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A Non-Contact Inspection Method to Determine the Transfer Length in Pre-tensioned Concrete Railroad Ties

Weixin Zhao, Robert L Murphy, Robert J Peterman, B. Terry Beck, Chih-Hang John Wu, Pelle N. Duong

Abstract

The traditional experimental method to determine the transfer length in pre-tensioned concrete members consists of measuring concrete surface strains before and after de-tensioning with a mechanical strain gage. This method is prone to significant human errors and inaccuracies. In addition, since it is a time-consuming and tedious process, transfer lengths are seldom if ever measured on a production basis for product Quality Assurance.

A rapid, non-contact method for determining transfer lengths in pre-tensioned concrete railroad ties has been developed. The new method uses laser-speckle patterns that are generated and digitally recorded at various points along the pre-tensioned concrete member. A prototype was fabricated as a portable self-contained unit for field testing. It incorporates a unique modular design concept that has several preferable features. These include flexible adjustment of the gauge length, easy upgradability to automatic operation, robustness and higher accuracy.

The laser speckle strain sensor was applied to transfer length measurements of typical pre-tensioned concrete railroad ties in a railroad tie plant. These prestressed concrete tie members are expected to withstand repeated axle loadings of 290 kN totaling 250 million gross tons annually occurring at speeds in excess of 110 km/h. The technique achieved a microstrain resolution comparable to what could be obtained using mechanical gauge technology. Surface strain distributions were measured on both ends of twelve ties, and their associated transfer lengths were subsequently extracted.

The measurements of transfer length using the laser speckle strain sensor were unprecedented since it was the first time that the laser speckle technique has been applied to pre-tensioned concrete inspection and particularly for use in transfer length measurements of concrete railroad

ties. It was also demonstrated that the technique was able to withstand the harsh manufacturing environment, making transfer length measurements possible on a production basis for the first time.

Introduction to Problem

Pre-tensioned concrete railroad ties are becoming increasingly popular in the United States, and are an essential component for higher speed railway lines. In order for these pre-tensioned concrete ties to function adequately over their expected service life, the prestress 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." Furthermore, repeated loading inside of the transfer length zone may have significant affect on the transfer length, which can lead to cracking and early bond failure. However, the repeated loading outside of the transfer length zone does not significantly affect the transfer length (Shahawy *et al*., 1990). Another important concern is time dependent effects on transfer lengths, where various research studies has indicated transfer length (these researches includes prestressing tendons of both wire and strands as well as in different size diameter tendons) increases of varying degrees over time (Barnes, 2000). Since the pre-tensioned concrete ties are relatively short, and have extremely large dynamic loads repeatedly applied near the member ends, most of the pre-tensioned concrete railroad tie producers use indented prestressing wires or indented prestressing strands rather than traditional 7-wire smooth prestressing strands. It is generally understood that these indentations serve to improve the bond between the steel and the concrete and therefore reduce the transfer length.

However, because the application of these indented reinforcing steels has been so limited, current design codes in the United States do not yet address indented prestressing wire or indented strands in terms of recommended design assumptions for transfer and development length (ACI Committee, 2008, AASHTO, 2007).

Moreover, there is currently not even a standardized indentation pattern (shape, size, depth of indent, etc.) that is used by all wire manufacturers. Thus, the corresponding bond behavior of these different wires when placed in various concrete mixtures, in terms of average transfer lengths and typical variations, is essentially unknown.

In order to determine and quantify the prestressing steel and concrete variables that affect the transfer length in Pre-tensioned concrete crossties, so that the proper performance of the ties can be ensured throughout their entire service life, it is important to find a way to measure the transfer length rapidly and accurately. This same technology could then also be employed as a quality assurance (QA) measure by tie producer plants to ensure that transfer lengths are within the ideal range and to identify the need to modify production processes if necessary. 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. An automated laser speckle strain sensor, because of its robustness, versatility and accuracy, provides the opportunity to perform transfer length measurements on potentially 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 drive consistency to unprecedented levels.

Background on Transfer Length

Pre-tensioned concrete railroad ties are fabricated by casting concrete around already tensioned steel wires or strands. After the casting process is complete and the concrete has hardened, a detensioning procedure is undertaken by cutting the reinforcing wires or strands at both ends of the concrete tie to release the tension. The stress transferred from the wires or strands to the concrete is developed gradually from each end of the tie, where the stress is zero, and to the location away from the end, where the stress is at its full value f_{se}, called effective stress, as shown in Figure 1. The length required to fully develop the effective stress f_{se}, is defined as the transfer length, which is determined by measuring and plotting the surface strain profile of the pre-tensioned concrete railroad tie (Peterman *et al*. 2000, Shawn and Ned 1995, Kaar *et al*. 1965).

Traditional Whittemore Method

Transfer lengths are determined experimentally by measuring the surface strain profile of the concrete in the region near the ends of the member. Traditionally, metal gauge points are mounted at 2 in. spacing on the surface of the concrete at the structural depth of the prestressing steel. These gauge points are either secured to the member using epoxy or by embedding them into the concrete. Prior to detensioning the prestressing tendon (wire or strand), the distance between the gauge points is measured using a mechanical gauge called Whittemore gauge. This gauge typically has a resolution of about 25-50 microstrain and a gauge length of 203.2mm (8 in.). 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.

Typically, to construct the surface strain profile for a prestressed member, the strain measured at three consecutive points is averaged to smooth the data. By averaging three consecutive points with a 203.2mm (8 in.) gauge, the surface strain is effectively being averaged over a 304.8mm (12 in.) length as shown in Figure 2.

