AN AUTOMATED TRANSFER LENGTH MEASUREMENT SYSTEM
FOR USE ON CONCRETE RAILROAD TIES

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ABSTRACT

Prestressed concrete ties have become the preferred choice for many railway lines in the United States. However, in order for prestressed concrete ties to function adequately over their expected life, and to ensure the safety of freight movements, the prestressing force must be fully introduced into the railroad tie at a location well before the rail load is applied. The length required to transfer the prestress force into the concrete member is referred to as the "Transfer Length."

Since the transfer length is critical to the long-term performance of prestressed concrete ties, an automated transfer-length measurement system was developed using laser-speckle imaging technology. The non-contact measurement device can scan the top surface of a concrete railroad tie before and after the de-tensioning operation, and then automatically plot the strain profile and determine the transfer length using a least-squares algorithm. The device has already been successfully used to measure transfer lengths at a precast concrete tie plant in the United States, and can serve as a tool to evaluate the effect of process and material changes on prestressing steel bond.

Keywords: Transfer length, railroad tie, strain measurement, pre-tensioned concrete

INTRODUCTION

Railroad ties are structural members that hold the steel track in place on railroad lines. Typically, the ties are made out of wood; however, concrete ties have become increasingly popular in the United States over the past 25 years. Concrete ties have many environmental and economical benefits over wood ties. Wood ties are normally treated with creosote to eliminate their susceptibility to rot and decay. However, a disadvantage of creosote is that it's a flammable material. Concrete ties eliminate the flammability problem, and also have longer life expectancy. Longevity is a major advantage since, from a safety point of view, failure of the cross-ties under train load can be catastrophic. Concrete ties have more mass and are less likely to move under thermal and mechanical loads induced on the steel rails. In addition to enhanced safety, this rigidity increases fuel economy of the trains and makes for a smoother ride along the track. Concrete ties also provide excellent gauge holding power and lateral load resistance.

Concrete ties have become the preferred choice for many railway lines in the Midwest, where heavy freight movement occurs.   To meet the demand imposed by the intense dynamic loading conditions found on the railroad, concrete ties are produced by prestressing the members. By prestressing each individual cross-tie, large compressive forces are introduced into the concrete member. This compressive force increases the load-carrying capacity. However, for prestressed concrete ties to work efficiently, the prestressing force must be fully introduced into the tie at a location well before the rail load is applied. Typically, the rail-seat is 21 inches from the end of the tie. The dimensions of a representative prestressed concrete tie are shown in Figure 1. The reinforcing wires or strands are made of high strength steel and are usually distributed in either rows or in a staggered pattern as shown in Figure 2.
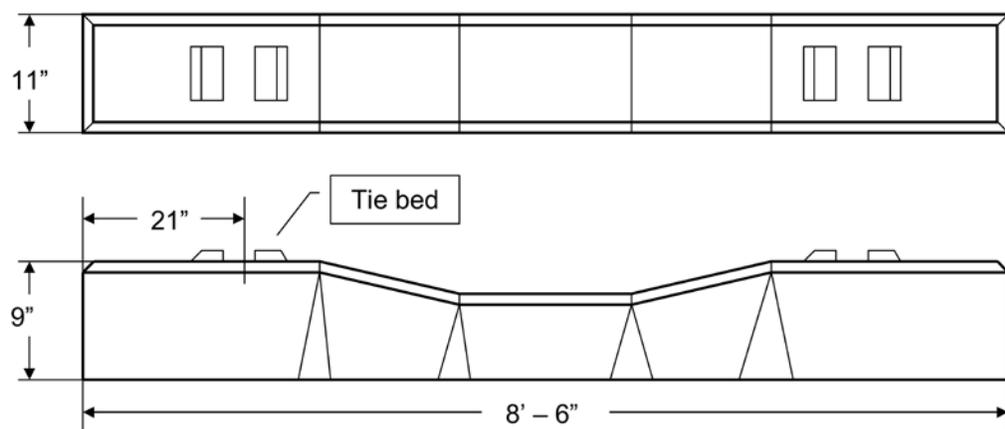

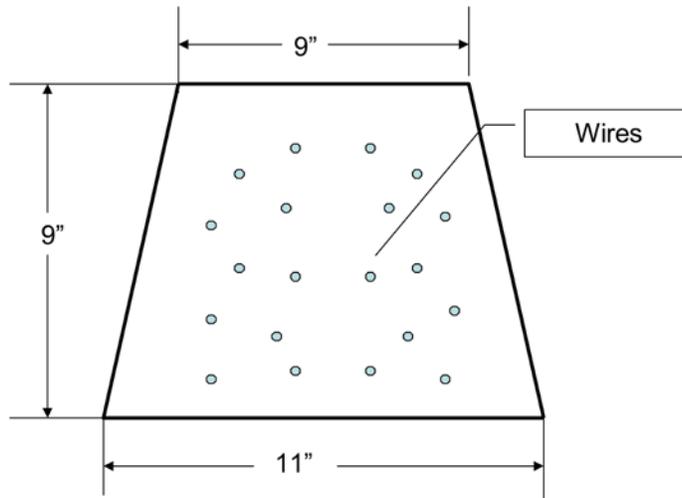Figure 1. The dimensions of a representative prestressed concrete tie

Figure 2. Reinforcing wires distributed in a staggered pattern

TRANSFER LENGTH MEASUREMENT

The length required to transfer the prestress force into the concrete is known as the "transfer length[1,2,3]", as shown in Figure 3. This transfer length can be determined from measurements of the surface strain profile on each end of a cross-tie. A typical strain profile measured from a pre-tensioned railroad tie is shown in Figure 4.
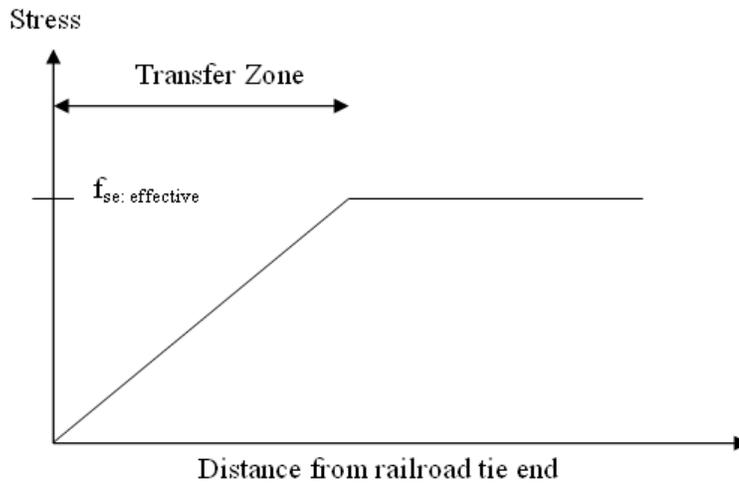

