Report No. K-TRAN: KSU-09-3
FINAL REPORT

# DEVELOPMENT OF A LASER-SPECKLE IMAGING DEVICE TO DETERMINE THE TRANSFER LENGTH IN PRE-TENSIONED CONCRETE MEMBERS WITH SCC AND CONVENTIONAL CONCRETE

Kyle Larson, Ph.D.
Weixin Zhao
Robert Peterman, Ph.D., P.E.
Terry Beck, Ph.D
John Wu

Kansas State University Transportation Center
Manhattan, Kansas

July 2010

A COOPERATIVE TRANSPORTATION RESEARCH PROGRAM BETWEEN:

KANSAS DEPARTMENT OF TRANSPORTATION
KANSAS STATE UNIVERSITY TRANSPORTATION CENTER
UNIVERSITY OF KANSAS

KANSAS DEPARTMENT OF TRANSPORTATION

1 **Report No.**
K-TRAN: KSU-09-3

2 **Government Accession No.**

3 **Recipient Catalog No.**

4 **Title and Subtitle**
Development of a Laser-Speckle Imaging Device to Determine the Transfer Length in Pre-Tensioned Concrete Members with SCC and Conventional Concrete

5 **Report Date**
July 2010

6 **Performing Organization Code**
**KSUTC-09-2**

7 **Author(s)**
Kyle Larson, Ph.D., Weixin Zhao, Robert Peterman, Ph.D., P.E., Terry Beck, Ph.D., John Wu

8 **Performing Organization Report No.**

9 **Performing Organization Name and Address**
Department of Civil Engineering
Kansas State University Transportation Center
2118 Fiedler Hall
Manhattan, Kansas 66506

10 **Work Unit No. (TRAIS)**

11 **Contract or Grant No.**
C1821

12 **Sponsoring Agency Name and Address**
Kansas Department of Transportation
Bureau of Materials and Research
700 SW Harrison Street
Topeka, Kansas 66603-3745

13 **Type of Report and Period Covered**
Final Report
May 2009 - April 2010

14 **Sponsoring Agency Code**
RE-0488-01

15 **Supplementary Notes**
For more information write to address in block 9.

16 **Abstract**

The current experimental method to determine the transfer length in prestressed concrete members consists of measuring concrete surface strains before and after de-tensioning with a mechanical strain gage. Since 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 de-tensioning times of the members being measured are often delayed, thereby resulting in artificially higher release strengths for the members evaluated.

A rapid, non-contact method for determining transfer lengths in pre-tensioned concrete members has been developed at Kansas State University. The new method utilizes 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 stains with a mechanical strain gage (Demec or Whittemore type). The new method has a higher accuracy, requires minimal setup, and can be implemented on a production-based time frame.

17 **Key Words**
Pre-tensioned concrete, strain gages, prestressed concrete, self-consolidating concrete, Imaging

18 **Distribution Statement**
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19 **Security Classification (of this report)**
Unclassified

20 **Security Classification (of this page)**
Unclassified

21 **No. of pages**
29

22 **Price**

Form DOT F 1700.7 (8-72)

# DEVELOPMENT OF A LASER-SPECKLE IMAGING DEVICE TO DETERMINE THE TRANSFER LENGTH IN PRE-TENSIONED CONCRETE MEMBERS WITH SCC AND CONVENTIONAL CONCRETE

**Final Report**

Prepared by

Kyle Larson, Ph.D.
Weixin Zhao
Robert Peterman, Ph.D., P.E.
Terry Beck, Ph.D
John Wu

Kansas State University Transportation Center
Manhattan, Kansas 66506

A Report on Research Sponsored By

THE KANSAS DEPARTMENT OF TRANSPORTATION
TOPEKA, KANSAS

July 2010

© Copyright 2010, **Kansas Department of Transportation**

## PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

## NOTICE

The authors and the state of Kansas do not endorse products or manufacturers. Trade and manufacturers' names appear herein solely because they are considered essential to the object of this report.

This information is available in alternative accessible formats. To obtain an alternative format, contact the Office of Transportation Information, Kansas Department of Transportation, 700 SW Harrison, Topeka, Kansas 66603-3745 or phone (785) 296-3585 (Voice) (TDD).

## DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the views or the policies of the state of Kansas. This report does not constitute a standard, specification or regulation.

# ABSTRACT

The current experimental method to determine the transfer length in prestressed concrete members consists of measuring concrete surface strains before and after de-tensioning with a mechanical strain gage. Since 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 de-tensioning times of the members being measured are often delayed, thereby resulting in artificially higher release strengths for the members evaluated.

A rapid, non-contact method for determining transfer lengths in pre-tensioned concrete members has been developed at Kansas State University. The new method utilizes 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 stains with a mechanical strain gage (Demec or Whittemore type). The new method has a higher accuracy, requires minimal setup, and can be implemented on a production-based time frame.

# ACKNOWLEDGEMENTS

This project was funded through the Kansas Department of Transportation (KDOT) and the Prestressed Concrete Institute (PCI) through a Daniel P. Jenny Fellowship. Specifically, the authors would like to thank Brian Miller and Paul Johal (PCI) and David Meggers (KDOT) for helping to make this a successful project.

The author would also like to thank Ed Volkmer, former graduate student at Kansas State University, who assisted with the fabrication of the prestressed members and the initial data collection and reduction.

# TABLE OF CONTENTS

# LIST OF FIGURES

# CHAPTER 1 - INTRODUCTION

In order 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 reinforcing-strand to the concrete. (Russell and Burns, January 1993)

Transfer lengths affect structural design considerations in two ways. First, current code provisions for shear design of prestressed members are based on the amount of pre-compression in the member. Both codes governing prestressed concrete design in the United States (the ACI (ACI Committee 318, 2008) and AASHTO Codes (AASHTO, LRFD Bridge Design Specifications)) suggest a transfer length (50 $d_b$ for ACI; 60 $d_b$ for AASHTO) to be used when checking shear provisions in prestressed concrete members. It has been previously shown that the prestress force in a concrete beam varies approximately linearly from zero at the member end to a constant value at a distance from the end of the beam equal to the transfer length. (Russell and Burns, January 1993) (Larson, Peterman and Esmaeily, 2007) 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 experimental determination of the transfer length is often performed when new mixes or strands are employed.