Laser-Speckle Technology and the Optical Strain 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 3.

The random reflected waves interfere with each other (constructively and destructively), resulting in a grainy image, as shown Figure 4. 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 (Yamaguchi 1981, Zagar *et al.* 1999).

There exist two basic categories of laser speckle strain measurement techniques: electronic speckle pattern interferometry (ESPI) and digital speckle photography (DSP). They relate to different methods of producing and processing the speckle image. The strain measurement systems based on ESPI can achieve very high resolution (Yang 2003, Chiang *et al.* 1976, Haasteren *et al.* 1994), but generally require stringent alignment of the sensor due to their small dynamic range, e.g. the maximum deformation or displacement that the technique can measure (Wegner 1999). This makes it impractical for the ESPI technique to be used for strain measurement on pre-tensioned concrete ties in the harsh manufacturing environment where the stringent alignment of the sensor is hard to achieve. DSP, on the other hand, generally has lower resolution than ESPI, but its resolution is high enough for the pre-tensioned concrete tie strain measurement application. More importantly, the DSP technique has a large dynamic range, which is a principal requirement in pre-tensioned concrete tie concrete beam strain measurement. The optical strain measurement technique that was developed for this study is actually based on DSP.

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. The cross-correlation function is defined by

$$Corr(x,y)=\sum_{i=1}^{M}\sum_{j=1}^{N}I_1(i,j)I_2(x+i,y+j) \tag{1}$$

where I_1 and I_2 are, respectively, the intensity matrix of the un-deformed speckle pattern and the deformed speckle pattern; M and N are the width and height of the speckle patterns. By varying the values of x and y, the maximum value of the correlation function can be found, and its coordinates give the relative displacement between the speckle pattern pairs (Zhao 2004).

A prototype of the optical strain sensor was fabricated in a portable light-weight self-contained unit for field testing, as shown in Figure 5. It has two identical modules attached rigidly to each other in a mirror setup with each module capable of detecting the surface movement independently. This unique modular design provided several preferable features including flexible adjustment of the gauge length, easy upgradeability to automatic operation, robustness and higher accuracy.

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 capture a pair of speckle images that are generated by point A and point B, 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 5, 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 203.2 mm (8 in.) for the current setup.

The capability of the optical sensor in strain measurement was validated by using a manual motion system shown in Figure 7. Two small concrete blocks were positioned side by side approximately 203.2 mm (8 in.) apart. The concrete block shown on the left was attached to a manual traverse system whose displacement was measured by a digital dial gauge having resolution of 0.001mm (Shars 303-3506). The concrete block on the right was held stationary. The system was used to create a relatively linear displacement between the two concrete blocks by displacing the concrete block on the left while the concrete block on the right remained stationary. The relative displacement between the two concrete blocks was increased from 0mm to 2.0mm, with 0.1mm increments and was measured by both the digital dial gauge and the laser speckle strain sensor. The results are shown in Figure 8. The readings by the two devices (optical strain sensor and dial gauge) have excellent agreement. The differences between the two sensor's readings are below 4 microns over the entire measurement range, as shown in Figure 9.

Measurements at a Concrete Railroad Tie Plant

The production of pre-tensioned concrete rail ties is a highly automated process. A concrete tie plant is capable of producing thousands of railroad ties each day. In order for these pre-tensioned concrete ties to function adequately over their expected service life, the prestressing force must be fully introduced into the railroad tie at a location well before the rail load is applied. For the railroad ties that the research team tested, the rail load is applied at a distance of 558.8mm (22 in.) from the end of the tie, which means the "Transfer Length", defined as the length required to transfer the prestressing force into the concrete railroad tie member, must be less than 558.8mm (22 in.). Currently the concrete railroad tie industry does not conduct transfer length measurements except for occasional research purposes. This is due to the fact that there does not exist a transfer length measurement method that is able to keep up with the working speed of the production line.

To initially evaluate the feasibility of the in-plant transfer length measurements using the laser speckle strain sensor, a field trip was made to a concrete railroad tie production plant in Nebraska. Subsequent field testing, the results of which are presented in this paper, was conducted in June

2011 at a plant in Arizona. While at the first plant, the research team noticed that when the railroad ties went through the saw-cutting procedure, the railroad tie surface, on a microscopic surface profile level, underwent severe abrasions including wetting and vacuum lifting, as shown in Figure 10. This procedure caused dramatic physical changes to the tie surface. The change of the concrete's microscopic surface profile in turn caused difficulty in matching the speckle image pairs.

To avoid this problem, microscopic reflective particles were bonded to the railroad tie surface to serve as artificial speckle before the initial readings were taken, as shown in Figure 11. The particles were much less vulnerable to the severe abrasions than the concrete surface itself and helped keep the correlation that was critical for the laser speckle strain sensor to be functional in this situation.

The laser speckle device works best when measurements are taken on flat surfaces. To ensure the concrete surface was flat over the area where readings were taken, steel bars were placed on the concrete at the time of casting as shown in Figure 12. Once the concrete had cured, the bars were removed and a flat concrete surface was left along the line where readings would be taken.

In order to facilitate the laser-speckle measurements, three small 6.35mm (¼ in.) diameter inserts were cast into each of the railroad ties immediately after pouring the concrete mix. The inserts allowed a manual traverse to sit on the top of the member surface conveniently. The sensor was installed on the manual traverse and was able to slide freely on it, as shown in Figure 13.

