# Reliable Transfer Length Assessment for Real-Time Monitoring of Railroad Crosstie Production

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# RELIABLE TRANSFER LENGTH ASSESSMENT FOR REAL-TIME MONITORING OF RAILROAD CROSSTIE PRODUCTION

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## ABSTRACT

Automated in-plant diagnostic testing of prestressed concrete railroad crossties is now within reach due to recent progress in robust surface strain measurement techniques. The newly developed non-contact Laser Speckle Imaging (LSI) technique has been shown to provide rapid and accurate surface strain profile measurement, which is a key requirement for rapid transfer length assessment. Accurate determination of transfer length is critical for maintaining continuous production quality in the modern manufacture of prestressed concrete railroad crossties.

Conventional assessment of transfer length generally presumes the underlying existence of a bilinear prestressing force distribution and a corresponding bilinear surface strain profile. Furthermore, it is well-known that this bilinear profile is smoothed due to the effects of finite gauge length during the process of measuring surface strain. In addition, recent extensive crosstie measurements in concrete railroad tie plants have shown significant departures from this simple bilinear profile, which bring to question the general validity and reliability of the traditional 95% AMS (95% Average Maximum Strain) method. Deviations from the simple bilinear profile shape were shown to be partially due to the non-prismatic shape of typical concrete railroad ties. In addition, extensive comparisons between predicted and measured surface strain profiles on numerous crossties suggest that the underlying strain distribution for crossties is best represented by an exponential strain profile, with an asymptotic approach to the fully-developed compressive strain. This is in contrast with extensive testing of prisms with fixed cross-section and fixed prestressing wire eccentricity, for which the surface strain appears to be best represented by the simple bilinear strain profile.

Clearly, departures from non-prismatic behavior have added complexity to transfer length measurement. If accurate and reliable measurements of this important quality control parameter are to be realized, these issues of transfer length uncertainty need to be addressed. This paper provides an experimental comparison of several possible alternative transfer length assessment procedures, in an attempt to answer important uncertainty questions which need to be addressed if rapid real-time transfer length is to be achieved. It is shown that in spite of considerable differences in the transfer length processing methods, and significant departures from prismatic behavior, the averaged results are in many cases consistent with the simple bilinear underlying strain profile assumption. Bias in the measurement of crosstie transfer length due to non-prismatic behavior will also be investigated in this paper.

## INTRODUCTION

Pre-tensioned concrete railroad ties are fabricated by casting concrete around already tensioned steel wires or strands. The stress transfers from the wires or strands to the concrete and is developed gradually from each end of the concrete tie, where the stress is zero, to locations well away from the ends where the stress reaches its full value. The length required to fully develop the prestressing force is defined as the ***transfer length*** [1,2,3]. In order for the prestressing force to be fully introduced into the railroad tie at a location well before the rail load is applied, the transfer length should be shorter than the distance from the rail seat to the end of tie. In most cases, the rail seat is 21 in. from the end of the tie [4].

The transfer length determination procedure consists of two steps. First, the surface strain distribution along the pre-tensioned concrete railroad ties is measured by using various mechanical, electronic or optical sensors [6,7,8,9]. The surface strain profile is then plotted and the transfer length value is extracted by using some prescribed computational algorithm. The most commonly used algorithm for assessing the transfer length is the 95% AMS (95% Average Maximum Strain) method [5], which inherently assumes a bilinear shape for the surface strain distribution. This bilinear shape is characteristic of prismatic beams, which exhibit a well-defined plateau region. Furthermore, a critical step in the implementation of the 95% AMS method is to identify the location of this plateau region that separates the two sections of the strain distribution into an approximately linearly increasing development region from the strain plateau [5]. This step enables evaluation of the Average Maximum Strain (AMS) required by the method.

Extensive measurements of the strain distribution on hundreds of prestressed concrete railroad ties, during field trips to all six major concrete railroad tie plants in the U.S. [9], have shown that most of the strain profiles deviate significantly from the bilinear strain profile shape assumed by the traditional 95% AMS method. Figure 2 shows a representative strain profile (full length, from end to end, 3-point boxcar averaged data) obtained from in-plant measurements on a prestressed concrete railroad tie. Note that when determining the transfer length for one end of the concrete tie, only half side of the plot is needed. The strain curve not only lacks an obvious plateau section but also exhibits several bumps. This kind of curve pattern is repeatedly observed in essentially all of the strain profiles we have measured on prestressed concrete crossties. Since the determination of a distinct plateau section in the strain profile is necessary to perform the 95% AMS method, the ambiguity in determining the plateau section makes it hard to implement the 95% AMS method on these strain data consistently and in an unbiased manner. Consequently, the resulting transfer length estimation will be subject to significant uncertainty. Furthermore, the assessment of the AMS for the plateau clearly will depend on the distance from each end over which measurements of the strain field are taken.