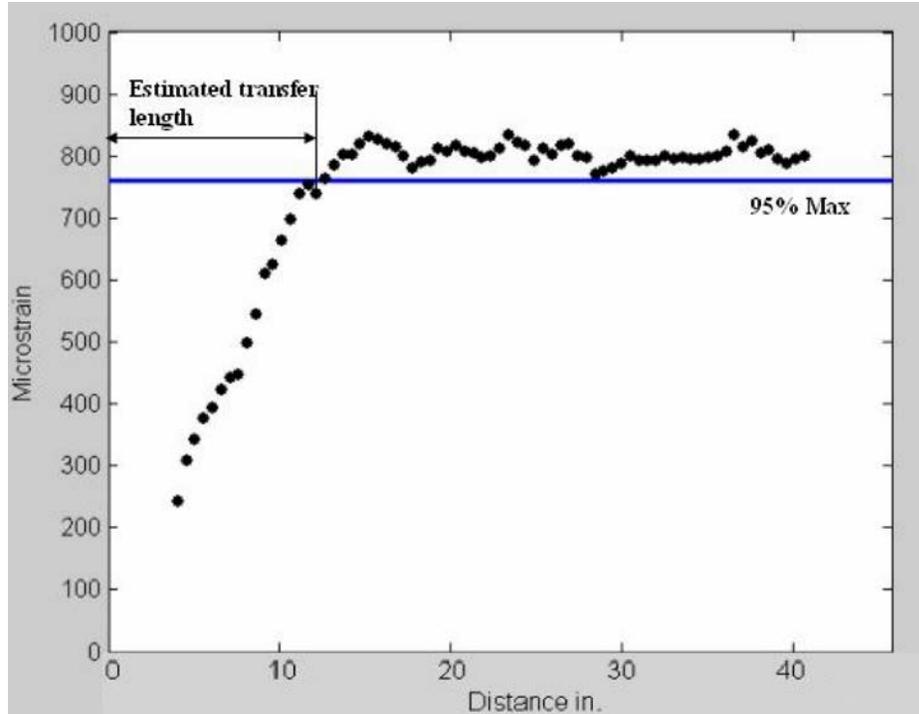Figure 3. Transfer zone on the pre-tensioned concrete railroad tie

Figure 4. A typical strain profile measured from a pre-tensioned railroad tie

Figure 5 shows the traditional device to measure transfer length, called the Whittemore gauge. This gauge typically has a resolution of about 25-50 microstrain and a gauge length of 8 in. To measure the transfer length using a Whittemore gage, metal gauge points are mounted at 2 in. or 1 in. spacing on the surface of the concrete member. These gauge points are either secured to the member using epoxy or by embedding them into the concrete as shown in Figure 6. Prior to detensioning the prestressing tendon (wire or strand), the distance between the gauge points is measured. After releasing the prestressing force, the distance between the gauge points is measured again. The surface strain can be found by determining the change in distance between the points and dividing by the gauge length.

Figure 5. Whittemore Gauge

Figure 6. Metal gauge points embedded in the concrete surface to facility the transfer length measurement by the Whittemore gauge

The strain is zero at the end of the tie and increases until it reaches an approximately constant strain value. When the strain becomes constant in the member, the prestressing force is transferred. To determine the transfer length value, the raw strain data is typically smoothed using a 3-point (boxcar) averaging technique, and then the 95% average maximum strain method (95% AMS) is applied[4]. This method is known to produce some inherent bias, is time consuming to evaluate manually, and also is subject to human judgment errors[5]. To facilitate a more rapid automated transfer length measurement method, there is also a need to improve the current 95% AMS method of processing the strain measurements. A new unbiased method of accomplishing this is discussed later as part of the proposed automated transfer length procedure.

MOTIVATION FOR AUTOMATED TRANSFER LENGTH MEASUREMENT

In order to use the transfer length as a quality assurance (QA) criteria by tie producer plants, it is necessary to develop a method to measure transfer lengths accurately and rapidly. This will allow producer plants to ensure that transfer lengths are within an acceptable tolerance, and to identify the need to modify production (e.g., concrete mix) if transfer length specifications are out of range. For instance, a common practice today at tie producer plants is to isolate a single production mold from a production line for high-scrutiny inspection that includes flexural and bond tests.

Currently the ratio of the prestressed concrete ties with out-of-specification transfer length is unknown because the concrete railroad tie industry does not conduct transfer length measurements except occasionally on a small scale for research purposes. It is believed that currently less than 1 out of 10,000 concrete railroad tie transfer lengths is checked by the concrete tie plant. This is due to the fact that the traditional transfer length measurement technique, using a mechanical gauge such as the Whittemore gauge, is not able to keep up with the working speed of the production line. Clearly, the tedious and labor-intensive practice required to conduct a transfer length measurement using the Whittemore gauge

would completely disrupt the highly automated production of a modern concrete railroad tie plant. An alternative device to measure the transfer length, called Laser Speckle Imaging (LSI) sensor, was developed previously by the authors[6,7]. It is based on a laser speckle technique and its operation has been verified through extensive manual testing. An earlier version of the manual LSI device, shown in Figure 7, has till now provided a convenient and accurate means to fairly rapidly measure transfer length and has been successfully employed to date by the authors for the measurement of hundreds of transfer lengths in a total of six railroad tie plants in the USA[8].