Before detensioning the railroad ties, initial laser speckle readings were taken every 12.7mm (0.5 in.) for the first 381.0mm (15 in.) from the ends of each tie and every 25.4mm (1 in.) thereafter along the beam by traversing the laser speckle strain sensor on the rail manually. The 12.7mm (0.5 in.) spacing was somewhat arbitrarily selected. It provided better spatial resolution than the 50.8mm (2 in.) spacing used by the traditional Whittemore. The increased spatial resolution was made possible by the ease of use of the laser speckle strain sensor, and the fact that minimal (i.e., no time-consuming) surface preparation was needed. The increased number of measurement points with the closer spacing also made it possible to apply improved smoothing methods to better filter out random scatter in the data. In addition, the closer spacing range was extended to 381.0mm (15 in.), essentially encompassing the transfer length region

After the railroad tie was detensioned 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 total time for measuring one side of a tie was about 3 minutes. This was made possible because no high precision traverse setup was required and simple visual manual positioning was adequate.

Because the laser speckle sensor was able to take higher spatial resolution measurements at 12.7mm (0.5 in.) increments, the research team concluded that a different approach than that of the traditional Whittemore method was needed to obtain improved transfer length values. As previously mentioned, the 3-point average of Whittemore readings at a 50.8mm (2 in.) spacing resulted in an average reading over a 304.8mm (12 in.) length. To obtain a similar average over a 304.8mm (12 in.) length, the average of nine consecutive speckle readings was used as shown in Figure 14. The transfer length was then determined by applying the 95% Average Maximum Strain method (AMS 95%) to this smoothed strain profile (Russell and Ned, 1993).

Presentation of Data

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.

Some of the results obtained at the plant using laser speckle strain sensor can be seen in Figures 15 – 18. The difference in the strain profiles for the 3-point average and 9-point average are shown. The 9-point average method produces data that is more smooth and easier to work with. Transfer length values obtained for the 3 and 9-point average are very similar. Figures 15 and Figure 16 show the surface strain profile for tie number 3 on side B during the first cast. Figures 17 and Figure 18 show the surface strain profile for tie number 1 on side B during the third cast. This was the procedure that the research group used to name the ties.

The values of the transfer lengths obtained from all twelve pre-tensioned railroad ties by using the laser speckle can be seen in Table 1. The two different readings for each tie are from the two ends that we measured on each tie. The various tables are separated by the cast number and the tables show the correlation between the 3 and 9-point average methods.

The average transfer length using the 3-point average was 213.4mm (8.4 in.) with a standard deviation of 66.0mm (2.6 in.). The average transfer length using the 9-point average was 221.0mm (8.7 in.) with a standard deviation of 66.0mm (2.6 in.). These values were considerably less than the rail seat distance of 558.8mm (22 in.). After analyzing the data from the railroad tie plant, it was determined that the transfer length values were satisfactory for each of the four concrete mix as well as wire types.

It can also be seen that 9-point average method appears to provide a more conservative estimation of the transfer length, by giving estimated values that are 3%-6% larger than those obtained using the 3-point average method. This is due to the fact that the averaging has an effect of lowering the surface strain profile in the vicinity of the transfer length. The 9-point average method lowers the strain profile more than the 3-point average method does, thus producing a larger transfer length estimation value.

Because the 9-point average method is easier to work with and better in dealing with outlying data points, the research team prefers the 9-point average method in calculating the transfer length value.

Discussion

The transfer length measurements conducted on pre-tensioned concrete ties at a railroad tie plant showed that the laser speckle technology provides a convenient and accurate mean to measure transfer length. The resolution of the transfer length determination depends mainly on two factors: 1. the resolution of the laser speckle sensor; 2. the estimation algorithm that is used to extract the transfer length value from the measured surface strain profile. As discussed previously and shown in Figure 7, the laser speckle sensor can achieve a resolution as high as 4 microns, or 20 microstrain if converted into strain using the nominal gauge length of 203.2mm (8 in.). With respect to the transfer length estimation algorithm, the 95% Average Maximum Strain method (AMS 95%) is the classical or traditional method used in the industry. However, this traditional transfer length estimation algorithm requires human intervention and is subject to possibly significant human error. A more accurate and reliable transfer length estimation algorithm using an unbiased statistical approach is currently under development.

The laser speckle technology proved to be a rapid and robust method to measure the transfer length of pre-tensioned concrete railroad ties, with short setup time and little preparation. The laser speckle sensor can be easily positioned on the concrete ties with the help of a manual traverse system, to take readings before and after detensioning. In fact, it only takes a couple of minutes to obtain transfer length measurements for each tie. The simplicity and speed of taking readings is vital if this procedure is to eventually be incorporated into industrial plant operation.

Because the laser speckle technique has been tested extensively both in a laboratory environment and in the field with favorable results, we are currently at the stage of development where it is possible to automate the transfer length measurement process. This will be accomplished by mounting the laser speckle sensor on a computer-controlled traverse. With the laser speckle sensor moving along the concrete railroad tie, the surface strain information can be automatically collected and the transfer length can be determined without human interference. An automated process would expedite the measurement process as well as give more accurate results. This would also be appealing to prestressing plants due to the ease of taking measurements in a short amount of time, so as to not disrupt production flow. Moreover, the very real possibility now exists of using the transfer length measurement as a quality control practice on a production basis.