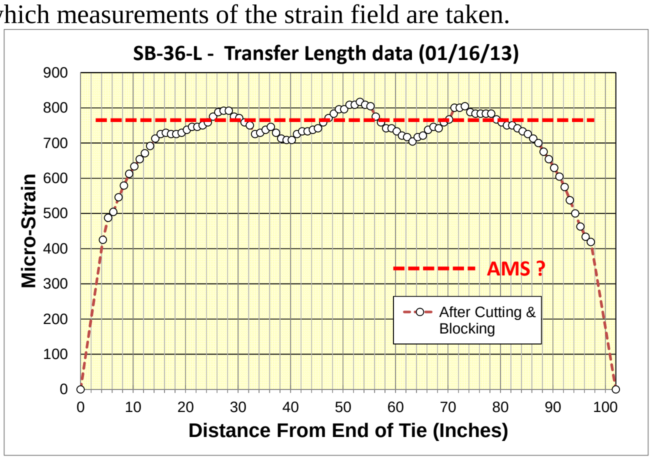


**Figure 1: A typical strain profile obtained from the prestressed concrete railroad tie (from end to end)**

For prismatic members, a statistically-based transfer length determination method, called the 'Zhao-Lee' (or ZL) method was developed and has been shown to produce unbiased and more accurate transfer length estimation than the 95% AMS method [9]. More recently, this method was generalized to include the non-prismatic behavior associated with concrete members, and in particular concrete crossties [12], in addition to allowing for an arbitrary underlying prestressing force distribution. The general curve-fitting procedure was illustrated on both real prism test data, as well as on actual in-plant crosstie surface strain measurements.

For prisms, it was shown that surface strain data appears to be somewhat better represented by a bilinear underlying prestressing force distribution. For non-prismatic members, in particular for railroad crossties, it was also shown that the exponential prestressing force distribution appears to best represent measurements of surface strain. For crossties, it was also shown that, consistent with the actual strain measurements, the surface strain is characterized by a series of bumps which significantly alter the strain profile from that of a prestressed prismatic member. These bumps, similar to those shown in the "plateau region of Figure 1, result from the varying cross-sectional area and prestressing wire eccentricity, and preclude accurate and reliable estimation of a so-called average maximum strain (AMS).

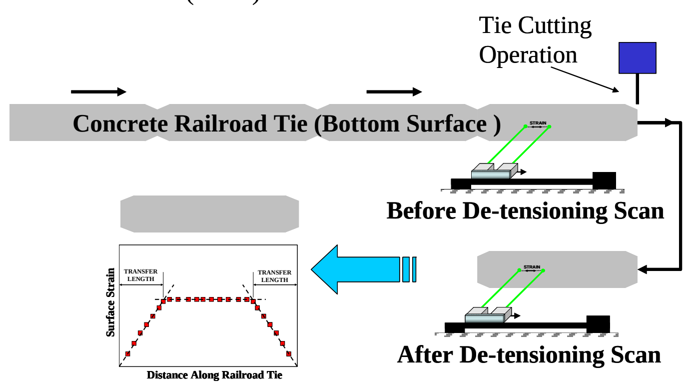


**Figure 2: Automated railroad tie transfer length measurement**

The development of the automated Laser-Speckle Imaging (LSI) sensor [7,8] has for the first time opened up the real possibility of in-plant assessment of transfer length for each and every manufactured crosstie. An example of such an automated system is shown schematically in Figure 2. Now that the strain measurement hardware has been successfully demonstrated, if accurate and reliable measurements of transfer length as a quality control parameter are to be realized, important issues of transfer length measurement uncertainty need to be given careful consideration.

This paper attempts to address some of the uncertainty issues associated with reliable transfer length measurement. Results are shown for several different variations of the previously developed modified ZL transfer length method [12] that have been applied to an extensive set of in-plant concrete crosstie measurements [9]. The crossties were manufactured with many different prestressing wire types, resulting in a wide range of transfer lengths. The surface strain measurements were obtained using the previously developed automated LSI system [7,8], shown in Figure 3.

 

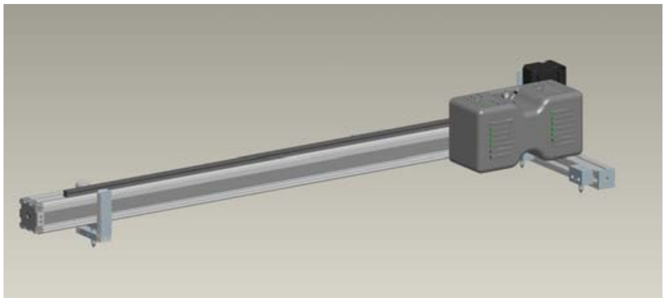

**Figure 3: The automated laser-speckle imaging (LSI) sensor mounted on a computer-controlled traverse**

Bias in the measurement of crosstie transfer length due to the non-prismatic behavior is also investigated in this paper, including the effect of the length of the strain measurement region and the importance of thermal strain compensation.