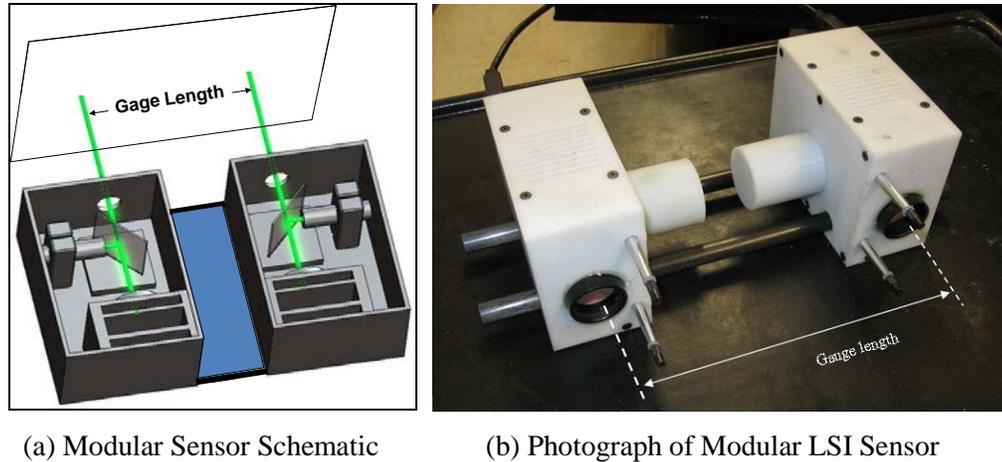(a) Modular Sensor Schematic   (b) Photograph of Modular LSI Sensor

Figure 7. Manual LSI sensor that was developed previously

This paper presents the development of an automated version of the above mentioned LSI strain sensor, which provides a significant improvement over the previous manual sensor based on several performance characteristics including robustness, repeatability, and speed. Since the automated LSI sensor is able to complete the transfer length measurement of a railroad tie in a mere couple of minutes, it also has the potential to one day provide real-time transfer length measurements on virtually every single tie in the production line on a daily basis, without disruption to the manufacturing cycle. In addition, transfer length is known to be affected by factors such as reinforcement characteristics (e.g. design, manufacturing process, drawing lubricants, etc), concrete (e.g. mix design, material, quality, placement, curing, vibration, etc), and prestress release, as well as the compatibility between a particular concrete and its reinforcement. Therefore, the automated laser speckle strain sensor is potentially an innovative and powerful tool for not only concrete tie producers but also any prestressed concrete manufacturer who strives to improve and control product quality and thereby drive production consistency and reliability to unprecedented levels.

LASER-SPECKLE METHODOLOGY AND THE AUTOMATED LSI SENSOR

To measure the transfer length more quickly and accurately, a non-contact method based on laser-speckle technology is employed to detect the surface strain of the pre-tensioned concrete railroad tie. Speckle is generated by illuminating a rough surface with

coherent light, as shown in Figure 8 (a). The random reflected waves interfere with each other (constructively and destructively), resulting in a grainy image, as shown Figure 8 (b). 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[9,10].

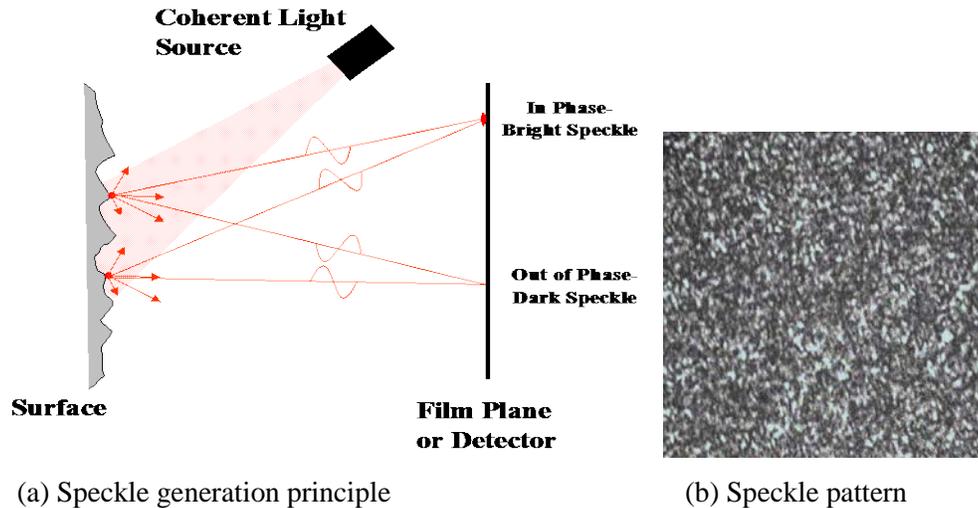(a) Speckle generation principle   (b) Speckle pattern

Figure 8. Laser-speckle methodology

To detect the surface strain or deformation, the grainy speckle pattern image is recorded before the surface is deformed and after the surface deformation. The deformation or displacement components can then be extracted by comparing the shift of the speckle patterns before and after a surface deformation. This is typically done statistically using a cross-correlation technique to measure the speckle displacement.

For the surface strain measurement, the optical strain sensor is first positioned onto the concrete surface before the detensioning. The two CCD cameras, in the left and right modules, as shown in Figure 7, capture a pair of speckle images that are generated by point A and point B in Figure 9, respectively. These two speckle images are denoted as A1 and B1. The sensor is then removed from the concrete surface. After the release of the prestress force, the optical sensor is positioned (mounted) back onto the surface. The cameras capture another pair of speckle images, which are denoted as A2 and B2. By applying a cross-correlation technique to the pair of speckle images A1 and A2 (before and after the detensioning processes), the displacement ΔA can be extracted. The displacement ΔB can be extracted from image B1 and image B2 in a similar fashion. As shown in Figure 9, the axial surface strain ε between point A and point B can thus be determined by $\varepsilon = (\Delta B - \Delta A)/L$, where L is the gauge length of the sensor.
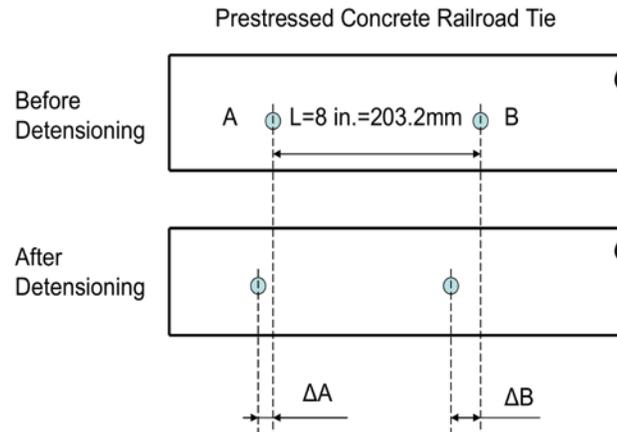
Figure 9. Strain measurement by the automated LSI sensor