Acknowledgements

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Cast 1

	Transfer Length (mm)	
	3-Point Average	9-Point Average
Tie 1-1	241.3	254.0
	368.3	355.6
Tie 1-2	177.8	203.2
	114.3	114.3
Tie 1-3	152.4	152.4
	241.3	254.0
Average	215.9	223.5

Cast 2

	Transfer Length (mm)	
	3-Point Average	9-Point Average
Tie 2-1	215.9	228.6
	330.2	304.8
Tie 2-2	340.4	373.4
	215.9	241.3
Tie 2-3	193.0	190.5
	203.2	203.2
Average	248.9	256.5

Cast 3

	Transfer Length (mm)	
	3-Point Average	9-Point Average
Tie 3-1*	165.1	177.8
Tie 3-2	203.2	190.5
	195.6	210.8
Tie 3-3	129.5	132.1
	190.5	203.2
Average	177.8	182.9

Cast 4

	Transfer Length (mm)	
	3-Point Average	9-Point Average
Tie 4-1	114.3	114.3
	203.2	215.9
Tie 4-2	266.7	279.4
	221.0	266.7
Tie 4-3	190.5	190.5
	203.2	215.9
Average	200.7	213.4

Table 1: Transfer length measurements using the 3 and 9-point average method. One side of Tie 3-1 was not measured because the inserts that were cast into the tie to facilitate the traverse positioning had worn off.

Captions

Figure 1. Transfer zone on the pre-tensioned concrete railroad tie

Figure 2. Typical layout of Whittemore points

Figure 3. Speckle generation principle

Figure 4. Speckle pattern

Figure 5. The laser speckle strain sensor prototype

Figure 6. Strain measurement

Figure 8. Comparison of laser speckle strain sensor and digital dial gauge

Figure 9. Difference between optical strain sensor and digital dial gauge measurements

Figure 10. Severe abrasions to the railroad tie surface at the saw-cutting machine

