

Development of a laser-speckle imaging device to determine the transfer length in pretensioned concrete members

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- A rapid, noncontact method for determining transfer lengths in pretensioned concrete members has been developed that generates and digitally records laser-speckle patterns at various points along the prestressed concrete member.
- The technique was verified against results obtained using the traditional method of adhering stainless steel discs and measuring surface strains with a mechanical strain gauge, a time-consuming and tedious process.
- The new method has a higher accuracy, requires minimal setup, and can be implemented on a production-based time frame.

To evaluate the structural performance of prestressed concrete members, it is often necessary to experimentally determine the deformations in the member due to applied forces. One typical example of this is the determination of the transfer length in prestressed concrete members. The transfer length is defined as the distance required to transfer the fully effective prestress force in the prestressing strand to the concrete.¹

Transfer lengths affect structural design considerations in two ways. First, current code provisions for shear design of prestressed concrete members are based on the amount of precompression in the member. Both codes governing prestressed concrete design in the United States (the American Concrete Institute's *Building Code Requirements for Structural Concrete [ACI 318-08]* and *Commentary [ACI 318R-08]*² and the American Association of State Highway and Transportation Officials' [AASHTO's] *LRFD Bridge Design Specifications*³) suggest a transfer length ($50d_b$ for ACI 318-05 and $60d_b$ for AASHTO LRFD specifications, where d_b is the nominal strand diameter) to be used when checking shear capacity in prestressed concrete members. The prestress force in a concrete beam has been shown to vary approximately linearly from zero at the member end to a constant value at a distance from the end of the



Figure 1. A small pretensioned concrete member was used to measure the transfer length.

beam equal to the transfer length.^{1,4-9} Therefore, significant deviations in the transfer length from the code-suggested 50 or 60 diameters could mean inadequate performance of the member in shear. For this reason, the transfer length is often empirically determined when new mixtures or strands are employed.

The transfer length can also have a significant effect on the flexural behavior of prestressed concrete members. Prestressed concrete girders can fail suddenly when flexural cracking propagates through the transfer zone of the strand.¹ Beams with debonded strand are especially susceptible to this phenomenon.¹⁰ Therefore, an accurate prediction of the transfer length is an important parameter used to determine whether flexural cracks will likely propagate into this zone before the member reaches its design capacity.

Transfer lengths are determined by measuring concrete surface strains at the ends of actual members or prismatic test specimens. Metal discs called gauge points are typically secured to the surface of the specimens at 2 in. (50 mm) spacing before releasing the tension in the strands. These points are typically mounted using epoxy or are directly embedded into the concrete. They are located at the structural depth of the prestressing steel (**Fig. 1**).

Distances are measured between the gauge points using a mechanical gauge with a typical resolution of about 20 μe . Surface strain readings are usually taken before tension release, immediately after release, and then periodically during the first few months after tension release.

The determination of transfer lengths in pretensioned concrete members has been done using the current procedure for more than 40 years. This method is time consuming and is subject to considerable human judgment and possible errors because the mechanical readings are taken and manually recorded. In addition, the labor-intensive process of installing the gauge points and taking repetitive

readings often prohibits taking these measurements before the concrete reaches an age of one or more days, thereby not representing typical release times as early as 14 hours to 18 hours. Thus, the implied transfer lengths obtained using the typical method often do not represent properties of the concrete at the actual tension release times for many prestressed members (when concrete is less mature and therefore weaker).

While the conventional measurement technique does not allow transfer lengths to be determined on a production basis, a rapid, noncontact method to accomplish this has been developed. The technology is called laser-speckle imaging (LSI). The objective of this study was to develop a rapid, noncontact test method for determining transfer lengths in pretensioned concrete members using LSI and to validate the method by obtaining concrete surface strains throughout the transfer length for several pretensioned concrete members.