An automated version of the LSI sensor was fabricated in a manner similar to the manual LSI sensor discussed above, and is shown in Figure 10. It has two identical optical modules configured as a mirror setup with each module capable of detecting the surface movement independently. Both optical system modules are mounted on a common plate made of carbon fiber, whose thermal expansion coefficient is close to zero. This configuration effectively eliminates the thermal strain error that could occur due to the heat generated by the cameras and other electronic circuits of the sensor.
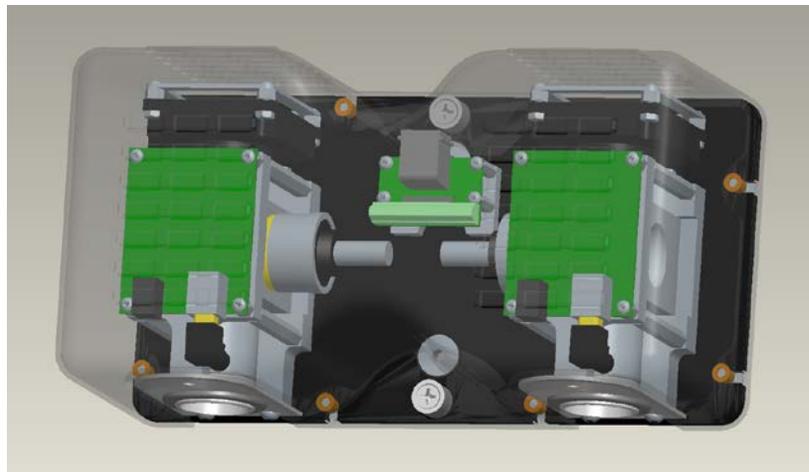

Figure 10. The LSI sensor

To automate the transfer length measurement of a railroad tie using the current LSI strain sensor, the authors mounted the LSI sensor on a computer-controlled traverse. This provided the capability to automatically traverse the LSI sensor along the transfer length region of the concrete railroad tie prior to and after the cutting operation (i.e., before and after de-tensioning) to assess surface strain, as suggested in Figure 11. Such an automated

system also provides the flexibility to easily adjust the spatial sampling frequency of the surface strain measurement to investigate optimal sample scenarios.
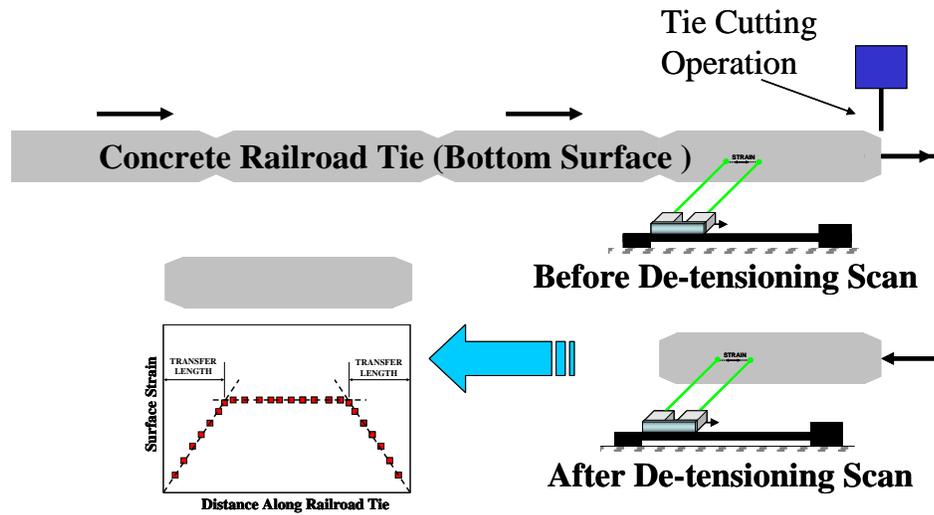

Figure 11. Automating the transfer length measurement: Traversing Method

A practical implementation of the automated traversing system has been completed and is illustrated in Figure 12 and Figure 13. System specifications include 24" scan length of measurement on each end of concrete cross-tie, 1 minute cycle time for approximately 60 distributed strain measurements per scan, and 0.010 in. repeatable sensor positioning accuracy.
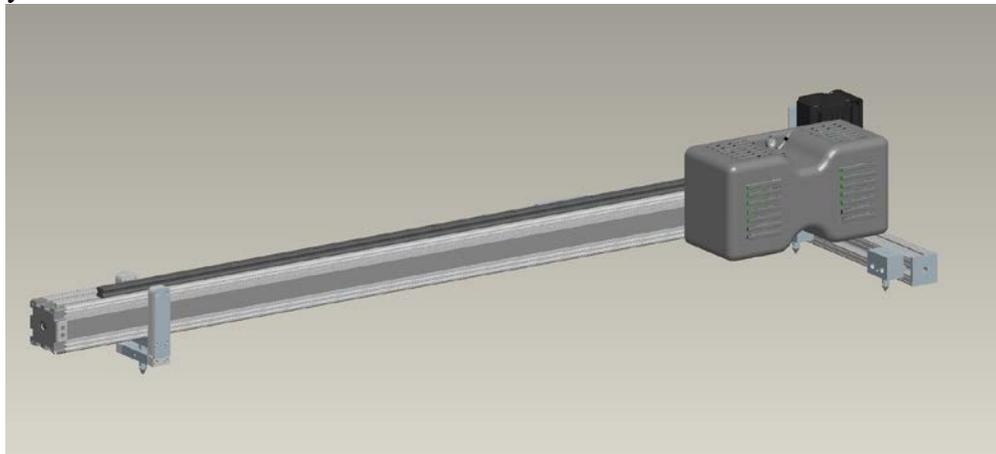