Figure 11. Railroad tie surface bonded with microscopic reflective particles

Figure 12. Inserts for laser speckle device

Figure 13. Laser speckle strain sensor mounted on a manual traverse

Figure 14. Layout of laser speckle readings

Figure 15. 3-point average of tie number 3 in cast 1

Figure 16. 9-point average of tie number 3 in cast 1

Figure 17: 3-point average of tie number 1 in cast 3

Figure 18: 9-point average of tie number 1 in cast 3

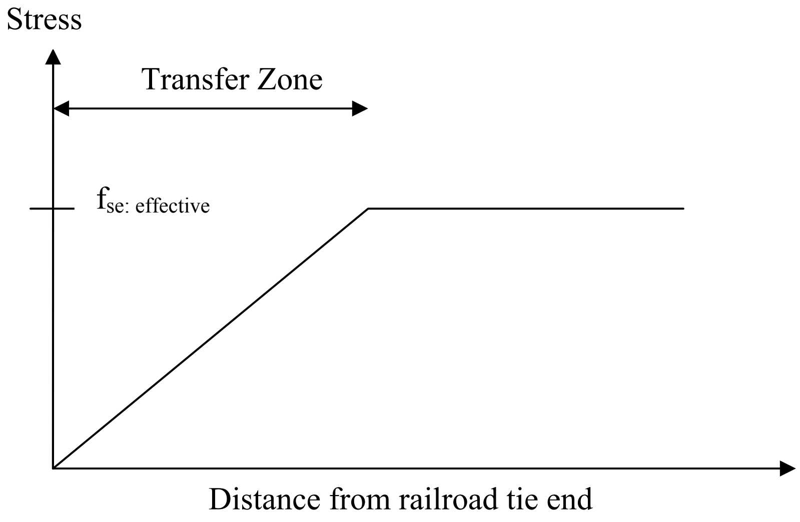


Figure 1. Transfer zone on the pre-tensioned concrete railroad tie

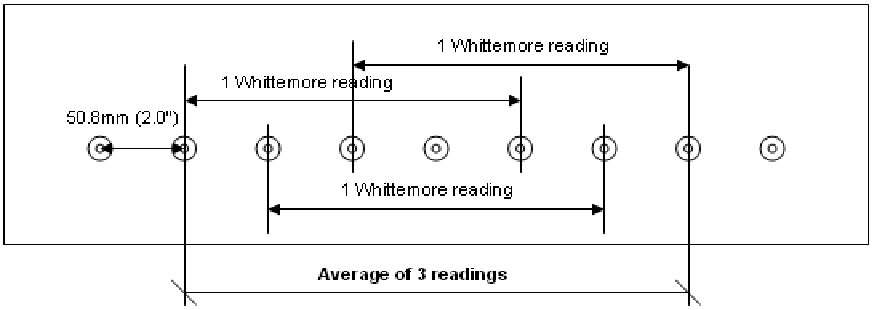


Figure 2. Typical layout of Whittemore points

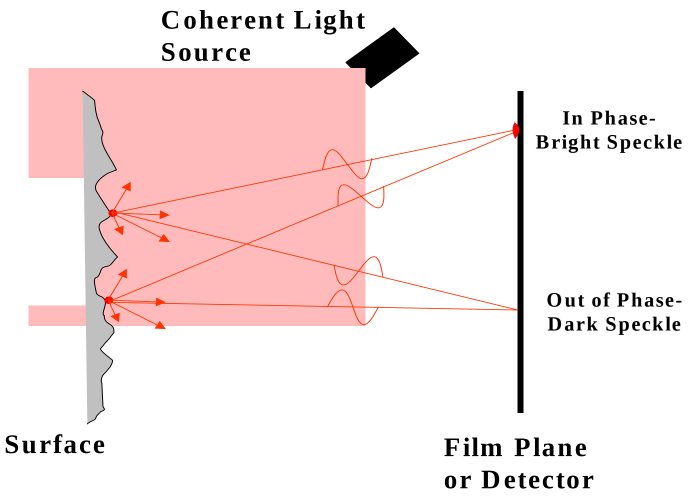


Figure 3. Speckle generation principle

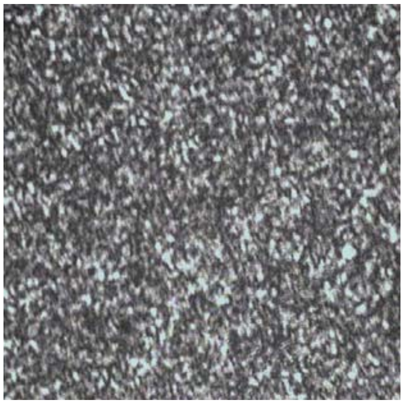


Figure 4. Speckle pattern

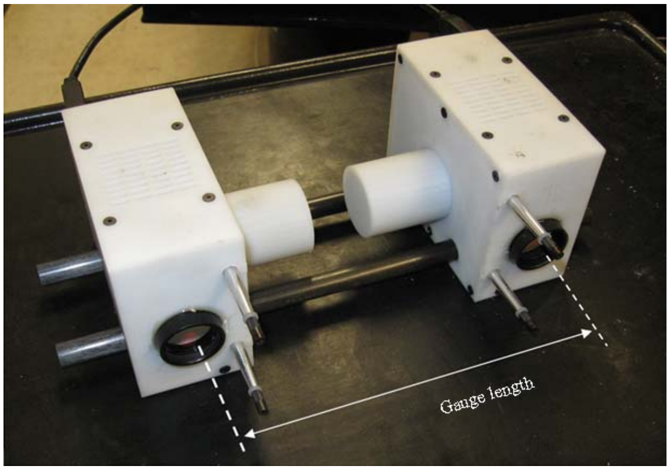


Figure 5. The laser speckle strain sensor prototype

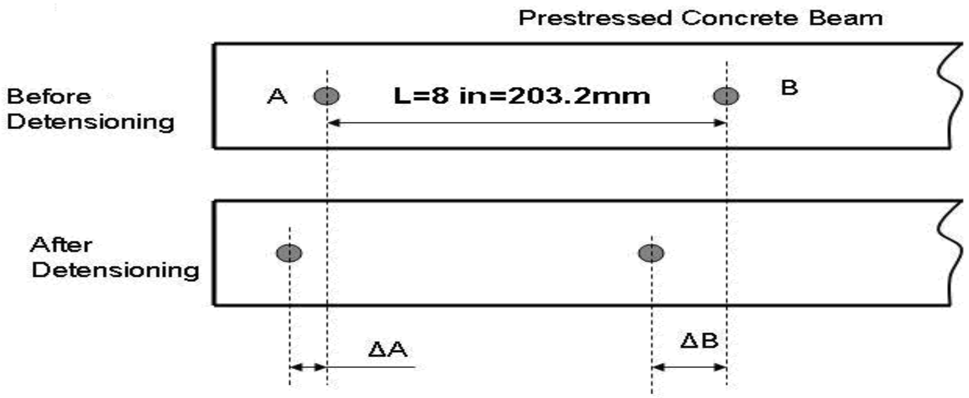


Figure 6. Strain measurement

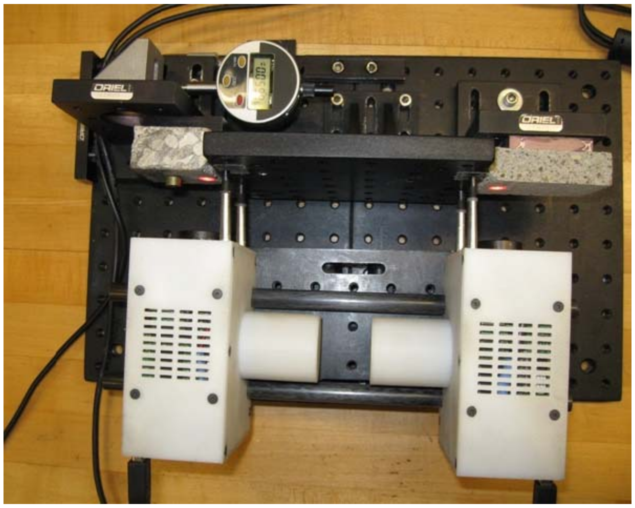


Figure 7. A two concrete blocks system for the validation of the optical strain measurement technology