Laser-speckle imaging methodology

A controlled calibration setup using a laboratory interferometer was employed to determine the accuracy of the current surface-strain measurement system (**Fig. 2**). Using the interferometer as the standard for displacement measurement, repeated measurements were taken by an experienced Whittemore strain gauge user, and it was determined that the accuracy of the experienced user was about ± 0.0002 in. (± 0.005 mm). This corresponds to a strain of ± 25 μe over the standard 8 in. (200 mm) gauge length. Thus, it was necessary for the optical system to have an accuracy of ± 25 μe .

Optical speckle techniques have evolved into powerful tools for the measurement of surface strain since digital image recording and processing have become widely available. They have the advantage of minimal surface preparation, work with almost all kinds of rough surfaces, and have high resolution.¹¹⁻¹³

Speckle is generated by illuminating a rough surface with coherent light (**Fig. 3**). The random reflected waves interfere with each other, resulting in a grainy image (**Fig. 4**, lower right). The speckle pattern could be thought of as a fingerprint of the illuminated area in the sense that the speckle pattern produced by every surface area is unique. Furthermore, when the surface undergoes movement or deformation, the speckle pattern in the image plane will also move or deform accordingly. Thus the displacement or deformation information of the object surface can be extracted by measuring the speckle pattern movement.

At the present time, no speckle strain technique had been applied to prestressed concrete surface measurement, except possibly in a very controlled laboratory setting. This