## THE NON-PRISMATIC CROSSTIE STRAIN PROFILE

The recently developed generalized Zhao-Lee method of transfer length assessment [12] accounts for the non-prismatic crosstie geometry, and forms the basis for the analysis of crosstie plant data given in this paper. For transfer length measurement, it is first necessary to represent the non-prismatic strain profile. Figure 4 shows a 3D (Abaqus®) model of a railroad tie that was built following the actual dimensions of a typical USA railroad concrete crosstie.

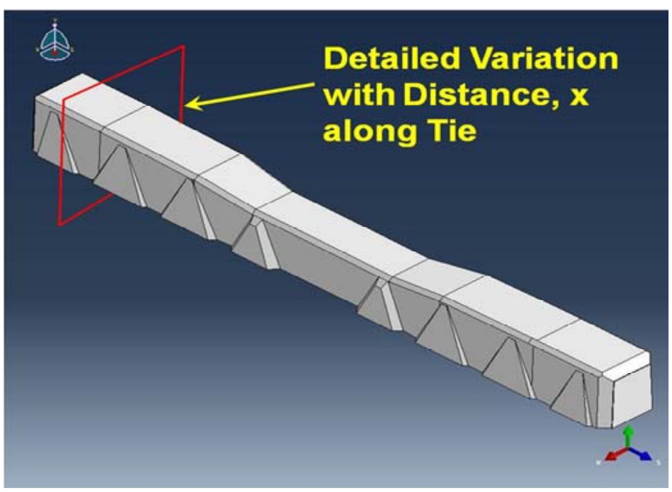


**Figure 4: 3D CAD model of concrete railroad crosstie**

At any given location along the railroad tie, the cross section is roughly the shape of trapezoid, as shown in Figure 5. The location of the centroid of the wire grid is illustrated as point C, *y* represents the distance from the centroid of the cross-section of the concrete tie to the bottom of the concrete tie, and *e* is the eccentricity, which is equal to the distance between the centroid of the multiple prestressing wire grid (typically 20 wires) and the centroid of the cross-section of the concrete crosstie. Since the tie is symmetrical about the middle section, these parameters only needed to be calculated from the 3D CAD model at 0.5 in. intervals from one end of the crosstie to the middle of the tie [12].

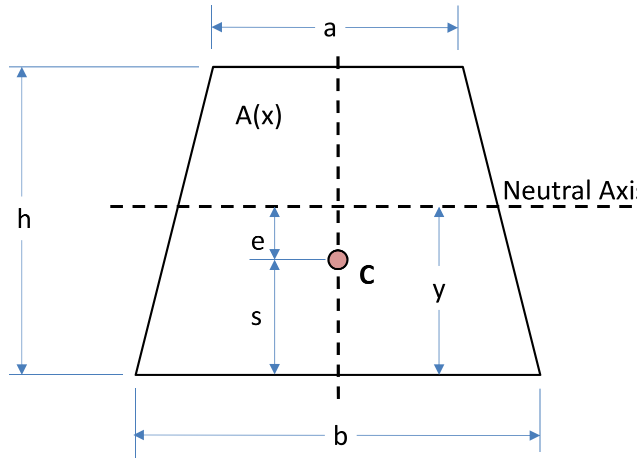


**Figure 5: Trapezoid shape representing crosstie cross sections**

Given the combined prestressing force in the wires at an arbitrary cross-section location, the surface strain on the bottom surface of a concrete tie at position *x* (the distance that the cross-section is from the end of the tie) can be calculated as

$$Strain(x) = \frac{P(x)}{E}\left[\frac{1}{A(x)} + \frac{e(x)y(x)}{I(x)}\right] \qquad (1)$$

where P(x) is the prestressing force or bond force at the location of x, E is Young's modulus, A(x) is the area of the cross-section, e(x) is the eccentricity of the wire grid centroid,

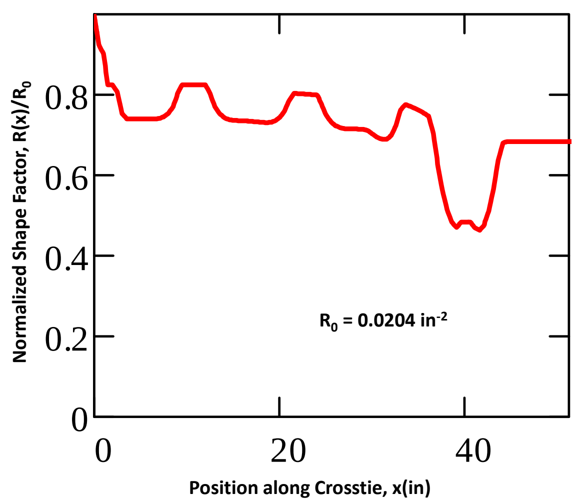


**Figure 6: Normalized Shape Factor for Crosstie**

y(x) is the distance from the bottom of the concrete tie to the neutral axis of the cross-section, and I(x) is the area moment of inertia of the cross-section of the concrete tie at position, x.