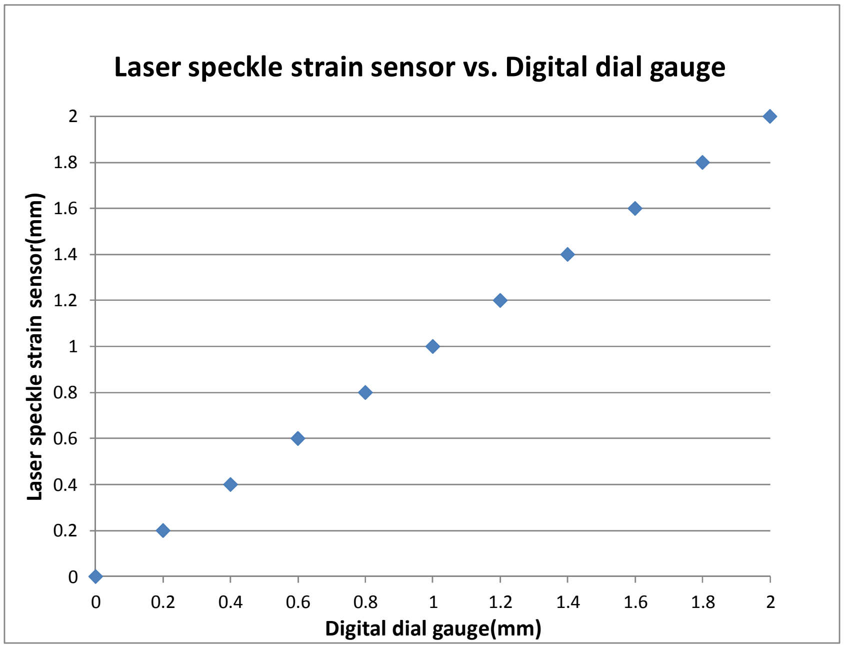


Figure 8. Comparison of laser speckle strain sensor and digital dial gauge

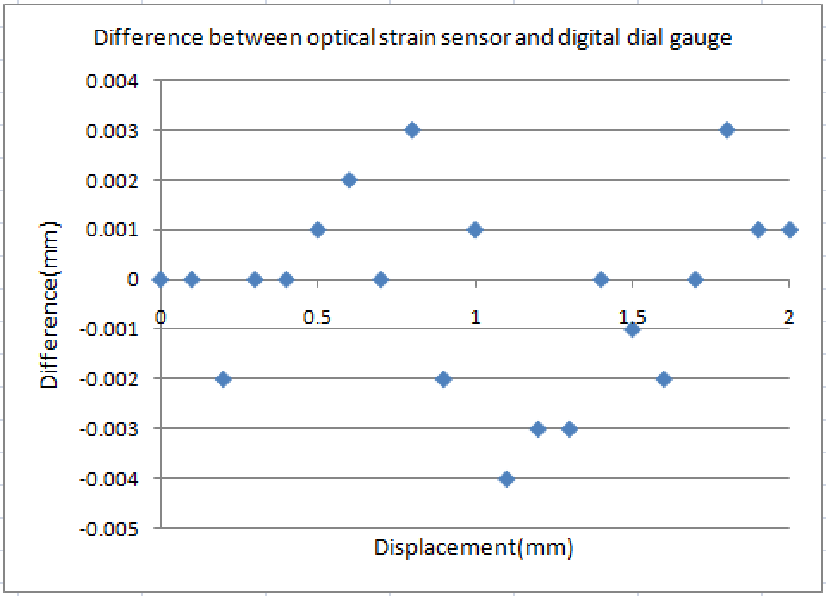


Figure 9. Difference between optical strain sensor and digital dial gauge measurements

(a) Cutting (b) Wetting and vacuum lifting

Figure 10. Severe abrasions to the railroad tie surface at the saw-cutting machine