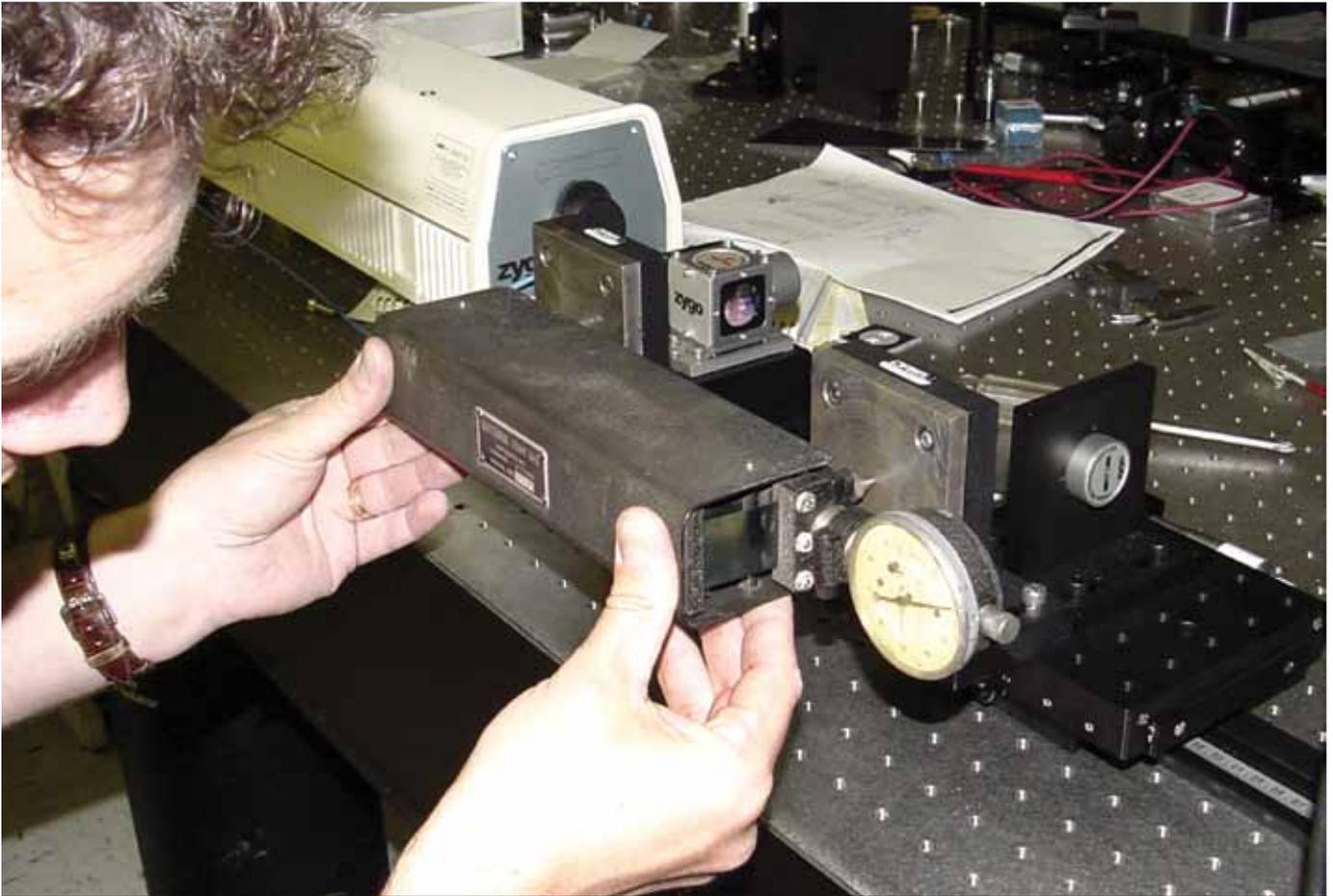


Figure 2. Determining the accuracy of a standard mechanical strain gauge (Whittemore type).

is because prestressed concrete surface strain measurement has some characteristics that make it difficult for a regular optical sensor to be used:

- The tension release process during the production of the prestressed concrete members involves the sudden release of large forces into the member. These forces produce intense vibrations that disrupt the relative position of the sensor and the concrete surface. To protect the optical sensor from damage, the sensor must be removed from the concrete surface after the initial reading and before the tension release process. This prevents some optical strain sensors, designed to be attached to the specimen surface throughout the measurement process, from being used.¹⁴
- The prestressed concrete surface strain is in the range of several hundred $\mu\epsilon$, which requires the strain sensor to have a large dynamic range.
- The concrete surface undergoes out-of-plane tilt (yaw and pitch) and roll (rotation to the axis perpendicular to the surface) as well as in-plane displacement components. Among them, only in-plane displacement components are useful in extracting the transfer length information, but the presence of the other axis movements generates additional speckle shifting and thus

disrupts the in-plane displacement measurement.

Therefore, an optical strain sensor for the prestressed concrete surface strain measurement must be removable from the specimen, have large dynamic range, and be insensitive to surface tilt.

An optical strain sensor based on a five-axis freedom

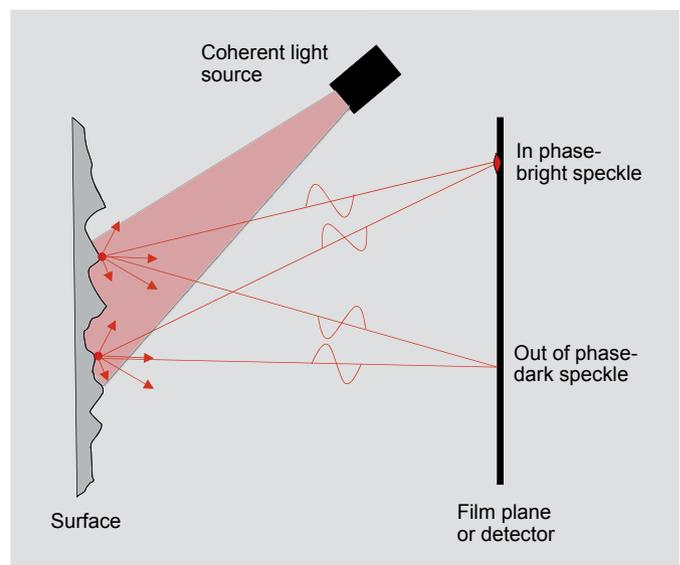


Figure 3. Concept of laser speckle.