The effect of the non-prismatic crosstie geometry on the local surface strain given in Equation (1) can be expressed in terms of a shape factor parameter, R(x), as follows:

$$Strain(x) = \frac{P(x)R(x)}{E} \tag{2}$$

where R(x) is given by

$$R(x) = \frac{1}{A(x)} + \frac{e(x)y(x)}{I(x)} \tag{3}$$

For the crosstie, the shape factor varies as shown in Figure 6. A simple linear interpolation method was used to provide a continuous representation of R(x) in between the values calculated from the 3D CAD model at 0.5 in intervals.

In contrast to prismatic concrete members whose area and eccentricity of the cross-section remain constant, the area and eccentricity of the cross section of the railroad concrete tie vary from location to location. The overall trends in the cross-sectional area and the eccentricity are due to the non-prismatic shape of the concrete tie, while the local variation of the area and eccentricity are caused by the scallops on both sides of the concrete tie. In particular, before the seat location of the tie, the cross-section centroid is above the wire's centroid, giving a positive eccentricity; whereas after the seat location, the cross-section centroid is below the wire's centroid, giving a negative eccentricity. This shift in prestressing eccentricity is intentionally designed to offset the bending that the concrete crosstie would experience during service [10]. It is the variation of these characteristic parameters, and the resulting variation in the shape factor, that cause the strain profile of the concrete tie to deviate from the simple bilinear shape.

## THE GENERALIZED ZHAO-LEE ALGORITHM FOR TRANSFER LENGTH MEASUREMENT

The original ZL method was able to produce unbiased and more accurate estimation of the transfer length for prismatic concrete members [9]. The extension to non-prismatic concrete members [12] was developed by incorporating the above crosstie shape factor variation of the concrete member into the transfer length estimation algorithm. The method of accomplishing this, based on the simple strain relationship given in Equation (1), is summarized below.

Suppose the underlining prestressing force distribution in a prestressed concrete railroad tie has a trend represented by the function *P(x)*. The actual form of the function *P(x)* is difficult to measure experimentally, but a bilinear function has been in use in the classical transfer length determination methods for many years. Previous work has shown that the bilinear assumption is more characteristic of prisms [12], and an exponential distribution is perhaps more representative of crossties [11]; however, the bilinear prestressing force distribution has a well-defined and unambiguous transfer length location represented by the breakpoint in the bilinear function. It also represents perhaps the simplest prestressing force distribution shape. This simplicity, and the well-defined nature of the transfer length position, will be advantageous in investigating certain bias characteristics later in this paper. Therefore, it will be assumed that *P(x)* varies linearly over the transfer length zone, from zero at the end of the pre-tensioned concrete member to the maximum level, and is described by

$$P(x) = \begin{cases} \frac{x}{T_L} P_{max} & x \le T_L \\ P_{max} & x > T_L \end{cases} \tag{4}$$

where $T_L$ is the transfer length and $P_{max}$ is the maximum prestressing force, as shown in Figure 7. The determination of the transfer length is, in essence, the problem of determining the function *P(x)*, i.e. its parameters $P_{max}$ and $T_L$, given the measured strain data points.

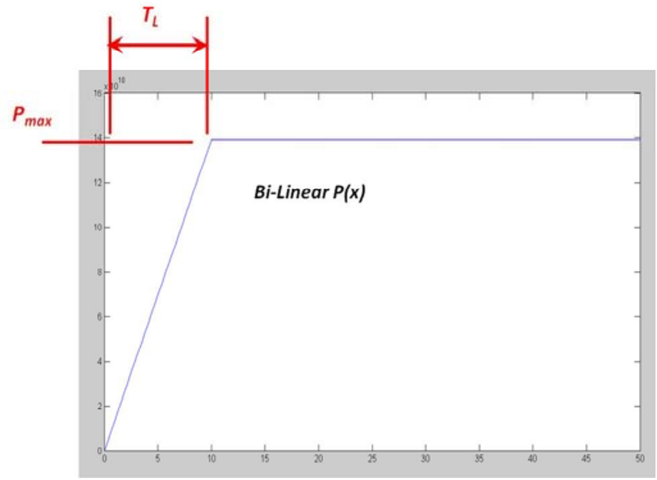


**Figure 7: Bilinear prestressing force distribution**

When using an ideal strain gauge of gauge length L to measure a strain profile, the measurements will be affected by gauge rounding [9], i.e. averaging of the strain across the finite gauge length. The strain, $S_{meas}(x, T_L)$, measured by an ideal strain gauge of gauge length L is given by

$$S_{meas}(x, T_L) = \frac{1}{L} \int_{x-\frac{L}{2}}^{x+\frac{L}{2}} Strain(x)dx \tag{5}$$

Taking the random error of the typical strain sensor into account, the ith strain measurement value $y_i$ at position $x_i$ will be $y_i = S_{meas}(x_i, T_L) + \varepsilon_i$ , where $\varepsilon_i$ is the random error. The random error is typically assumed to follow a normal distribution with mean zero and standard deviation $\sigma$ ; $i = 1...N$ . The Transfer Length Determination Problem for non-prismatic concrete members can then be stated as follows: Given a set of data points $(x_i, y_i)$, $i = 1...N$ , find $P_{max}$ and $T_L$ so as to minimize the mean squared error (MSE) between the function $S_{meas}(x_i, T_L)$ and the measured $y_i$ data. The MSE function is defined by

$$MSE(P_{\max}, T_L) = \frac{\sum_i (S_{meas}(x_i, T_L) - y_i)^2}{N} \quad (6)$$

The minimization problem can be solved using statistical techniques, similar to the process described in an earlier paper by the authors [9].