The transfer length can also have a significant impact on the flexural behavior of prestressed members. Sudden failures in prestressed concrete girders can occur when flexural cracking propagates through the transfer zone of the strand. (Russell and Burns, January 1993) Beams with de-bonded strand are especially susceptible to this phenomenon. (Kaar and Magura, 1965) Therefore, an accurate prediction of the transfer length is an important parameter used to determine whether flexural cracks will likely propagate into this zone prior to the member reaching its design capacity.

Transfer lengths are experimentally determined by measuring concrete surface strains at the ends of actual members or prismatic test specimens. Metal discs called “gage points” are typically secured to the surface of the specimens at 50 mm (2 inches) spacing prior to de-tensioning the strands. These points are typically mounted using an epoxy or directly embedded into the concrete and are located at the structural depth of the prestressing steel (see Figure 1.1).

**Figure 1.1: Small Pre-tensioned concrete member used to measure the transfer length.**

Distances are measured between the gage points using a mechanical gage having a typical resolution of about 20$\mu\varepsilon$. Surface strain readings are usually taken prior to de-tensioning, immediately after de-tensioning, and then often periodically during the first few months after de-tensioning. Figure 1.2 shows a plot of surface strains obtained in this manner.

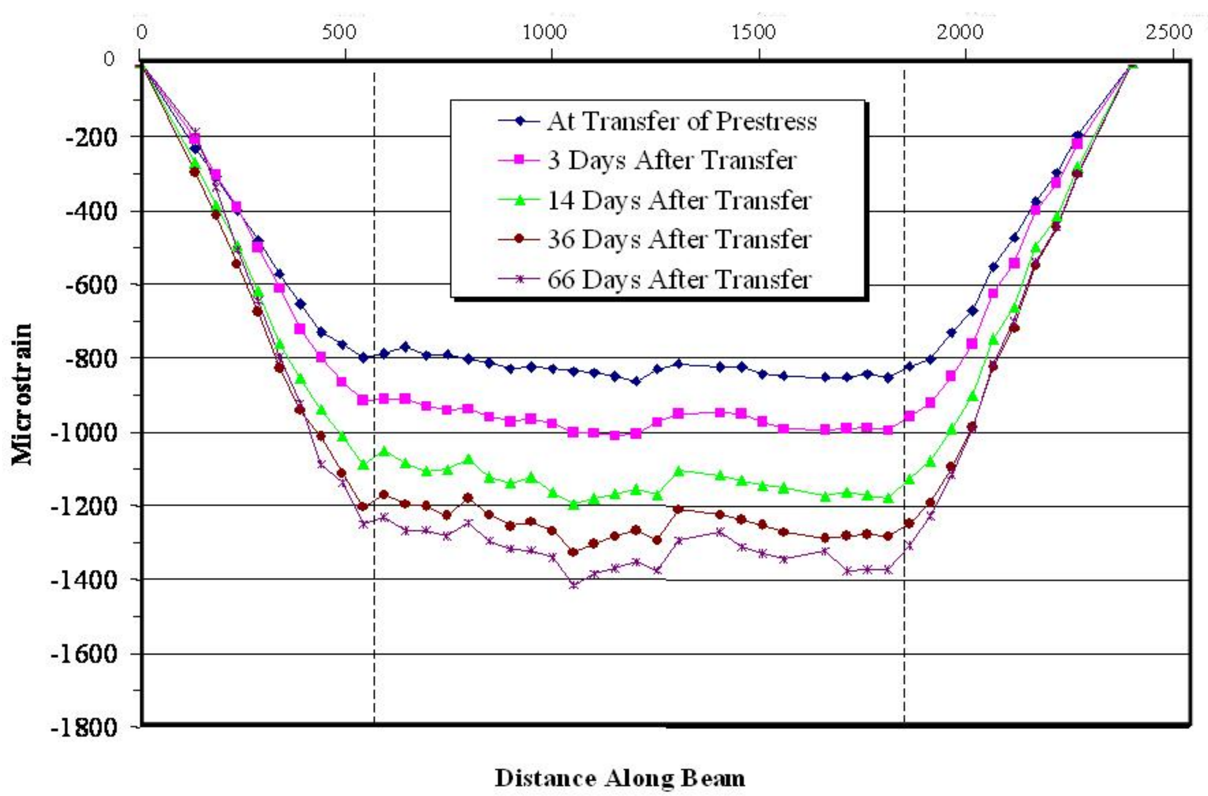


**Figure 1.2: Measured surface strains along pre-tensioned concrete prism.**

The determination of transfer lengths in pre-tensioned concrete members has been done using the current procedure for more than 40 years. This method is extremely time-consuming, and is subject to considerable human judgment and possible errors as the mechanical readings are taken and manually recorded. In addition, the labor-intensive process of installing the gage points and taking repetitive readings often prohibits these measurements from being made prior to the concrete achieving an age of one or more days; thereby not representing typical release times as early as 14-18 hours. Thus, the implied transfer lengths obtained using the typical method often do not represent the actual de-tensioning 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, non-contact method to accomplish this has been developed at Kansas State University (KSU). The technology being utilized at KSU is called Laser-Speckle Imaging (LSI). The objective of this study, therefore, was to develop a rapid, non-contact test method for the determination of transfer lengths in pre-tensioned concrete members using LSI, and to validate the method by obtaining concrete surface strains throughout the transfer-length for several pre-tensioned concrete members.

## 1.1 Laser Speckle Imaging Methodology

In order to determine the accuracy of the current surface-strain measurement system, a controlled calibration setup utilizing a laboratory interferometer was employed (Figure 1.3). Using standard metrology procedures, it was determined that the accuracy of an experienced user was about ± 0.0002 inches. This corresponds to strain level of ±25 micro-strain when measuring over the standard 8-inch gage length. Thus, at the outset of this experimental program, it was deemed necessary that the optical system must have an accuracy of less than or equal to ±25 micro-strain.