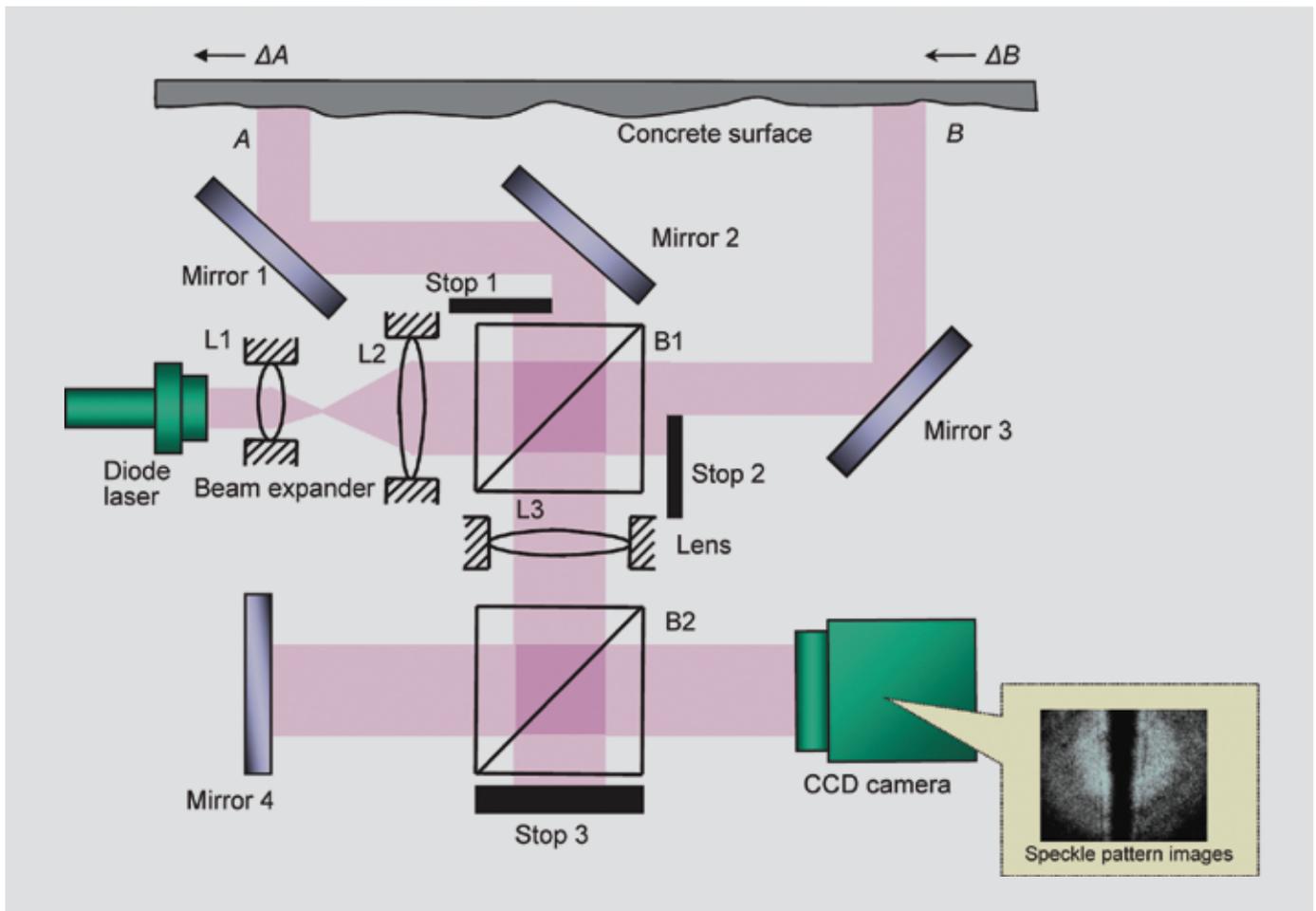


Figure 4. Basic sensor operation principle. Note: CCD = charge-coupled device.

movement measurement technique^{15,16} was developed. The optical system of the sensor is configured to have large dynamic range and is able to measure the surface displacement accurately without being affected by other axis movements.