## EFFECT OF THERMAL STRAIN OFFSET ON TRANSFER LENGTH ASSESSMENT

Figure 8 shows an evaluation of the transfer length for the full-length crosstie measurements in Figure 1. The dashed line represents the direction application of the minimization relationship given in Equation (6). It is apparent that the fitted strain profile is not so well represented by the extracted parameters and, in particular, the transfer length assessment appears to be too short (only 12.5 in) as suggested by the rather steep rise in the strain profile near the crosstie ends. This results from the forcing of the strain profile through zero strain at each end of the tie. However, from the trend of the strain profile at each end of the tie, it appears that the strain should exhibit a strain offset at each end. The existence of this offset is due to the fact that frequently during the in-plant measurement process, considerably time passes between the baseline measurements (prior to de-tensioning) and those subsequent to the de-tensioning and cutting operation. There is thus sufficient time for appreciable cooling of the concrete tie, and this introduces a type of parasitic thermal strain or offset in the resulting strain measurements.

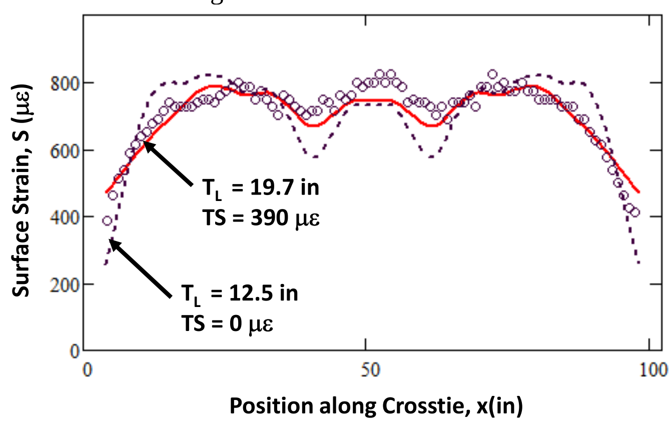


**Figure 8: Effect of thermal strain offset on full-length crosstie transfer length measurement**

To compensate for this effect, a thermal offset parameter, *TS*, is introduced into the expression for the measured strain as follows:

$$S_{meas}(x, T_L, \mathrm{TS}) = \frac{1}{L} \int_{x-\frac{L}{2}}^{x+\frac{L}{2}} \left[ Strain(x) + TS \right] dx \quad (7)$$

where *TS* is the effective thermal strain or offset shift. This introduces an additional unknown parameter into the MSE minimization procedure, resulting in the following more general expression:

$$MSE(P_{\max}, T_L, \mathrm{TS}) = \frac{\sum_i (S_{meas}(x_i, T_L, TS) - y_i)^2}{N} \quad (8)$$

Applying this more general algorithm to the data in Figure 7, then yields the red solid line shown in Figure 8, which exhibits a significant improvement in the fit to the measured strain data and a considerably longer transfer length (19.5 in). Clearly, the incorporation of this thermal strain effect can have a significant influence on the transfer length determination.

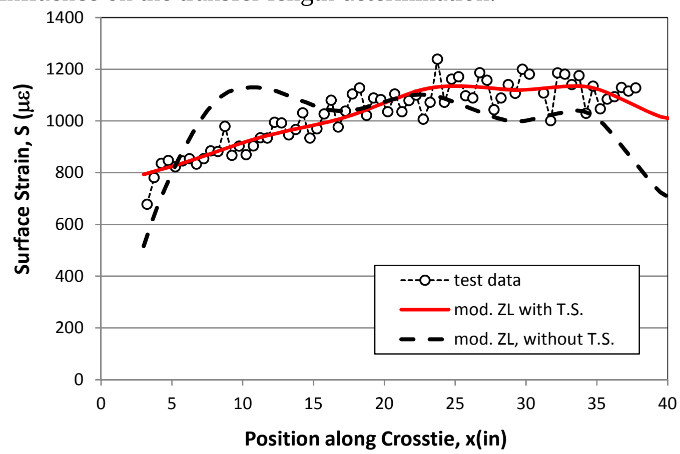


**Figure 9: Effect of thermal strain offset on typical in-plant crosstie data**

As an additional example of the significance of this thermal offset, consider the measured crosstie strain profile shown in Figure 9. The dashed line corresponds to the modified (generalized) ZL transfer length algorithm with no thermal offset, while the solid red curve includes a thermal offset parameter that is extracted during the minimization process associated with Equation (8). Without thermal offset, the resulting transfer length is only 6.3 in, whereas with thermal strain included the resulting transfer length is 24.9 in. With this much potential variation, it is quite clear that proper assessment of the thermal offset will be critical to accurate transfer length determination in an automated in-plant operation.