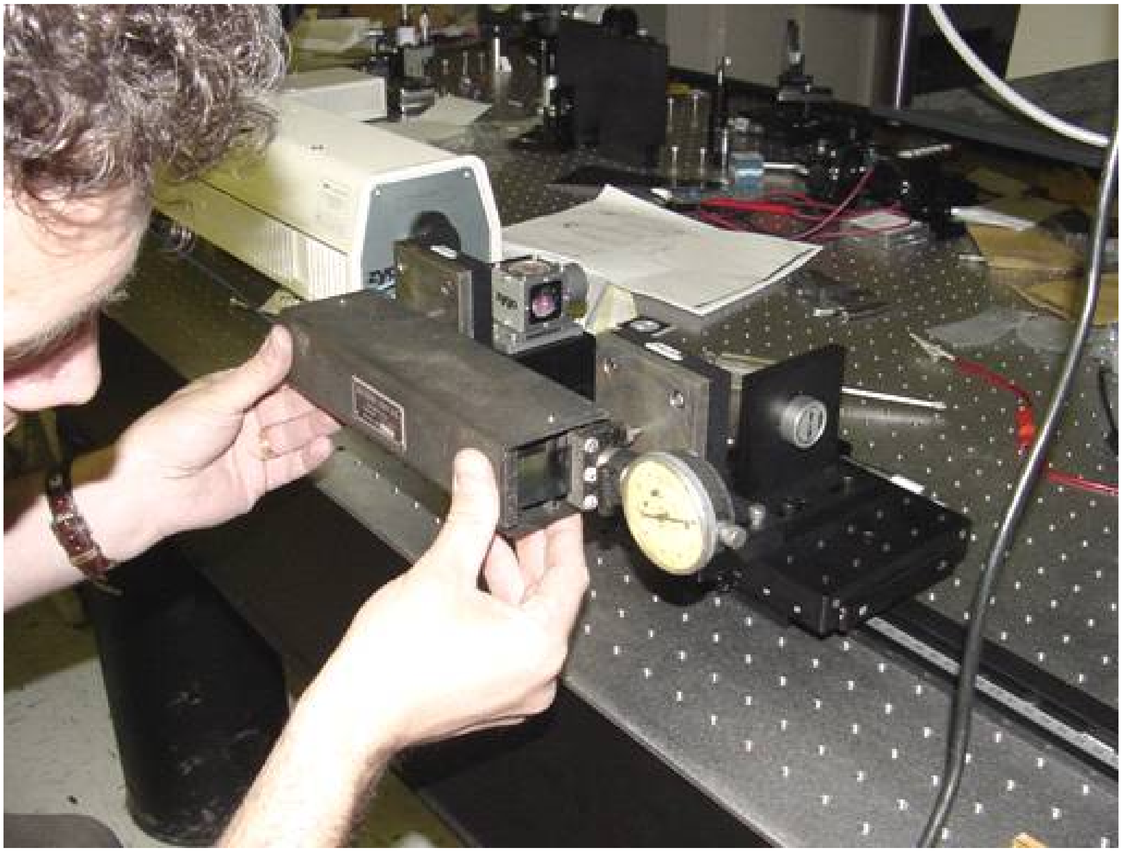

**Figure 1.3: Determining the accuracy of a standard mechanical gage (Whittemore type).**

Optical Speckle techniques have evolved into powerful tools for the measurement of surface strain since digital image recording and processing have become widely available. It has the advantage that minimal surface preparation is needed and works with almost all kinds of rough surfaces, along with high resolution. (Yamaguchi, 1981) (Johnson, 1998) (Sjödahl, 1999)

Speckle is generated by illuminating a rough surface with coherent light as shown in Figure 1.4. The random reflected waves interfere with each other, resulting in a grainy image, as shown Figure 1.5. 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 area 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.