Figure 4 shows a diagram of the sensor. A laser is collimated by lenses L1 and L2 and then directed to the specimen surface at point A and point B, respectively, by a polarization beam-splitter B1. The reflected waves from the diffusive surface are directed through polarization beam splitter B1 and lens L3. Right behind the lens is a nonpolarizing beam splitter B2 that sends the laser beam to mirror M4. The light beams then go back through beam splitter B2 and are finally captured by a charge-coupled device (CCD) camera.

Because there are two laser beams (which produce images that are reflected from point A and point B on the object surface), the camera actually captures two speckle patterns. The analysis of the speckle images would be difficult if the two speckle patterns overlapped each other. To prevent this from happening, half of each laser beam is blocked with stop 1 and stop 2, such that only half of the areas around point A and point B are illuminated. This results in two side-by-side speckle patterns generated by point A and point B on the digitized images captured by the CCD

camera (Fig. 4).

During the measurement, the optical strain sensor is mounted onto the concrete surface before tension release. The camera captures a speckle image with two side-by-side speckle patterns in it (Fig. 4). These two patterns are denoted A1 and B1. After tension release, the optical sensor is mounted back onto the surface. The camera captures another image with two speckle patterns, which are denoted A2 and B2. By comparing the pair of speckle patterns A1 and A2 and using well-known cross-correlation methods, the displacement ΔA of one pattern relative to the other can be extracted. The displacement ΔB can be extracted from pattern B1 and pattern B2 in a similar way. The surface strain S between point A and point B thus can be calculated by

$$S = \frac{\Delta B - \Delta A}{L}$$

where

L = the gauge length

= 8 in. (200 mm) for the current setup

Laboratory verifications of LSI technique

To test the accuracy and sensitivity of the LSI methodology and the feasibility of using this method to determine concrete surface strains, a laboratory setup was fabricated and used to conduct direct comparisons with conventional strain measurement methods. **Figure 5** shows the test setup used. A concrete prism was compressed in a universal testing machine and the concrete surface strains were recorded using both the LSI technique and with surface-mounted electrical resistance strain gauges (ERSGs). This prism, which had ERSGs mounted on all four vertical faces, was successfully used to assist the researchers in isolating the longitudinal (axial) strain component from other distortions that are inherently present due to varying degrees of bending. Excellent correlation between the two methods was achieved in the laboratory.

The next stage in the validation procedure was to compare surface strain results between the LSI technique and Whittemore strain gauge readings when a large strain change occurred in a short time (that is, the tension release of a prestressing strand).

To accomplish this, several pretensioned concrete members were fabricated using different concrete mixtures. The mixture proportions used in this study corresponded to self-consolidating concrete mixtures that were part of a larger PCI study.⁶ The members had a trapezoidal cross section (**Fig. 6**) that was used as part of the development of a simple quality assurance test reported previously.¹⁷

The pretensioned concrete members were each 9 ft 6 in. (2.9 m) long. The transfer lengths were measured on one side of each member using both the traditional Whittemore strain gauge and the noncontact LSI method. To facilitate the laser-speckle measurements, an aluminum rail was mounted to the side of the member (**Fig. 7** and **8**). The rail was attached to the members using small 1/4-in.-diameter (6 mm) inserts that were cast into the sides of the pretensioned concrete members.