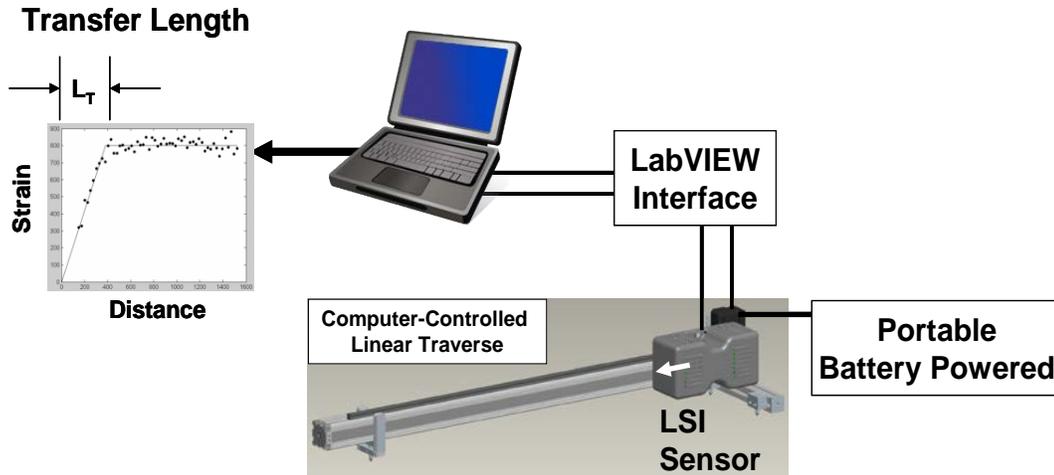Figure 12. The automated traversing system with translating LSI sensor

Figure 13. Overall automated LSI sensor traversing system

Currently a laptop computer provides both USB and RS232 communications with the traverse system and the LSI sensor. The traverse control and data acquisition are included in one software, with the data processing being conducted on the same computer too. As suggested in Figure 14, two scans are required for transfer length measurement one prior to de-tensioning and one subsequent to the cutting operation. The surface strain is calculated and plotted automatically after the raw images are captured.
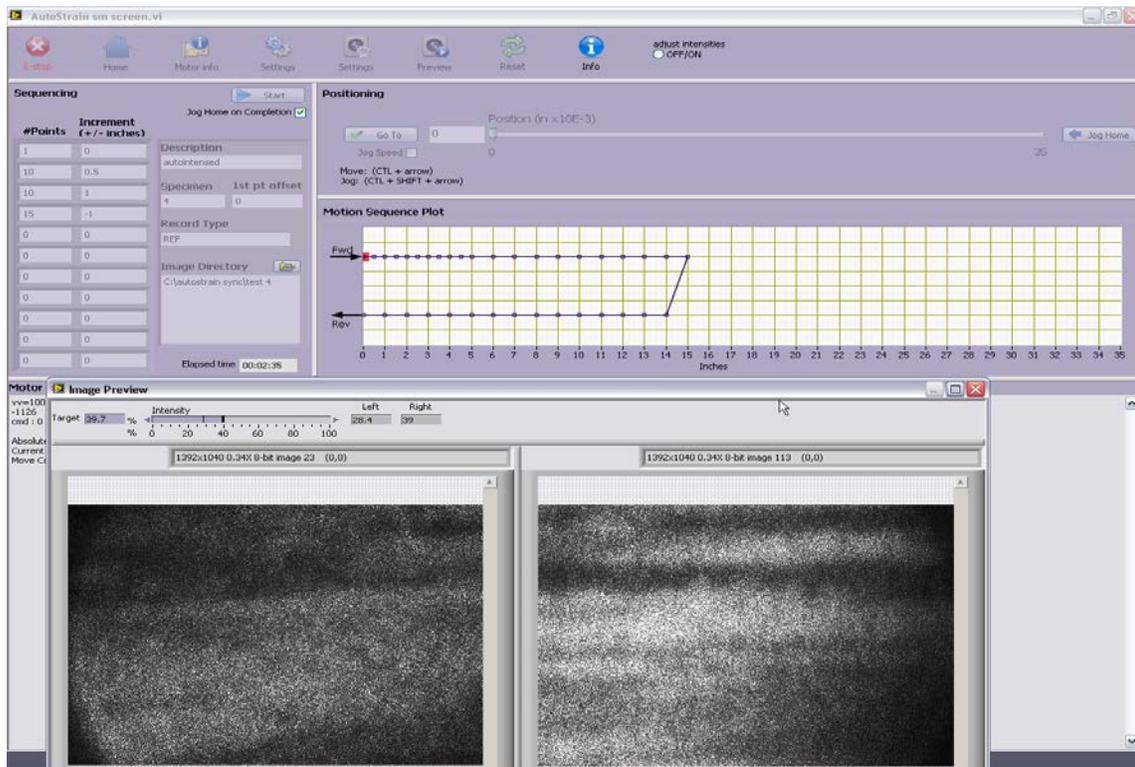

Figure 14. Traverse control and LabVIEW data acquisition interface

DETERMINATION OF THE TRANSFER LENGTH FROM LSI STRAIN DATA

After the surface strain profile is obtained, the transfer length can be extracted. The so-called 95% Average Maximum Strain (95% AMS) method is the classical method to extract the transfer length from the measured surface strain data[4]. This method consists of the 3 basic steps described below.

Step 1: Every three consecutive strain data points are averaged to smooth the data (i.e., boxcar averaging) as shown in Figure 3.

Step 2: The plateau area of the strain profile is determined (by operator judgment from the observed strain profile), and this maximum strain value is then multiplied by 95%. The resulting value is denoted as the "95% average maximum strain".

Step 3: A horizontal line is drawn at the level of the 95% average maximum strain. The location of its intersection (again determined by operator judgment) with the smoothed strain profile indicates the estimated value of the transfer length.