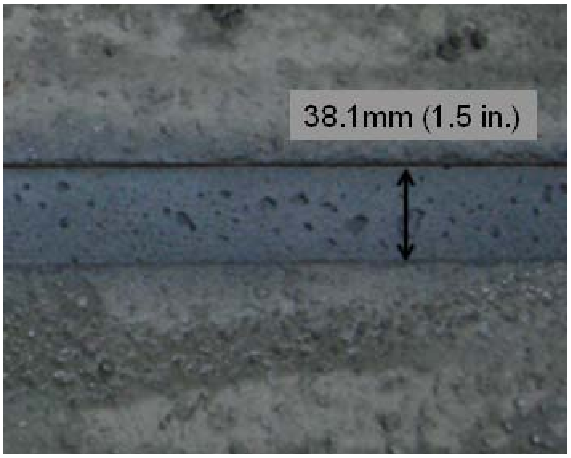


Figure 11. Railroad tie surface bonded with microscopic reflective particles

Figure 12. Inserts for the laser speckle device

Figure 13. Laser speckle strain sensor mounted on a manual traverse

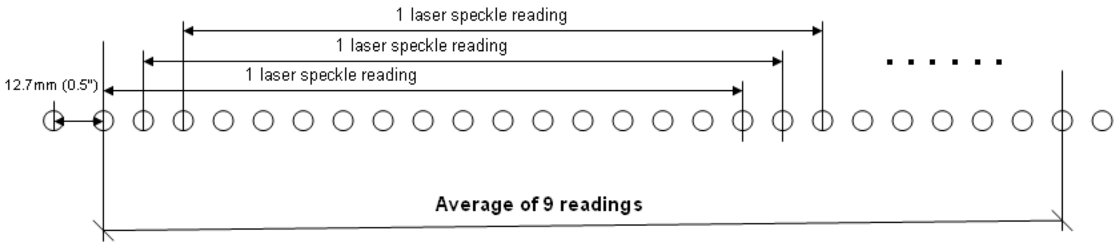


Figure 14. Layout of laser speckle readings

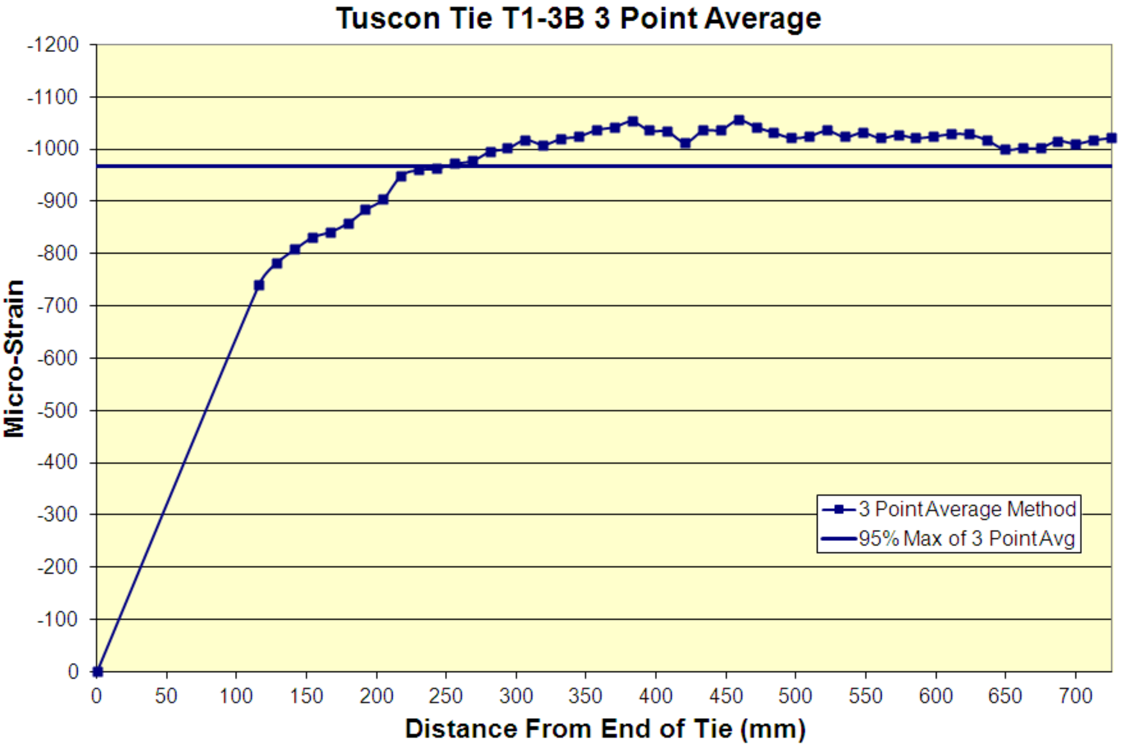