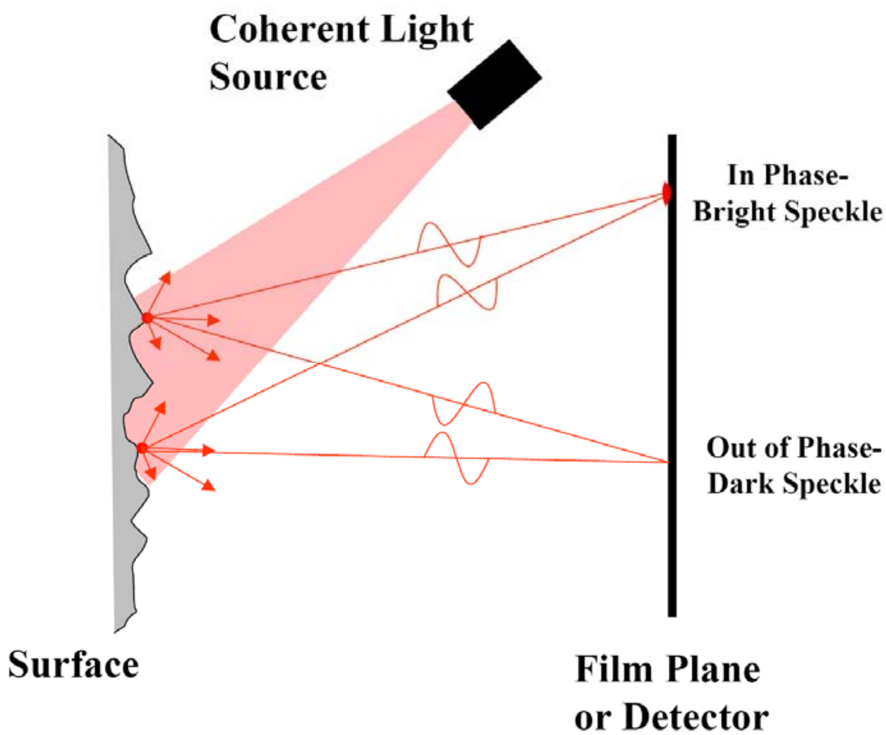


**Figure 1.4: Concept of Laser Speckle.**

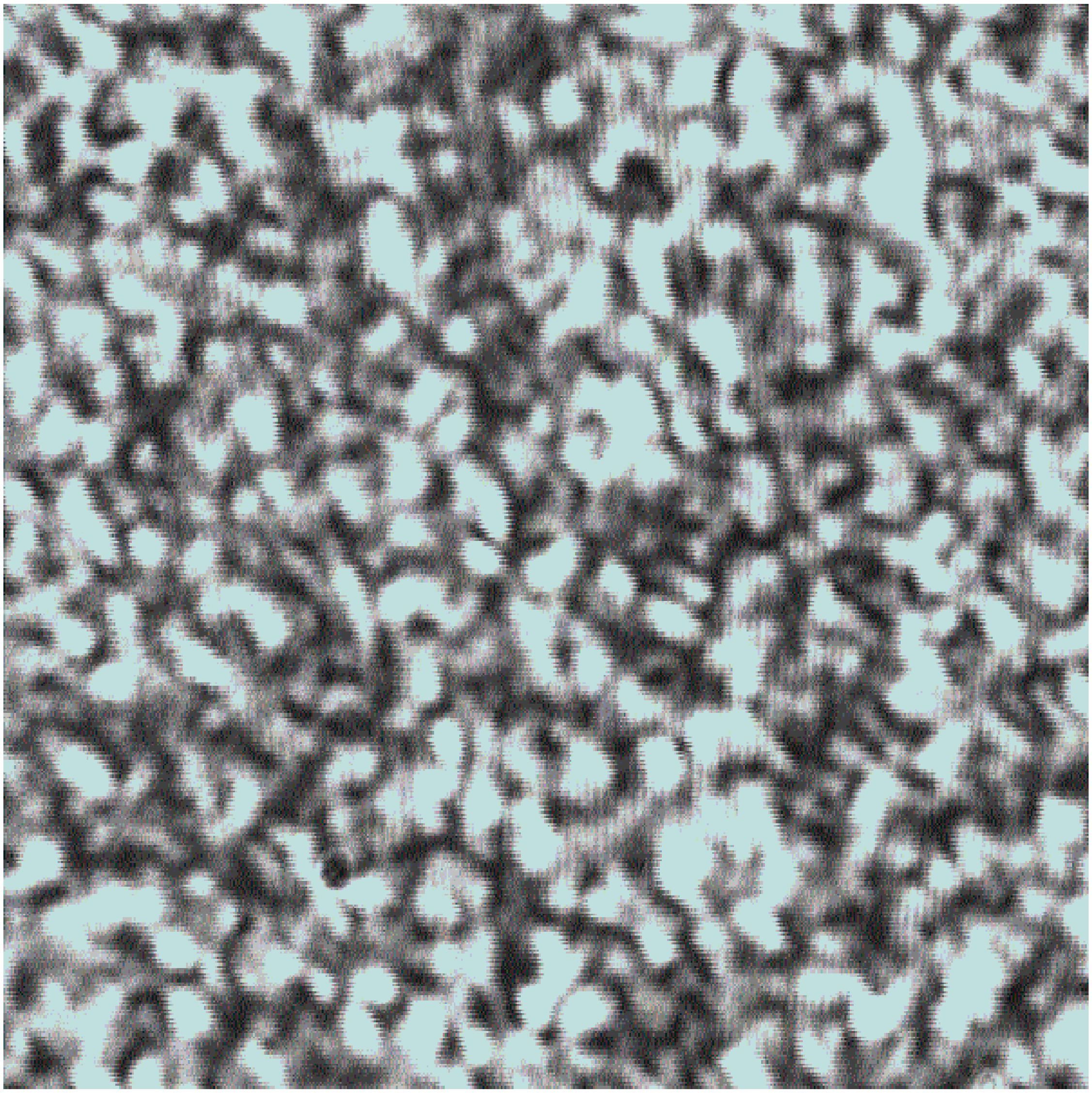

**Figure 1.5: Photo showing speckle pattern generated by concrete surface.**

At the present time, no speckle strain technique has been applied to the prestress concrete surface measurement. This is because prestress concrete surface strain measurement has some characteristics that make it difficult for a regular optical sensor to be used. Firstly, the de-tensioning process during the production of the prestressed members involves the sudden release of large forces into the member. These forces produce intense vibrations which will disrupt the relative position of the sensor and the concrete surface.

To protect the optical sensor from damage it is thus required to remove the sensor, after the initial reading, from the concrete surface prior to the de-tensioning process. This prevents some optical strain sensors, designed to be attached to the specimen surface throughout the measurement process, from being applied to the job. (Wegner and Ettermeyer, 1999) Secondly, the prestress concrete surface strain is in the range of several hundred micro-strain (με), which requires the strain sensor to have a large dynamic range.

Thirdly, the concrete surface undergoes complicated movement components, including out-of-plane tilt (yaw and pitch), roll (rotation to the axis perpendicular to the surface), as well as the in-plane displacement components. Among them, only in-plane displacement components are useful to extract 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 application must be removable from the specimen, have large dynamic range and be insensitive to surface tilt.

An optical strain sensor based on a 5-axis freedom movement measurement technique (Zhao, Beck and Wu, 2004) (Wu et al, 2009) was developed at Kansas State University. The optical system of the sensor is configured to have large dynamic range and be able to measure the surface displacement accurately without being affected by other axis movements.

The diagram of the sensor is shown in Figure 1.6. A laser is collimated by lens L1, 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 the polarization beam-splitter B1 and the lens L3. Right behind the lens is a non-polarizing beam-splitter B2 that sends the laser beam to Mirror M4. The light beams then go back through the beam splitter B2 and are finally captured by a Charge Coupled Device (CCD) camera.