Results

Surface strain measurements for the trapezoidal specimens were obtained using both the standard (Whittemore) strain-gauge technique and LSI (optical) technique. **Figure 9** shows that the LSI technique results in a smoother data line with less scatter than that generated using the existing surface strain measurement technique with the Whittemore strain gauge. The LSI technique has been validated on members cast in both indoor and outdoor operations. Thermal effects, due to temperature differences between the measuring instrument and measured object, are similar to those exhibited by the traditional Whittemore strain gauge method, as the coupling of the gauge points in the optical



Figure 5. Comparison of laser-speckle imaging method with electrical resistance strain gauges on concrete prism in a universal testing machine.

fixture was accomplished using a steel mounting plate.

Because the LSI technique relies on the optical pattern recognition of images before and after movement, changes or weathering to the concrete surface could limit the ability of this technique to measure long-term effects. However,

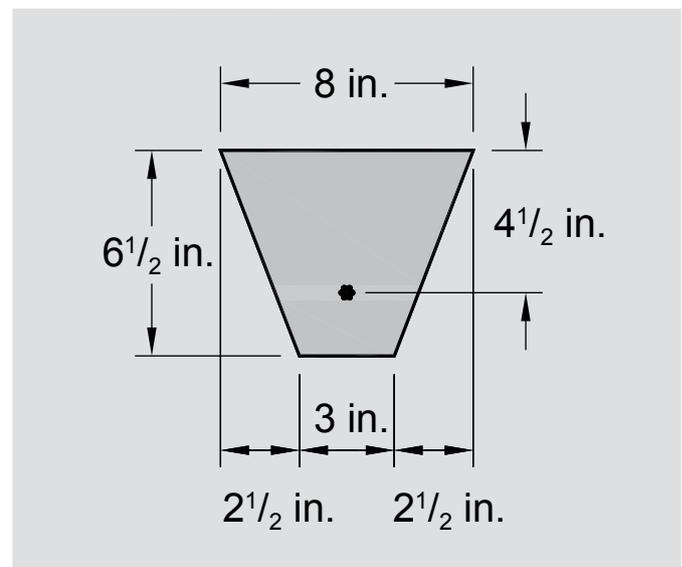


Figure 6. Trapezoidal cross section of the pretensioned members used to verify the laser-speckle transfer length measurement technique. Note: 1 in. = 25.4 mm.



Figure 7. The measurement of surface strains was accomplished using both the traditional surface-mounted method and the noncontact laser-speckle imaging method.

the LSI method works well during the first month after tension release. The peak strains varied along the length of the member, producing an asymmetric shape. This was due to a slight horizontal eccentricity of the strand in the small trapezoidal cross section, which produced biaxial bending in the member.

Conclusion

The LSI technique is a viable method to measure transfer lengths in pretensioned concrete members. The LSI technique, using the current optical arrangement, is more accurate than the existing Whittemore strain gauge technique because it eliminates human bias and improves repeatability of measurement. Furthermore, the technique does not require extensive operator training to achieve reliable measurements, as does the Whittemore strain gauge technique. The accuracy of the LSI technique has been shown to be less than $10 \mu\epsilon$, compared with a $25 \mu\epsilon$ accuracy for the Whittemore strain gauge technique. Much of the error associated with the use of the Whittemore strain gauge technique is due to poor repeatability, resulting in a large random error contribution. Thus, without operator training, it is difficult to get reliable transfer length measurements with the traditional Whittemore strain gauge technique.

The LSI method offers a significant improvement in the reliability of estimating the transfer length.

The researchers are working to automate the process of traversing along a concrete member and capturing the corresponding LSIs in increments of $\frac{1}{4}$ in. (6 mm). This will enable a near-real-time determination of transfer lengths through computerized postprocessing of the digital images in the field. It is envisioned that LSI will become an effective quality-control technique to screen out deleterious combinations of strand and concrete mixtures and to determine the effect of changes in these parameters on strand bond.

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Figure 8. Similar outdoor measurements were made to investigate the thermal characteristics of the device.