The 95% AMS method has been used by the engineers and researchers to determine the transfer lengths of pre-tensioned concrete members for decades[3,4]. However, it requires human judgment, which makes it subject to possibly significant human errors. In addition, it has been proved that the transfer length estimation by the 95% AMS method is a biased estimation that tends to be larger or smaller than the actual transfer length value depending on the gauge length of the strain sensor and the spatial sampling frequency[5]. Furthermore, the 95% AMS method is usually conducted manually since it is hard to be implemented as computer software. Plotting, averaging, determining the plateau, and locating the intersection point usually take dozens of minutes. At first glance, the time that is spent on performing the 95% AMS method might not look significant, considering the much longer time required to collect the surface strain data using the traditional mechanical gauge. However, since the automated LSI system has become available, it is now possible to obtain the strain data for a pre-tensioned concrete member in just a couple of minutes. Thus, a faster method is now needed to allow rapid processing of the raw strain data to give accurate estimations of the transfer length along with associated confidence limits.

In response to the disadvantages of the 95% AMS method, a new transfer length estimation method, called the "Zhao-Lee method" (ZL method) has been developed by the authors[5]. It is based on a least–squares technique and provides unbiased estimation of the transfer length. In addition, it is robust to (i.e., minimally affected by) local outliers and missing data points, free of human judgment errors, and would also work well for the strain data collected by strain sensors of various gauge lengths or sampling intervals. The approach of the Zhao-Lee method is to turn the transfer length determination problem into a problem to find the optimal location of the intersection point that minimizes a target function, where the target function is generated by assuming the surface strain to be bilinear as suggested in Figure 15, with the rounding effect of the gauge length of the sensor taken into account.
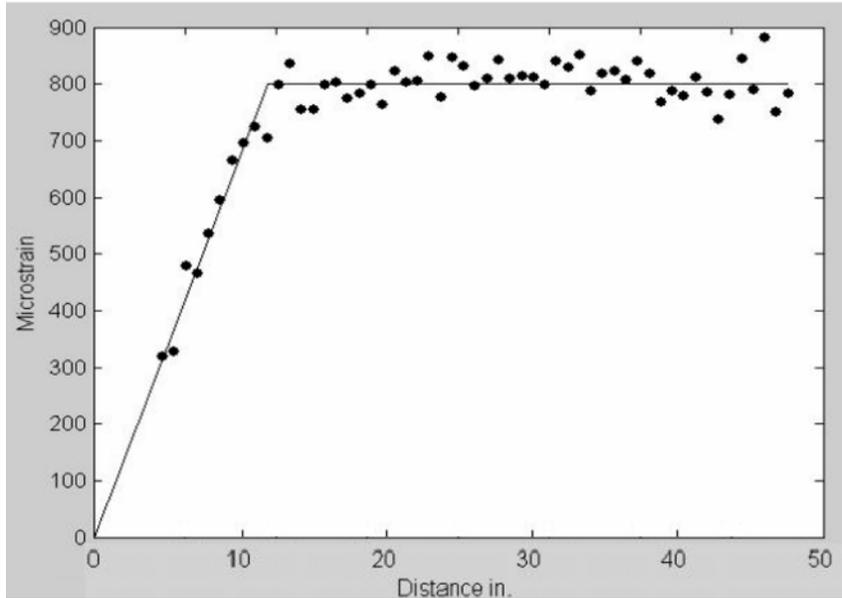
Figure 15. The bilinear model assumption for the surface strain profile

It has been shown by simulations that the estimation accuracy of the ZL method appears to be better than that of the 95% AMS method. In particular, the ZL method is able to estimate the transfer length values with a 95% confidence interval narrower than ±1.5 in., when the gauge length is larger than 4.00 in. In addition, the ZL method gives an unbiased estimation. Applying the ZL method to the real surface strain data of railroad tie also shows that the ZL method produces a more precise estimation[5].

The algorithm of ZL method has been implemented as a built-in module of the data-processing software for the automated LSI system. The software reads the raw images captured by the LSI device, conducts the necessary data-processing procedures and then reports transfer length estimation automatically.

DEMONSTRATION OF AUTOMATED TRANSFER LENGTH MEASUREMENT

In order to demonstrate the capability of the automated LSI sensor to measure the transfer length, a pre-tensioned concrete prism was poured as the specimen. The automated LSI system was mounted on the top of the concrete prism surface, as shown in Figure 16. With the LSI sensor traveling along the concrete prism, 60 surface strain data points were collected in 1 minute for one end of the concrete prism. By doing this before and after the de-tensioning, the surface strain profile was measured and the transfer length was subsequently reported.

Figure 16. An automated LSI sensor positioned on a concrete prism

To evaluate the repeatability of the automated LSI system, a total of 8 repetitions of real prism strain data were taken on the same side of the concrete prism. For each repetition, the automated LSI system was repositioned on slightly different location on the prism intentionally, to make sure the 8 repetitions were independent of each other. Table 1 shows the transfer length values obtained from the 8 repetitions. It can be seen that the repeatability of the transfer length measurement by the automated LSI system is very good, with the standard deviation of the transfer length equal to only about 0.2 in. Furthermore, the transfer length of the same concrete prism was measured by using the Whittemore gauge and the result was 9.1 in., showing an excellent agreement between the Whittemore gauge and the automated LSI sensor.

Table 1. Transfer lengths measured on a pre-tensioned concrete prism (Unit: in.)

Repetition #	1	2	3	4	5	6	7	8	Standard deviation
Transfer length	9.2	8.8	9.4	9.3	9.0	9.2	9.0	9.0	0.2

In the experiment described above, the prism surface strain was measured by the automated LSI sensor at 0.5 in. spacing. It is predictable that the higher spatial sampling frequency of the surface strain data is measured, the more accurate the transfer length can be determined. It is very easy for the automated LSI system to employ different spatial sampling frequency of the surface strain measurement, depending on the specific objective of various applications. Ongoing research by the authors is now focusing on determination of the optimal spatial sampling frequency; that is, what sampling interval along the tie is just sufficient to provide an acceptable uncertainty in the estimation of transfer length.

AUTOMATED MEASUREMENTS AT A CONCRETE RAILROAD TIE PLANT

In order to verify the capability of the automated LSI sensor to measure the transfer length in the industrial environment, the authors traveled to a concrete railroad tie plant in January 2012, and conducted transfer length measurement on the railroad ties being produced

in the plant. Because of the manufacturing process, strain measurements are made on the upward-facing bottom surface of the ties.

