitoring of the tendon forces in post-tensioning (PT) systems is paramount. Fiber-optic technology may offer the means to accomplish that objective. Information about this PT monitoring technology was presented at a 2022 Federal Highway Administration (FHWA) technology exchange,[1] which is featured in the FHWA article on page 51.

Recent research conducted at Purdue University and sponsored by the FHWA included a test program to measure the strain of prestressing strand using two optical fiber cables embedded within the epoxy coating of the strand (**Fig. 1**).[2] The objective of the research project was to evaluate the performance of optical fiber sensors embedded in the epoxy coating along the length of prestressing strands as a long-term method of monitoring tendon forces and identifying changes such as loss of prestress in new PT bridges. The research project consisted of three phases:

- Phase I: Tensile tests on the prestressing strands to determine correction (calibration) factors to be applied to the measured strain data from the optical fiber sensors (that is, determining the effective modulus of elasticity of the optical fibers embedded in the epoxy coating of the strand).
- Phase II: Tests on strands tensioned in a laboratory testing bed to evaluate the accuracy and reliability of the strain readings collected from the optical fiber technology compared with other sensing techniques.
- Phase III: Measuring and evaluating strains of the optical fiber sensor–embedded strands during flexural load tests on two 28-ft-long post-tensioned concrete beam specimens. Experimental results were also compared with analytical models.

The Optical Fiber System

Two 0.9-mm (0.035-in.)-diameter optical fiber cables extend along the full length of the strand and are embedded in the epoxy coating, which has one of two surface finishes: grit impregnated for bonded applications and smooth for unbonded applications. To connect the optical fibers to the Brillouin optical time-domain reflectometry (BOTDR) module that is used to measure the strain within the fibers, the fibers are stripped from the ends of each coated strand and are then fusion-spliced to optical fiber extension cables. A pulsed light wave travels along the length of the fiber and for any section under tension, a shift in the frequency of the backscattered light indicates a change in strain within the fiber. The acquisition of the strain data may take several minutes. A benefit of this optical fiber technology is that the strain data can be collected along the length of the strand and not just at a few discrete points. The BOTDR module used in this research project provided strain values at a spacing of 3.15 in.

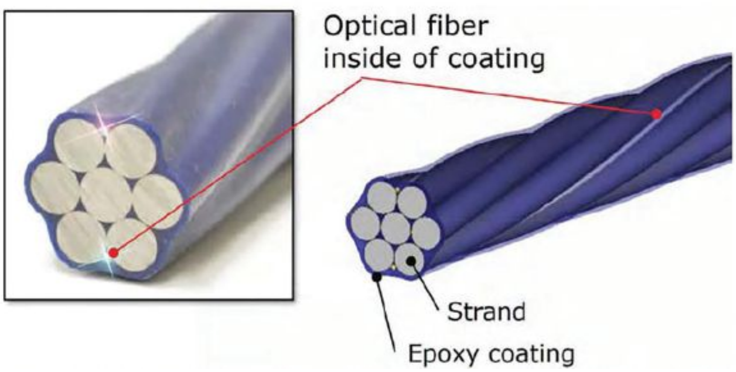
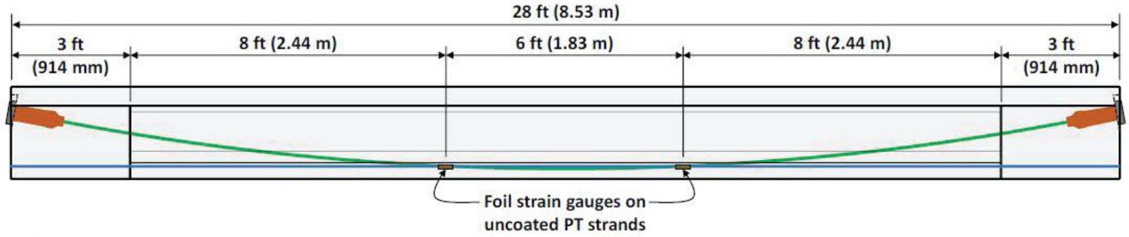


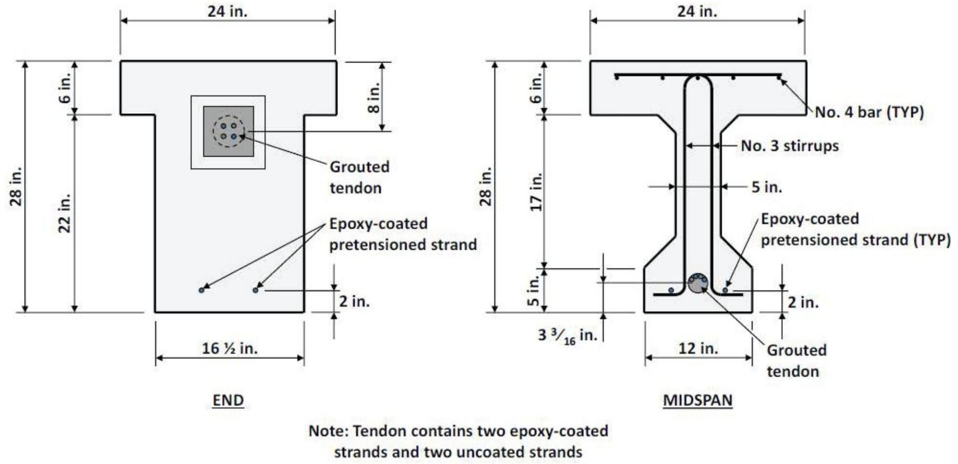
Figure 1. The epoxy-coated, seven-wire, 0.6-in.-diameter prestressing strand with two embedded 0.9-mm (0.035-in.)-diameter optical fiber cables. Figure: Sumiden Wire Products.