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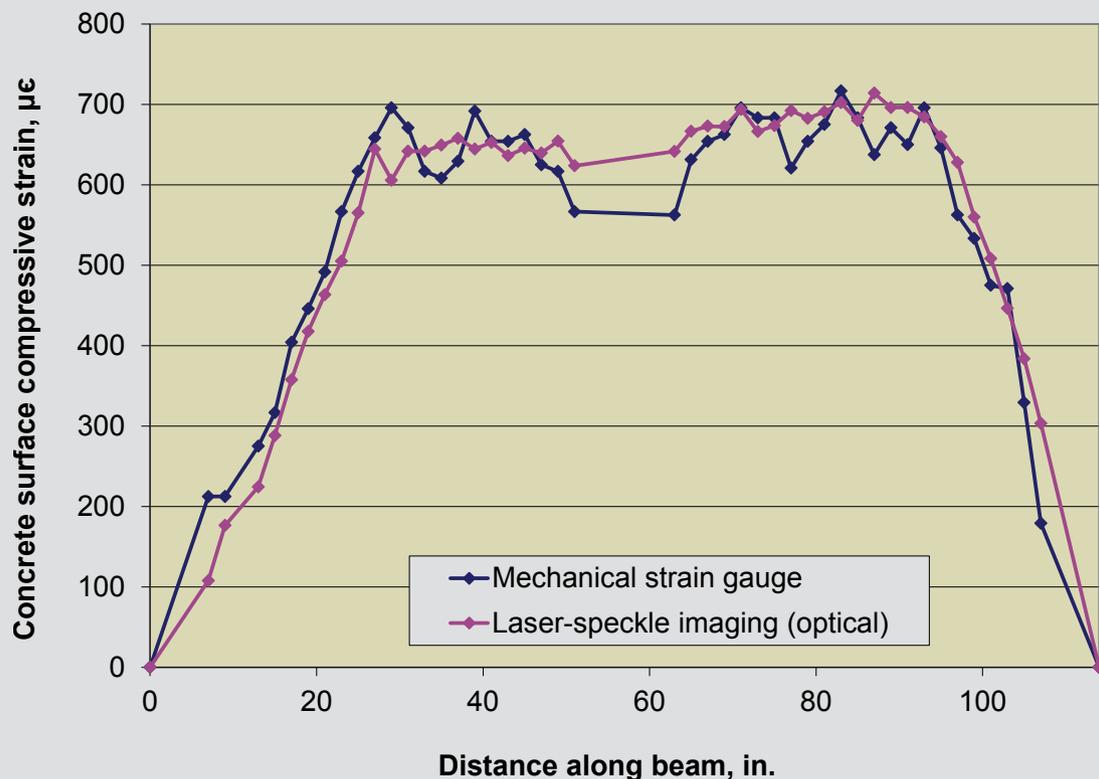


Figure 9. Comparison of raw (unsmoothed) strain measurements immediately after detensioning of a pretensioned specimen.

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Notation

d_b = strand diameters

L = gauge length

S = strain

ΔA = displacement at point A

ΔB = displacement at point B

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Abstract

The current experimental method to determine the transfer length in prestressed concrete members consists of measuring concrete surface strains with a mechanical strain gauge before and after releasing tension. Because this is a time-consuming and tedious process, transfer lengths are seldom measured on a production basis. Furthermore, when transfer lengths are determined using the current method, the times to release tension of the members being measured are often delayed, thereby resulting in artificially higher release strengths for the members evaluated.

A rapid, noncontact method for determining transfer lengths in pretensioned concrete members has been developed. The new method uses laser-speckle patterns that are generated and digitally recorded at various points along the prestressed concrete member. The technique was verified against results obtained using the traditional method of adhering stainless steel discs and measuring surface strains with a mechanical strain gauge. The new method has a higher accuracy, requires minimal setup, and can be implemented on a production-based time frame.

Keywords

Laser-speckle imaging, strand bond, transfer length.

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