The surface of the concrete must remain smooth and consistent throughout the measurement process, in order for the laser-speckle device to work properly. Steel bars were placed in the concrete during the time of casting (Figure 17). Once the concrete had cured, the bars were removed and left a smooth surface for the LSI sensor to take measurements.

Figure 17. Steel bars cast in fresh concrete

Once the base readings (i.e., prior to de-tensioning) are taken on the concrete tie surface, the surface must remain relatively unchanged, otherwise secondary readings of strain cannot be taken. If the surface features are substantially altered after the base readings are made, the speckle pattern will not represent a "fingerprint" for each individual surface feature location. This is a major problem when taking measurements at a prestressed concrete tie plant. The plant introduces many factors that can alter the concrete surface structure. Factors that can affect concrete surface structure include water used during the cutting operation, dust, handling of the ties by positioning machines and vacuum manipulators, and early release of the prestressing force.

To avoid this problem, microscopic reflective particles were bonded to the railroad tie surface to serve as an artificial speckle "tag" before the initial readings were taken, as shown in Figure 18. The particles were much less vulnerable to the severe abrasions than the concrete surface itself and helped keep the image correlation that was critical for the LSI sensor to be functional in this situation. The procedure shown in Figure 17 for surface preparation is relatively straight-forward and can be done very quickly. Rapid and minimal special surface preparation is a requirement for in-plant operation.
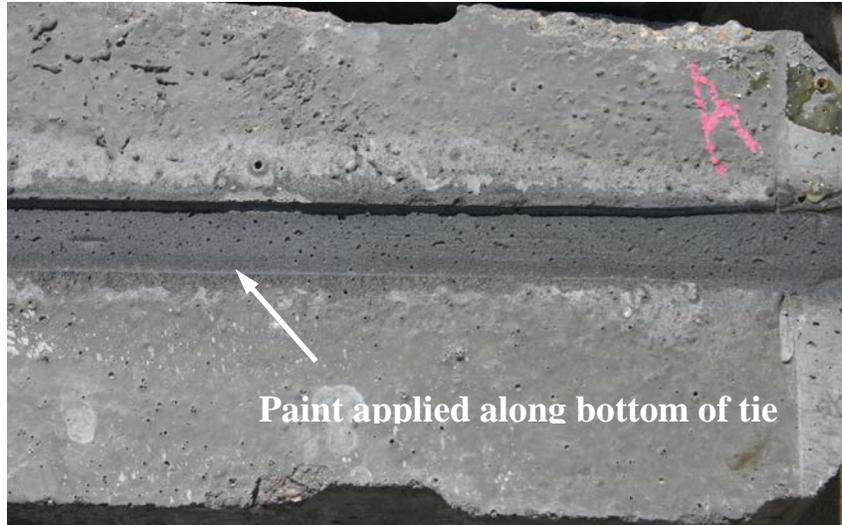
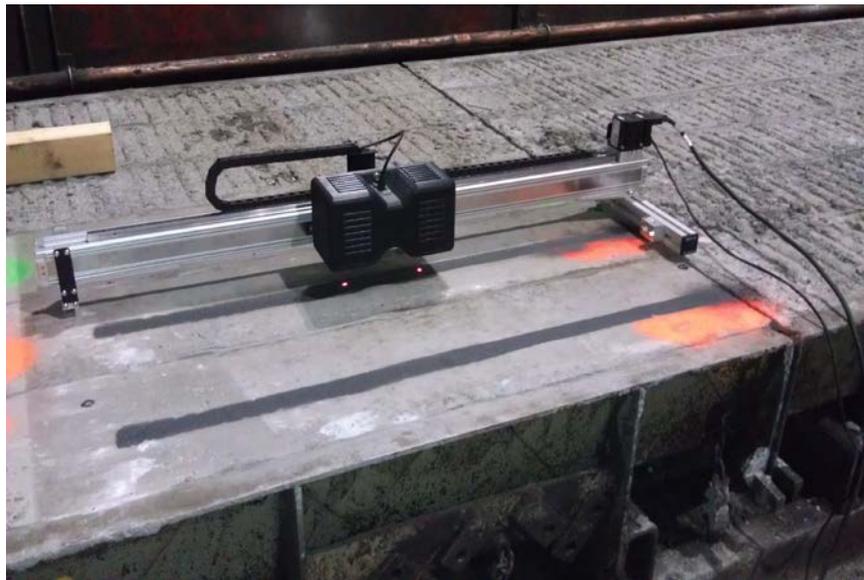Figure 18. Protective paint applied to concrete tie surface

Figure 19. Automated LSI traversing system on concrete ties in plant

Figure 19 shows the setup of the automated LSI system on the railroad tie in the plant. Before de-tensioning the railroad ties, initial laser speckle readings were taken every 0.5 in. The 0.5 in. spacing was somewhat arbitrarily selected, though higher spatial sampling frequency is also possible. The increased spatial resolution was made possible by the ease of use of the LSI sensor, and the fact that minimal (i.e., no time-consuming) surface preparation was needed. After the railroad tie was de-tensioned and cut, readings were taken once again. The two sets of readings were compared, correspondingly, to extract the strain information at each location, which in turn was used to plot the strain profile of the railroad tie for the transfer length determination. The whole procedure was done automatically with the total time for measuring one side of a tie being only about 1 minute. An example of the surface