## BIAS ERRORS DUE TO NON-PRISMATIC RAILROAD CROSSTIE BEHAVIER

It is desired to investigate the possible bias error resulting from the complex strain profile exhibited by the non-prismatic crossties. The original ZL transfer length processing algorithm assumed an underlying bilinear surface strain profile, which is the traditional shape used in all early methods of transfer length assessment. If the general non-prismatic strain profile represented by Equation (1) is assumed to be the "true" strain profile, and the "true measured" strain profile is assumed to then correspond to Equation (5), then it is of interest to see how an effective bilinear strain profile would do in capturing the transfer length. This will be investigated here along with the effect of the length of the strain measurement region on the transfer length bias error. For simplicity, thermal strain offset effects will not be considered here.

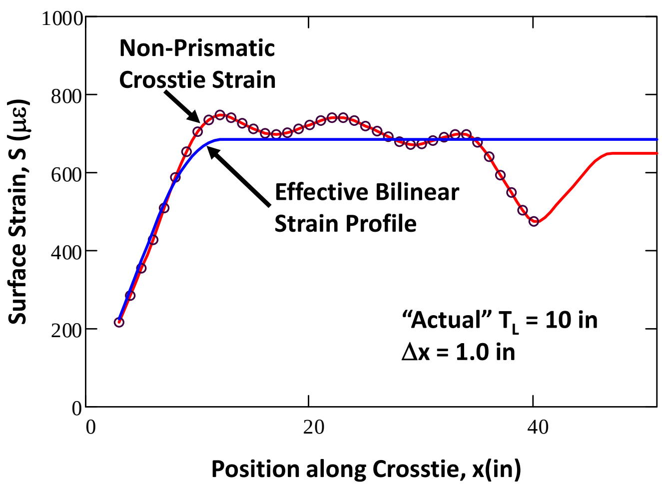


**Figure 10: Comparison of non-prismatic strain and effective bilinear strain profiles ($L_{meas}$ = 40 in)**

Figure 10 shows an example of the predicted "true" crosstie strain field over a measurement length of $L_{meas}$ = 40 in, with an underlying bilinear prestressing force distribution and a "true" transfer length of 10.0 in. The data points represent ideal surface strain measurements taken at 1.0 in intervals over the measurement length, with a gauge length of L = 6.0 in. The solid blue curve represents an effective bilinear strain profile fitted to the more general non-prismatic profile using the general MSE minimization procedure described above. For the effective bilinear strain profile, the shape factor reduces to a constant—corresponding to a fixed cross-section prism. This procedure is representative of using the classical prismatic crosstie assumptions to fit to the actual non-prismatic crosstie strain distribution. The resulting transfer length is conceivably a function of the sampling interval, Δx, the length of the strain measurement interval, $L_{meas}$ , and the magnitude of the transfer length itself, although the affect of sampling interval is small.

Figure 11 shows a comparison of the predicted bias in transfer length assessment as a function of the magnitude of the transfer length for both a 30 in and a 40 in measurement length. The results were calculated for sampling intervals of 0.5 in, 1.0 in, 2.0 in, 4.0 in and 8.0 in, and for four different transfer length magnitudes of 5 in, 10 in, 15 in, and 20 in. For each measurement length, the predicted bias error (calculated transfer length minus "actual" transfer length) is negative. This would indicate that the measured transfer length would likely be lower than the actual transfer length. Furthermore, the trend in the bias error is to increase approximately linearly with the magnitude of the transfer length. For the 40 in measurement length, the potential bias errors are about 10% of the transfer length itself, whereas for the 30 in measurement length, the bias errors are only around 5% of the transfer length magnitude. The shorter (or truncated) measurement length encroaches less into the region of significant strain drop-off along the crosstie. Hence, there is likely to be less indicated bias error. The apparent scatter in the calculated points shown in Figure 11 is due to the effect of the different sampling intervals, Δx. The points represent averages of the calculated transfer length bias error over the different sampling intervals processed.