Beam Test Specimens

Two 28-ft-long concrete beam specimens—an I-beam and a box beam—were cast in the laboratory (**Fig. 2** and **3**). Both beams had 3-ft-long end blocks, an 8-ksi design concrete compressive strength, no. 3 stirrups, and 0.6-in.-diameter strands. At the time of the research project, the only specialty strands available were manufactured in Japan to meet the applicable Japanese Industrial Standard (JIS G 3536)[3] instead of ASTM A416.[4] (A domestic supplier is in the process of adding capability to produce this strand.) Each specimen contained four epoxy-coated optical fiber sensor–embedded prestressing strands. **Table 1** lists flexural reinforcement details of the beam specimens. Each post-tensioned tendon in the test specimens included at



(a) I-beam elevation



(b) I-beam cross sections

Figure 2. Elevation view and cross sections of the I-beam specimen. The I-beam specimen had a draped, four-strand grouted post-tensioned tendon and two straight pretensioned strands.[2]

least one uncoated strand and one epoxy-coated strand with two optical fibers. This combination represents potential field conditions where only one or two sensor-embedded strands are included in grouted tendons with uncoated strands.

Although the optical fiber technology was being evaluated for in-service bridge conditions, it was also used in this project during the PT operations. For context, the jacking stresses were approximately 210 and 205 ksi for the uncoated and epoxy-coated strands, respectively. (Due to equipment limitations, the pretensioned epoxy-coated strands in the I-beam were jacked to about 180 ksi.) The strands in the tendons were tensioned individually and incrementally. The research team observed the following during the PT process:

- Significant friction losses occurred during the tensioning of strands within the draped tendon of the I-beam specimen. The individual tensioning of each of the four strands likely increased the friction losses of the strands as they interacted inside the duct.
- The friction losses in the straight tendons of the box beam were insignificant.
- A reduction in strain for one strand due to elastic shortening of the beam was noted while another strand in the same beam was being tensioned.
- Based on the reduction in strand strain at anchorage set, the calculated value of anchorage-set distance was approximately ⅜ in., which is not unreasonable for epoxy-coated strand.

Data Collected during Beam Testing

Each 28-ft-long beam specimen was tested in the same manner. The ends were simply supported 1 ft inboard from each end, and identical point loads were applied 3 ft on each side of the beam's midpoint. A load cell measured the applied load at each point, and linear potentiometers were used to measure the displacements of the beam at midspan and at the two load points. Loading was increased in increments, and the BOTDR module measured the strain

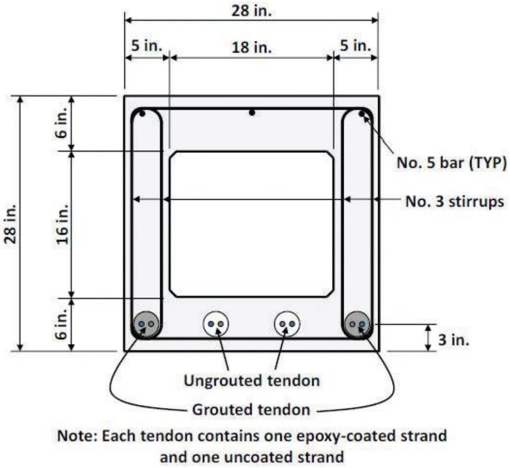


Figure 3. Cross section of the box beam specimen showing the locations of the four (two grouted and two ungrouted) straight, post-tensioned tendons. Each tendon contained two strands. The solid end sections and the two intermediate diaphragm sections are not shown.[2]

Table 1. Flexural reinforcement of beam specimens

Box beam	I-beam
Four straight, post-tensioned tendons—two grouted and two ungrouted—in the bottom flange. Each tendon consisted of one epoxy-coated, optical fiber sensor–embedded strand and one uncoated strand.	Pretensioned with two bottom-flange straight epoxy-coated, optical fiber sensor–embedded strands and one draped, post-tensioned grouted tendon consisting of two optical fiber sensor–embedded strands and two uncoated strands.