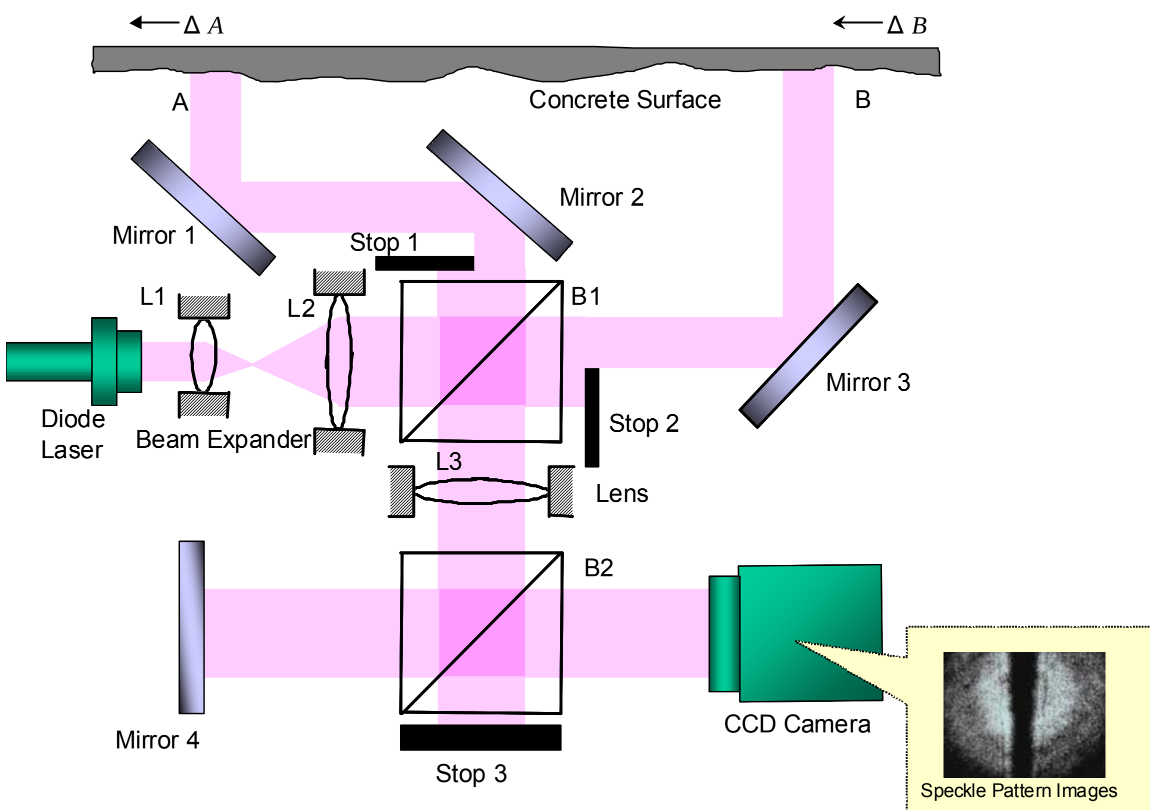


**Figure 1.6: Diagram showing basic sensor operation principle.**

Since there are two laser beams, reflected from point A and point B on the object surface that are sent to the camera, the camera actually captures two speckle patterns. The analysis of the speckle images will be difficult if the two speckle patterns overlap each other. To prevent this from happening, half of each of the laser beams is blocked with Stop 1 and Stop 2; such that only half area around point A and point B are illuminated. This results in two side-by-side speckle patterns, generated by point A and point B respectively, on the digitized images captured by the CCD camera as shown in Figure 1.6.

During the measurement, the optical strain sensor is mounted onto the concrete surface before the de-tensioning. The camera captures a speckle image with two side-by-side speckle patterns in it as shown in Figure 1.6. These two patterns are denoted as A1 and B1. After the de-tensioning, the optical sensor is mounted back onto the surface. The camera captures another speckle image with two speckle patterns, which are denoted as A2 and B2. By comparing the pair of speckle patterns A1 and A2 with correlation technique, the displacement $\Delta A$ can be extracted. The displacement $\Delta B$ can be extracted from pattern B1 and pattern B2 in a similar way. The surface strain between point A and point B thus can be calculated by, where L is the gauge length, 8" for the current setup.

### 1.2 Laboratory Verifications of LSI technique

In order 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 the conventional measurement technique. Using this setup as seen in Figure 1.7, a concrete prism was compressed in a universal testing machine and the concrete surface strains were recorded using both the laser-speckle technique and with surface mounted electrical resistance strain (ERS) gages. This setup was successfully used to assist the researchers in isolating the longitudinal (axial) strain component from the other distortions that are inherently present due to varying degrees of bending and torsion, and excellent correlation between the two methods was achieved in the laboratory. A direct comparison between the two techniques can be seen in Figure 1.8.

**Figure 1.7: Comparison of Laser-Speckle Method with Electrical Resistance strain gages on concrete prism in a universal testing machine.**