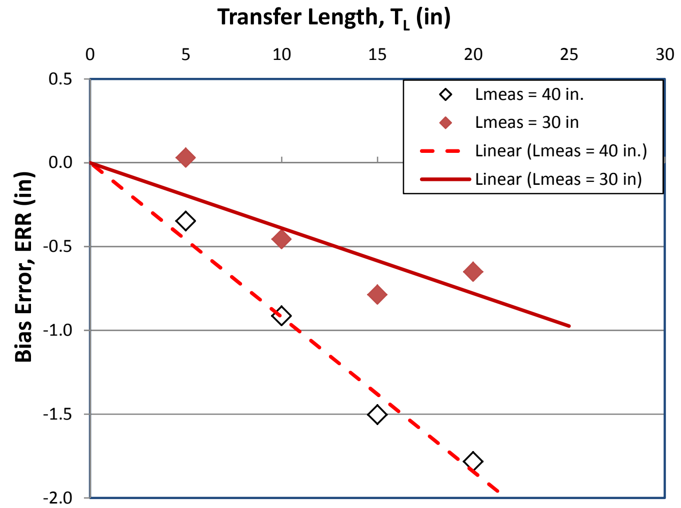


**Figure 11: Bias in traditional assessment of transfer length based on bilinear surface strain**

It should be noted that the bias error estimates shown in Figure 11 are likely worst case estimates, since they are based on the very simple 1D non-prismatic crosstie model. Clearly there are some deviations from this simple model observed in Figure 8, which shows the measured and predicted strain profile over the full length of a crosstie. These deviations appear to be more significant in the middle region of the tie, where the cross sectional area is smaller and there may be some "creep" effect taking place. This has yet to be verified.

## APPLICATION OF THE GENERALIZED ZHAO-LEE METHOD TO CONCRETE RAILROAD TIE STRAIN DATA

During field trips to all six major concrete tie plants in the United States, several hundred transfer length measurements were made using the manual Whittemore gage as well as using the automated Laser-Speckle Imaging (LSI) device [7]. Most of data were measured using the LSI device at the CXT concrete railroad tie plant in Tucson, AZ. In addition to these in-plant transfer length measurements on concrete crossties, extensive laboratory measurements on prisms have been conducted under more controlled conditions for the same wire types.

Figure 12 shows the results of laboratory measurements of transfer length on prisms, for a wide variety of different prestressing wire types. The prestressing wires in this Figure are organized according to basic wire indent pattern shape, and the measured transfer lengths range from about 5 inches up to in excess of 20 inches.

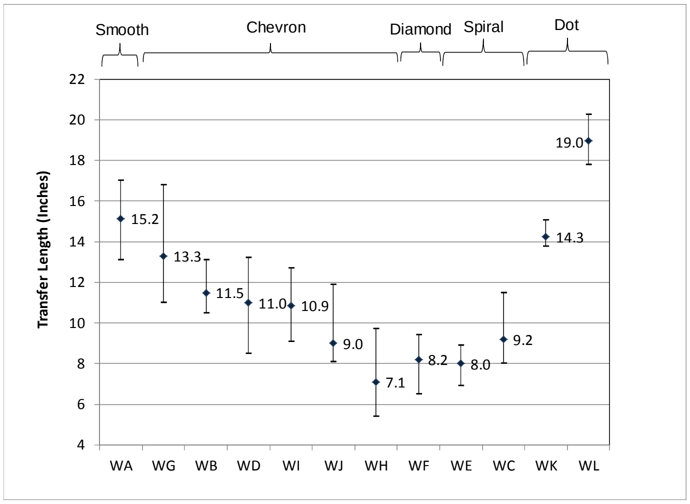


**Figure 12: Prism transfer length measurements for different types of prestressing wire**

Figure 13 shows, for comparison purpose, in-plant transfer length measurements on crossties for this same range of prestressing wire types. It is evident that there is a significant increase in the "scatter" in the measurements. This may be due to the inherent difficulties in conducting in-plant measurements in the harsh environmental conditions, along with issues such as significant thermal strain offset.

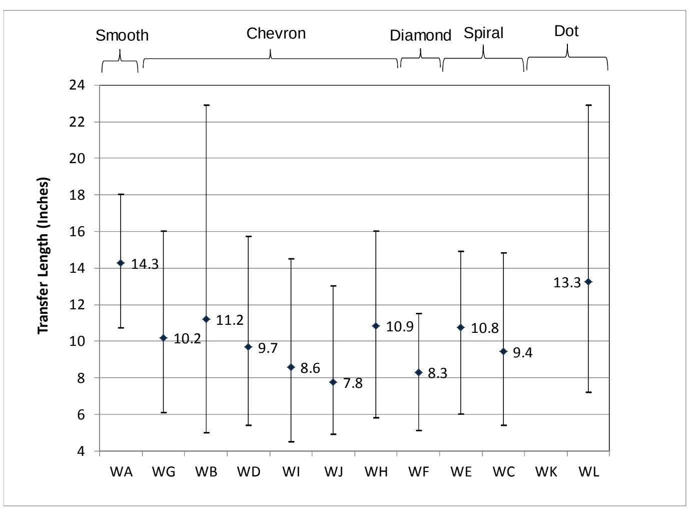


**Figure 13: In-plant crosstie transfer length measurements for different types of prestressing wire**

In an attempt to assess the significance of various transfer length processing issues, and potentially explain at least a portion of the scatter in the data shown, different processing algorithms were compared for the assessment of transfer length associated with the in-plant crosstie data. Figure 14 shows such a comparison, along with the combined data shown in Figures 12 and 13. The data shown in Figure 14 includes the prism and crosstie transfer length measurements in Figures 12 and 13, which were obtained using the traditional form of the ZL method with the inherently bilinear strain profile assumption. In addition, the generalized ZL method, which accounts for the non-prismatic crosstie cross-section behavior, was used both with and without the thermal strain offset compensation procedure. As can be seen from the results, the processing algorithms for the general non-prismatic profile case provide very little improvement in the scatter of the transfer length measurements. Hence, there is likely another influence, yet to be identified, which is the main contributor to this increased scatter (in comparison to the laboratory testing results on prisms).