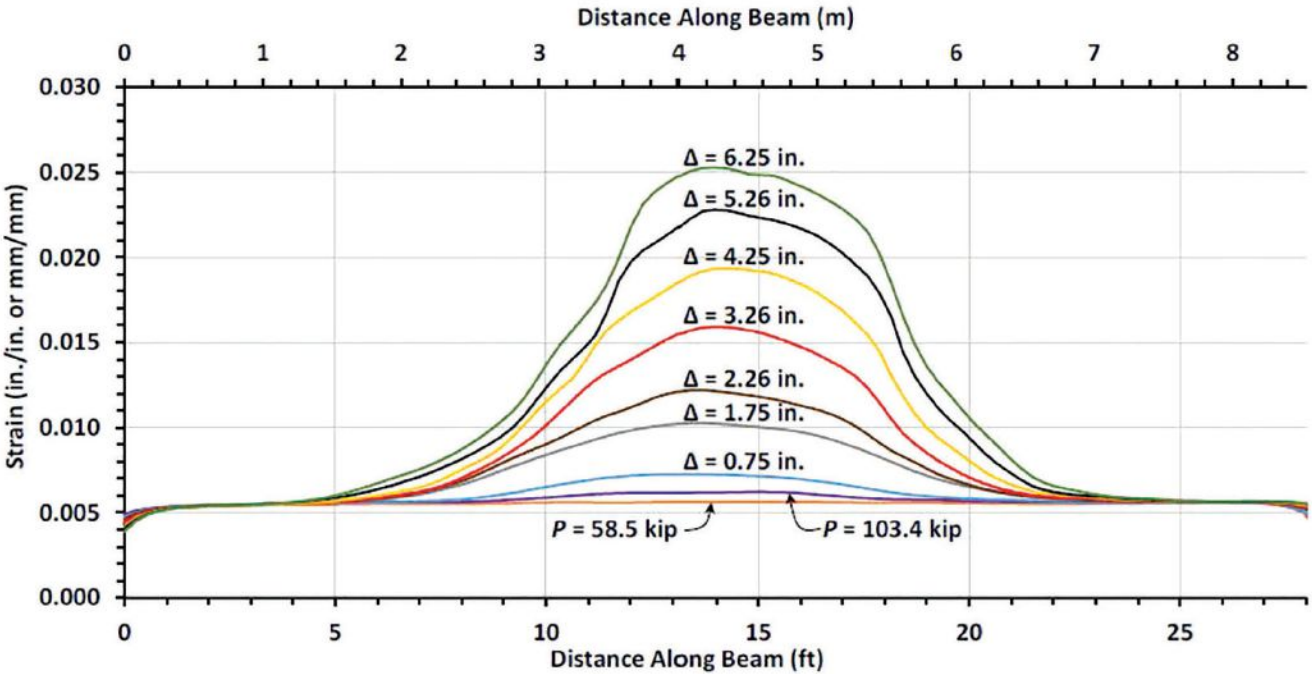


Figure 4. Example of the Brillouin optical time-domain reflectometry strain data collected during the load test of the I-beam specimen. During each step of the load test, the midspan deflection was measured with a linear potentiometer.[2]

in the strands between each load step. **Figure 4** illustrates the BOTDR strain data collected and the accompanying midspan displacements measured during the load test of the I-beam specimen. Only the correction factor for the effective modulus of elasticity for the optical fiber was applied to the raw strain data.

Because the experimental data were robust (each beam specimen in the testing program contained four epoxy-coated, optical fiber sensor–embedded strands, each strand had two optical fibers, and strain data were collected at each load step), the research team was well armed to make comparisons with analytical models. The report[1] provides extensive discussion, not presented here, on the comparison between the experimental and analytical strains, as well as the differences between the behavior of the bonded and unbonded tendons.

Further Investigation

There are two areas that warrant further investigation. Temperature in the lab setting only varied about 10°F during the testing, and any error in strain values introduced by temperature fluctuations was neglected. In the field, the range of temperatures would be much greater. Although the optical fiber technology can measure temperature along with strain, the setup of the equipment can introduce uncertainties, leading to unreliable temperature measurements.

The other area needing further study is nonlinear stress-strain behavior of the strand. In this research program, the strains were mainly within the linear range of the prestressing steel. The accuracy and reliability of data in the nonlinear range of the steel were not within the scope of the study.

Conclusion

The researchers concluded that the use of optical fiber sensor–embedded prestressing strands combined with BOTDR provides, within limitations, a feasible and reliable means for monitoring the strain in post-tensioned tendons in the field. This nondestructive technology would help verify and ensure the long-term durability of post-tensioned systems in concrete bridge structures.

References

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3. Japanese Industrial Standards Committee. 2014. *Steel Wires and Strands for Prestressed Concrete*. JIS G 3536. Tokyo, Japan: Japanese Standards Association.
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EDITOR'S NOTE

According to Jon Cornelius, president of Sumiden Wire Products Corporation (a project partner for the research study), fiber-optic-embedded, epoxy-coated prestressing strand is unlike any other construction material. It is an incredibly durable, highly corrosion-resistant steel prestressing strand with a built-in strain measurement capability over its entire length. Given the critical role that prestressing steel strands play in many construction applications, this marriage of existing fiber-optic strain measurement technology with the well-established benefits of prestressing steel strands gives an owner the ability to know the health of a structure from the initial construction phase through the entire service life.