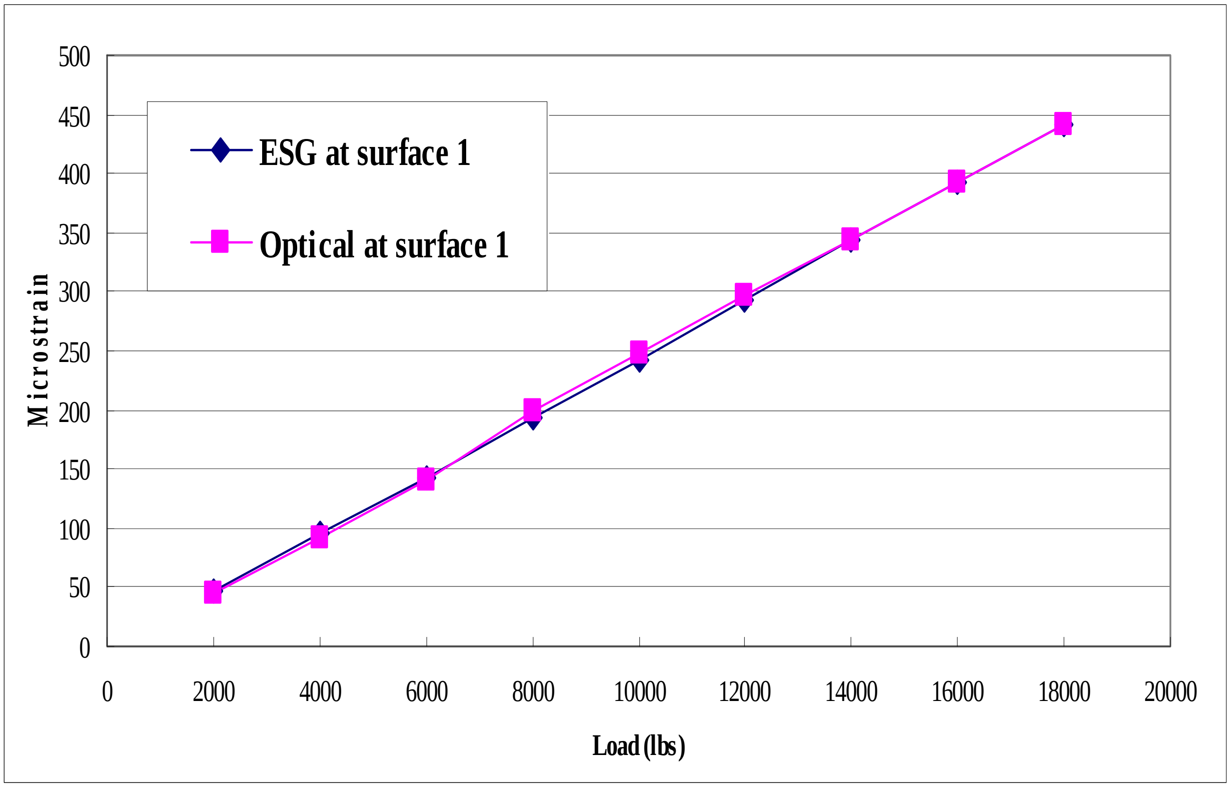


**Figure 1.8: Comparison of strains recorded with Laser-Speckle Method and with Electrical Resistance strain gages on concrete prism in a universal testing machine. Note, the maximum difference was 6 micro-strain over the entire measurement range.**

The next stage in the validation procedure was to compare surface strain results between the LSI technique and Whittemore readings when a large strain change occurred in a short period of time (i.e. the de-tensioning of prestressing strand).

In order to accomplish this, several pre-tensioned concrete members were fabricated using different concrete mixtures. The mixtures used in this study corresponded to SCC mixtures that were part of a larger PCI study and previously reported. (Peterman, 2007) The members had a trapezoidal cross-section as shown in Figure 1.9. This cross-section was employed as part of the development of a simple quality assurance test that was previously reported. (Peterman, 2009)

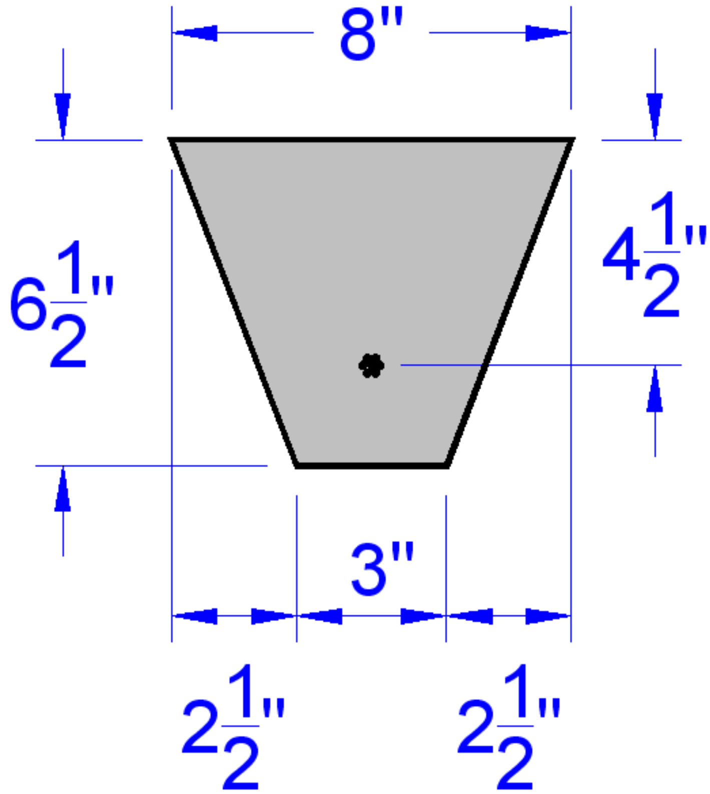


**Figure 1.9: Trapezoidal cross-section of the pre-tensioned members used to verify the laser-speckle transfer-length measurement technique.**

The pre-tensioned members were each 9'-6" long. The transfer lengths were measured on one side of each member, using both the traditional Whittemore gage and the non-contact laser-speckle method. In order to facilitate the laser-speckle measurements, an aluminum rail was mounted to the side of the member (Figures 1.10 and 1.11). The rail was attached to the members using small ¼-inch-diameter inserts that were cast into the sides of the pre-tensioned concrete members.

**Figure 1.10: Measurement of surface strains was accomplished using both the traditional surface-mounted method and the non-contact laser-speckle method.**