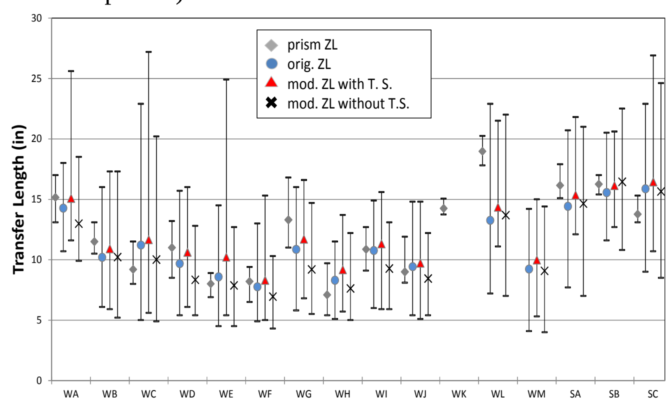


**Figure 14: Comparison of different transfer length processing algorithms for crossties and prisms**

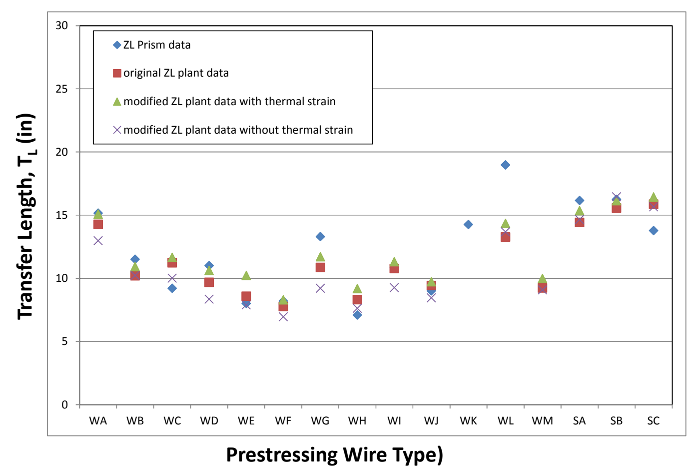


**Figure 15: Comparison of averaged transfer length measurement data for prisms and crossties**

In spite of the relatively large amount of scatter in the in-plant transfer length measurements, it is extremely interesting to note that the averages of the transfer length data (grouped by wire type and by measurement method) are in excellent agreement, as shown in Figure 15.

## CONCLUSION

In this paper the previously generalized form of the Zhao-Lee (ZL) method for transfer length evaluation was utilized to investigate errors in processing measured surface strain on concrete railroad crossties. Crossties represent non-prismatic members, and require consideration of the varying cross-section shape and the characteristics of the underlying prestressing force distribution for assessing the transfer length. The previously developed Mean Square Error (MSE) statistical algorithm was used to determine the transfer length, assuming an underlying bilinear prestressing force distribution for simplicity.

The importance of accounting for thermal strain offset was shown through a comparison of both full-range crosstie strain measurements as well as for measurements near one end of a typical crosstie. Large differences in the resulting transfer length were shown to exist when comparing both with and without thermal strain effects, indicating that compensation for thermal strain is extremely necessary to achieve accurate measurement of transfer length in a plant environment.

Bias errors resulting from application of the traditional bilinear strain field assumption were estimated through simulation using the general non-prismatic strain profile as the “true” strain field for comparison purposes. The effects of transfer length magnitude and strain measurement range were both considered, and the bias error was shown to be negative in all cases with a maximum magnitude of about 10% of the transfer length, depending on the measurement length.

Different processing algorithms, with and without thermal strain considerations, were used to evaluate transfer length measurements conducted on hundreds of crossties under actual in-plant field testing conditions, for a wide range of different prestressing wire types. It was shown that in spite of considerable differences in the transfer length processing methods, and significant departures from prismatic behavior, the averaged results were very consistent with the simple bilinear underlying strain profile assumption, and with the transfer length measurements on prisms obtained in a controlled laboratory testing environment.

This work represents a next step in an attempt to answer important uncertainty questions which need to be addressed if rapid real-time transfer length is to be achieved, and if such measurements of transfer length are eventually to be used in a practical in-plant production setting as a quality control parameter.

## ACKNOWLEDGMENTS

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