strain profile obtained by using automated LSI device is shown in Figure 20. Note the transfer length estimated by the Zhao-Lee method is reported at the upper right corner of the plot.
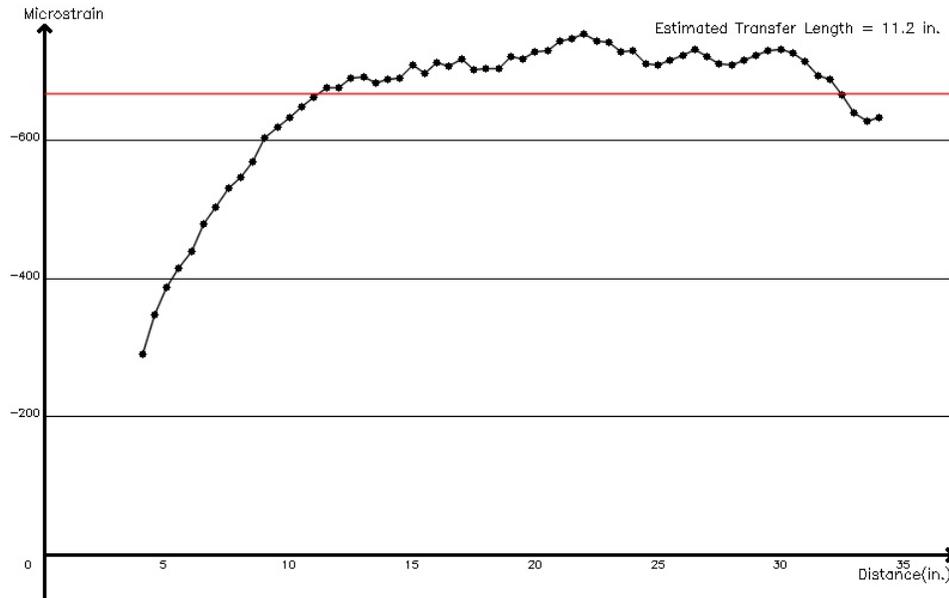

Figure 20. An example of the strain profile plot and the transfer length estimated by the Zhao-Lee method

To provide the plant with information regarding the quality of their concrete tie product, the research team took transfer length measurements on four different combinations of concrete mixes and wire sources from different producers. Taking transfer length measurements on various possible combinations could help the plant identify problems in their mixes or the wire if they exist.

For comparison purpose, the Whittemore gauge was also used to measure the transfer length of three railroad ties for each casting setting. The raw strain data obtained by Whittemore gauge was analyzed by the traditional 95% AMS method to estimate the transfer length.

For all the 4 castings of the ties, a total of 41 transfer lengths were measured by the automated LSI device, and 12 transfer lengths were measured by the Whittemore gauge. The transfer length results are summarized in Figure 21. Due the different surface preparations, an individual concrete tie was either measured by the LSI sensor or the Whittemore gauge, but not by both. Thus a one-to-one comparison between the two sensors on the same concrete tie is not applicable. Therefore, the transfer lengths measured by the two technologies were plotted in separate columns.
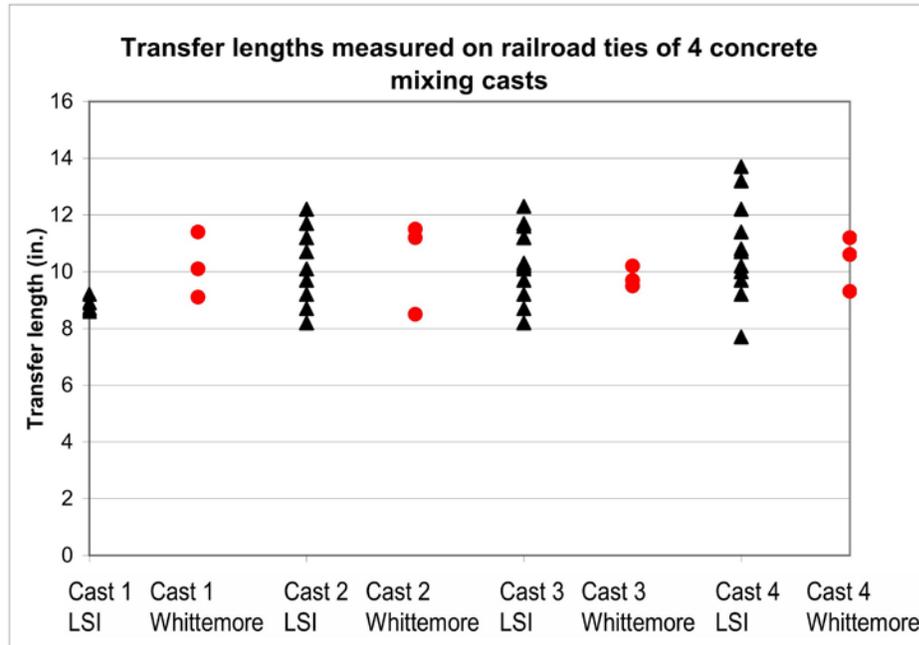
Figure 21. Transfer length results from railroad concrete ties of 4 different concrete mixing casts

The plot shows the transfer length values measured by both devices, the automated LSI system and the Whittemore gauge, were quite consistent. The total number of the transfer lengths measured by the automated LSI sensor were four times the number obtained using the Whittemore gauge, which reflects the higher operation speed and ease of use of the automated system. In addition, all the transfer length values were observed to be considerably less than the rail seat distance of 21 in.

CONCLUSIONS

The development of an automated version of a new non-contact device, based on Laser Speckle Imaging (LSI), has been presented for measuring the transfer length of prestressed concrete railroad cross-ties.   This new type of sensor has previously been shown to perform well for transfer length measurements in prestressed concrete beam applications, during manual testing with an earlier version of the device.   In this paper a newer dual-module design is utilized to automate the surface strain measurement process by means of a computer-controlled traversing system.

The automated LSI device was shown to provide accurate transfer length measurement comparable to those obtained using the traditionally Whittemore mechanical gauge, but at much higher speed, higher spatial resolution and increased repeatability. With the current traversing hardware and LabVIEW interface, a 60-point sequence of surface strain measurements at 1-inch increment can be measured in about one minute on each end of a railroad concrete tie. Spatial resolutions (i.e., sampling intervals) as small as a mm are possible with the automated system. In addition, through the use of the unbiased Zhao-Lee

algorithm based on least-squares technique for transfer length assessment, a much more reliable measurement free from human bias is achieved, along with the potential for determining the transfer length uncertainty from the statistical characteristics associated with the fitting algorithm. This more detailed uncertainty analysis is currently under development.

The performance of the current system has been demonstrated in recent field trip measurements conducted in an actual railroad concrete tie production plant, by limited sampling of the manufactured ties. This new automated LSI strain sensor, represents the next step toward the goal of fully-automated in-plant operation of transfer length measurement for real-time quality control monitoring of the railroad concrete tie production process. It is now quite feasible to envision continuous on-going transfer length measurement to ensure the quality of bond.

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