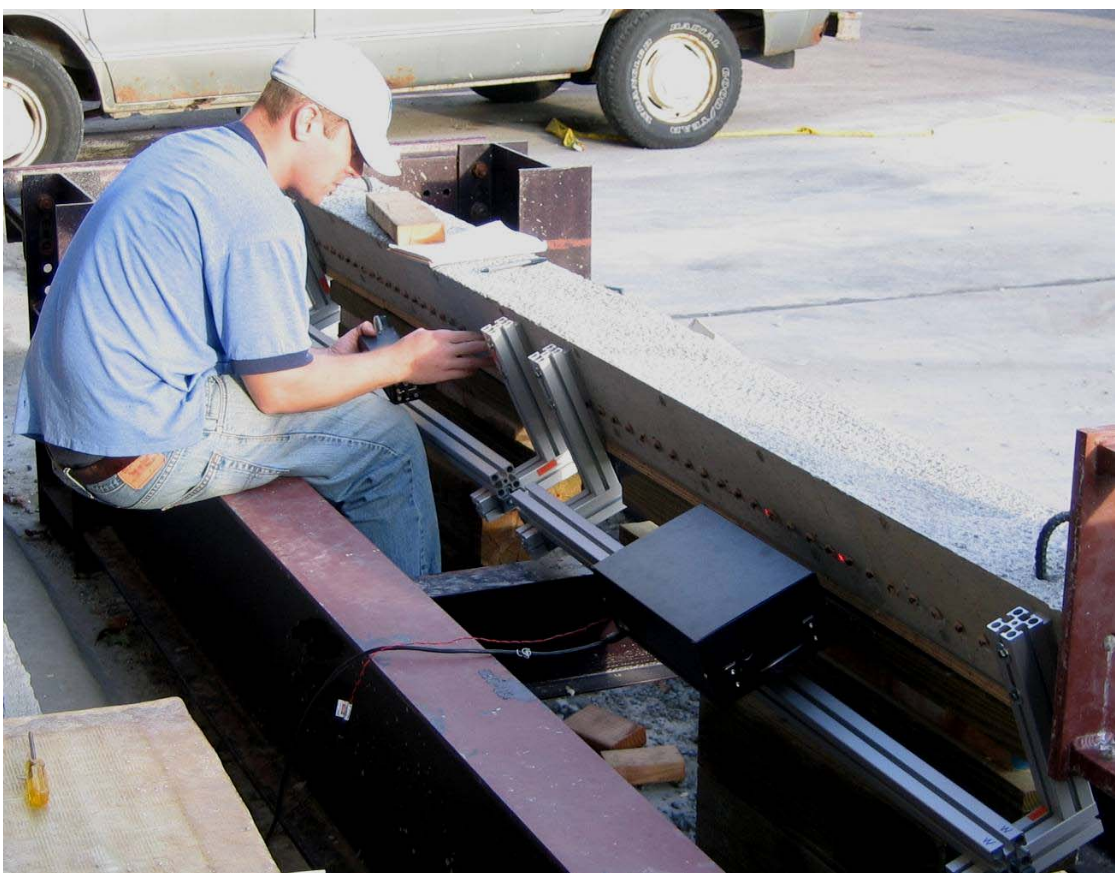

**Figure 1.11: Similar outdoor measurements were made to investigate the thermal characteristics of the device.**

# CHAPTER 2 - RESULTS

Surface strain measurements for the trapezoidal specimens were obtained using both the standard (Whittemore) technique and LSI (optical) technique. It can be seen in Figure 2.1 that the LSI results in much smoother data with less scatter than that generated using the existing surface strain measurement technique using the Wittemore gauge. The LSI technique has been validated on members cast in both indoor and outdoor operations. Thermal effects are similar to those exhibited by the traditional method, as the coupling of the gage points in the optical fixture was accomplished using a steel mounting plate.

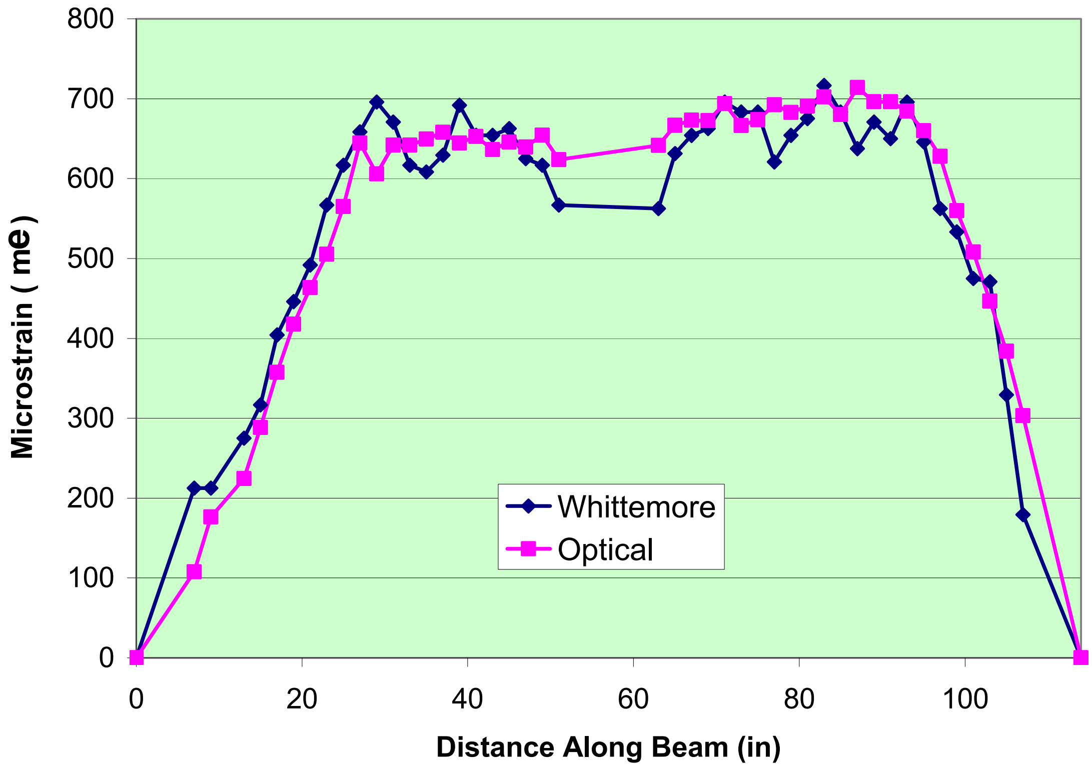


**Figure 2.1: Comparison of raw (un-smoothed) strain measurements immediately after de-tensioning of a pre-tensioned specimen.**

Because the laser-speckle 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, as shown in Figure 2.2, the LSI method works extremely well during the first month after de-tensioning. Note, in this figure the peak strains vary 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 bi-axial bending in the member.