Figure 15. 3-point average of tie number 3 in cast 1

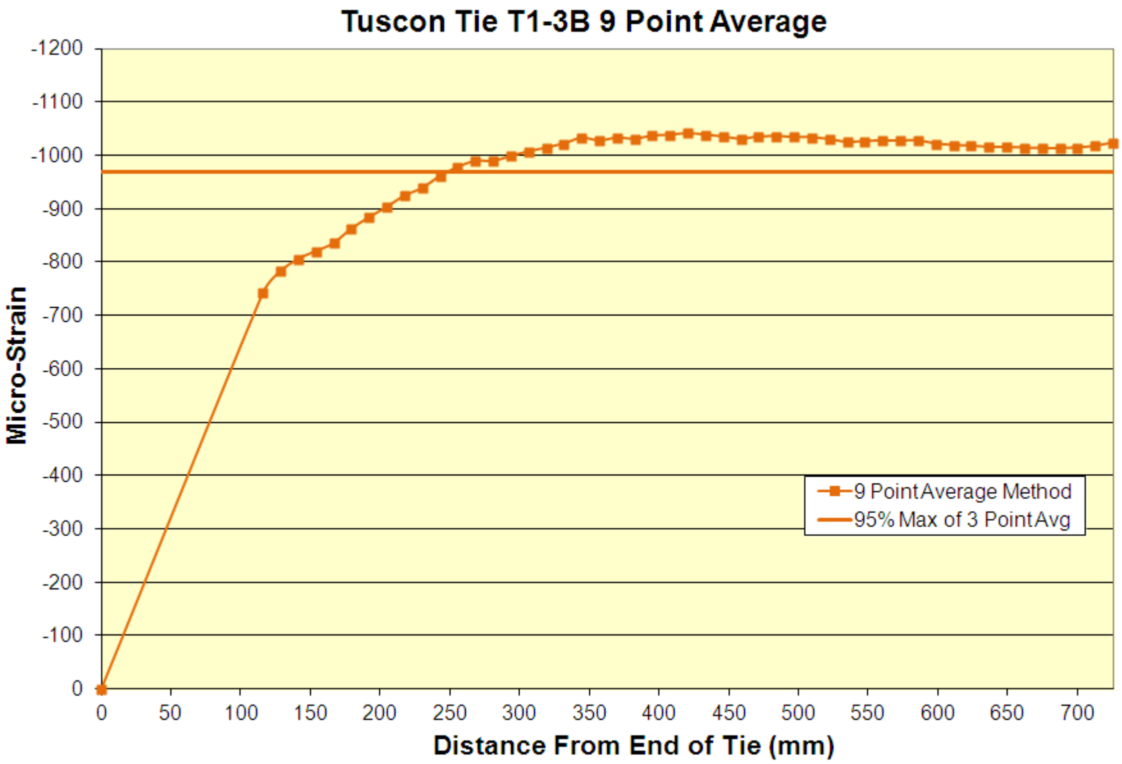
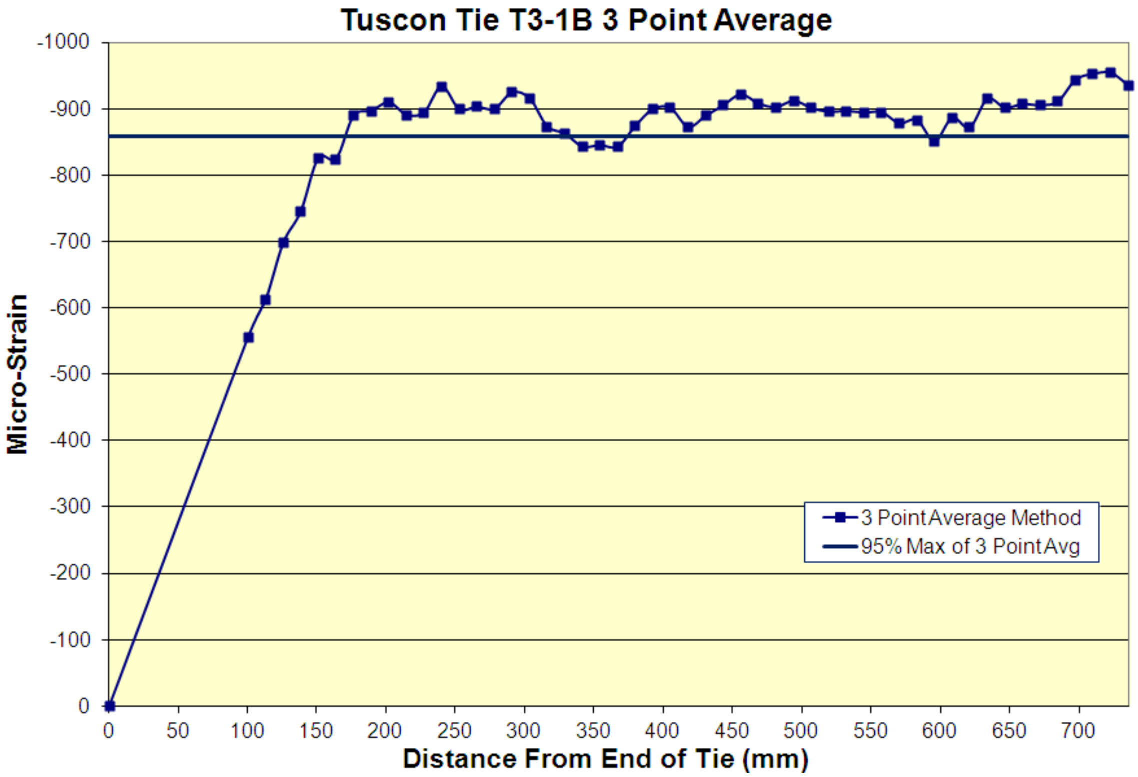
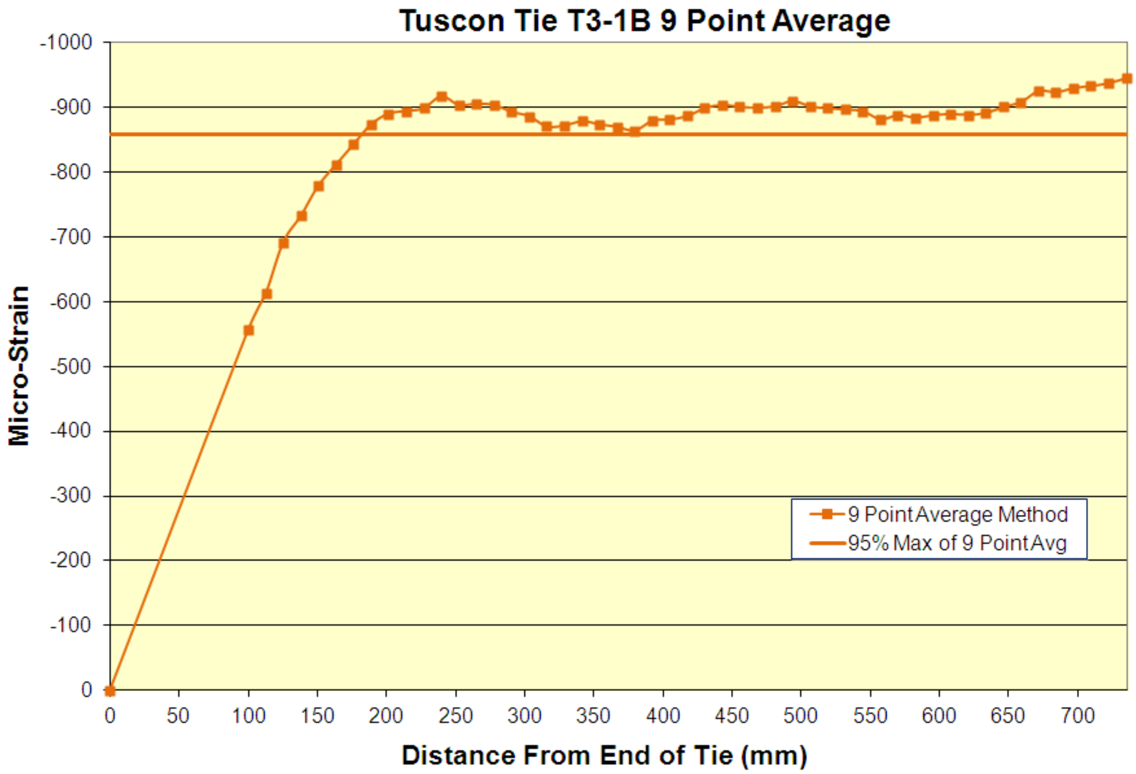


Figure 16. 9-point average of tie number 3 in cast 1



1

Figure 17: 3-point average of tie number 1 in cast 3



1

Figure 18: 9-point average of tie number 1 in cast 3