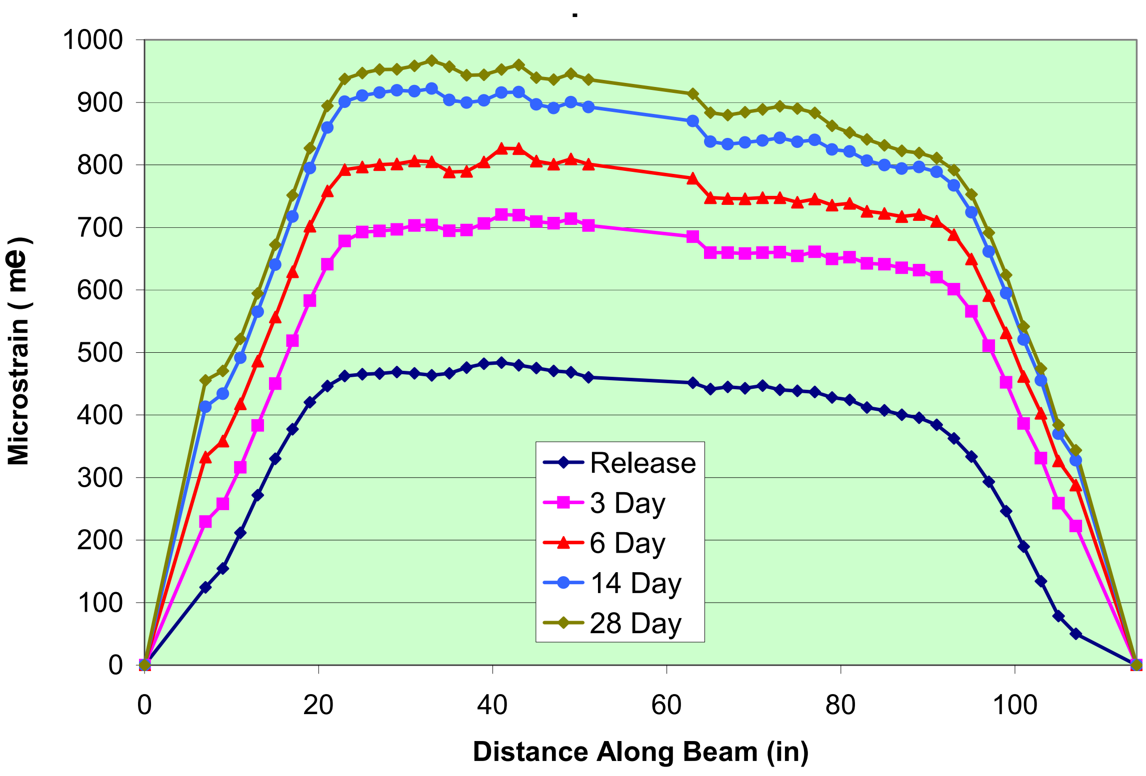


**Figure 2.2: Comparison of optical surface-strain measurements during the first 28-days after de-tensioning.**

## 2.1 Conclusions

Based on the work completed to date, the following conclusions may be drawn.

1. The laser-speckle imaging technique is a viable method to determine the transfer lengths in pre-tensioned concrete members.
2. The LSI technique, using the current optical arrangement, is considerably more accurate than the existing Whittemore technique, as it eliminates all human bias. The accuracy of LSI technique has been shown to be less than 10 microstrain, compared to a 25 microstrain accuracy for the Whittemore Technique.

The researchers are currently working to automate the process of traversing along a concrete member and capturing the corresponding laser-speckle images at every ¼-inch increments. This will enable the near-real-time determination of transfer lengths through computerized post-processing 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/or to enable the effect of changes in these parameters on strand bond.

# REFERENCES


AASHTO, *LRFD Bridge Design Specifications*, 4th Ed., American Association of State Highway and Transportation Officials, Washington, DC, 2007.

ACI Committee 318, “Building Code Requirements for Structural Concrete (ACI 318-05) and Commentary (ACI 318R-05),” American Concrete Institute, Farmington Hills, MI, 2008.

Barnes, R. W., Grove, J. W., and Burns, N. H., “Experimental Assessment of Factors Affecting Transfer Length,” ACI Structural Journal, V. 100, No. 6, November-December 2004, pp. 740-748.

Johnson, Peder “Strain field measurements in industrial applications using dual-beam digital speckle photography”, Optics and Laser in Engineering, 30, 1998

Kaar, P., and Magura, D., “Effect of Strand Blanketing on Performance of Pretensioned Girders,” PCI Journal, V. 10, No. 6, Dec. 1965, pp. 20-34.

Lane, Susan N., “A New Development Length Equation for Pretensioned Strands in Bridge Beams and Piles.” Publication No. FHWA-RD-98-116, Federal Highway Administration, Washington, D.C., December, 1998.

Larson, K., Peterman, R., and Esmaeily, A., “Bond Characteristics of Self-Consolidating Concrete for Prestressed Concrete Bridge Girders,” PCI Journal, July/August 2007, pp. 44-57.

Oh, B.H., and Kim, E.S., “Realistic Evaluation of Transfer Lengths in Pretensioned, Prestressed Concrete Members,” *ACI Structural Journal*, V. 97, No. 6, November-December, pp. 821-830.

Peterman, R. J., Ramirez, J. A., and Olek, J., “Influence of Flexure-Shear Cracking on Strand Development Length in Prestressed Concrete Members,” *PCI Journal*, V. 45, No. 5, Sept-Oct 2000, pp. 76-94.

Peterman, R. “The Effects of As-Cast Depth and Concrete Fluidity on Strand Bond,” PCI Journal, May/June 2007, pp. 72-101.

Peterman, R. J. “A Simple Quality Assurance Test for Strand Bond” PCI Journal, Spring 2009, pp. 143-161.

Russell, B.W. and Burns, N. H., “Design Guidelines for Transfer, Development and Debonding of Large Diameter Seven Wire Strands in Pretensioned Concrete Girders,” Texas Department of Transportation, Research Project 3-5-89/2-1210, 286 pp., January 1993.

Sjödahl, M. “A whole field speckle strain sensor”, Proc. SPIE Conf. on Opt. Eng., Yokohama, 1999

Wegner, R., Ettemeyer, A. “The miniaturization of speckle interferometry for rapid strain analysis”, Proceedings of SPIE, v. 3824, page30-36, June,1999, Munich, Germany

Wu, C.-H., Zhao, W., Beck, T., & Peterman, R. “Optical Sensor Developments for Measuring the Surface Strains in Pretensioned Concrete Beams, Accepted for Publication in Strain, International Journal for Experimental Mechanics, Published Online: Mar 27 2009

Yamaguchi, I., “A Laser-Speckle Strain Gauge” , J Phys.E.Sci. Instrum., vol. 14, no 11., Nov. 1981

Zhao, W., Beck, B.T., Wu, John, “A Novel Optical Technique for Measuring 5-axis Surface Movement” , Proceedings of SPIE Optics East, Philadelphia, Pennsylvania, 25-28, October, 2004

# K - TRAN

**KANSAS TRANSPORTATION RESEARCH**
**AND**
**NEW - DEVELOPMENTS PROGRAM**


**A COOPERATIVE TRANSPORTATION RESEARCH PROGRAM BETWEEN:**

**KANSAS DEPARTMENT OF TRANSPORTATION**

**THE UNIVERSITY OF KANSAS**

**KANSAS STATE UNIVERSITY**