EFFECT OF SURFACE-STRAIN SAMPLING INTERVAL ON THE RELIABILITY OF PRETENSIONED CONCRETE RAILROAD TIE TRANSFER LENGTH MEASUREMENTS

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ABSTRACT

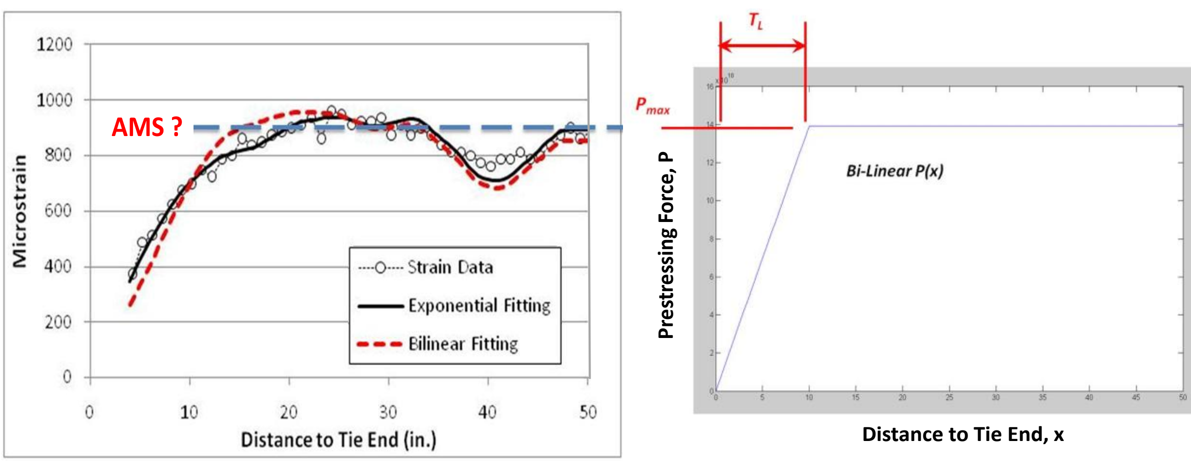
The feasibility of fully-automated in-plant transfer length measurement for prestressed concrete railroad cross-ties has been suggested from recent progress in the development of robust optical surface strain measurement. The non-contact Laser Speckle Imaging (LSI) technique provides rapid and accurate surface strain profile data—a key requirement if continuous monitoring of cross-tie transfer length is to be achieved in a production plant setting as a quality control parameter. Using an automated LSI system, strain data was taken at an unprecedented resolution of 0.5 inch increments during recent extensive in-plant crosstie testing. This provided a large data base for investigation of the minimum sampling interval required for accurate transfer length measurement. Using high-resolution in-plant strain data from a sampling of crossties,, the effect of sampling interval on transfer length assessment is evaluated and compared with previous theoretical analysis of transfer length measurement uncertainty. Statistical analysis of this real in-plant crosstie data shows that the influence of sampling interval on crosstie transfer length uncertainty agrees well with analysis developed earlier for constant cross-section prismatic members. Furthermore, these results indicate that it may be possible to rapidly and accurately assess transfer length with only a few discrete measurements of surface strain along the crosstie.

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

INTRODUCTION

Pre-tensioned concrete railroad ties are typically 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]. If the transfer length is longer than the distance to the rail seat, the load bearing capability of the tie is reduced and this may eventually cause failure in-track. The transfer length depends on a number of variables, including wire indent pattern characteristics, presence of lubricants on the wire, and properties of the concrete. The only way to tell if the transfer length is in the proper range is to assess it from the measured strain profile. Hence, for reliable long-term crosstie performance, transfer length potentially represents a critical in-plant quality control parameter if it can be accurately measured during production.

The transfer length determination procedure first requires that the surface strain distribution along the pre-tensioned concrete railroad ties be 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.



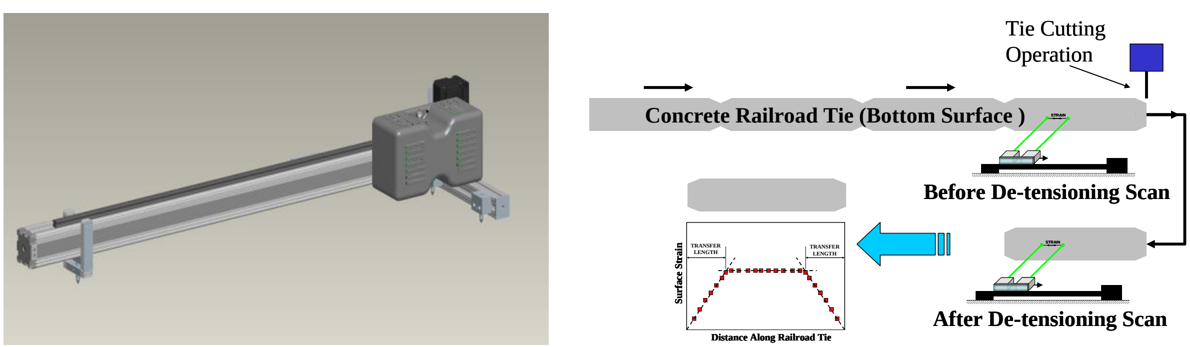
(a) Crosstie Strain Profile (b) Bilinear Prestressing Force

Figure 1: Typical Crosstie Strain Profile and Bilinear Prestressing Force Distribution

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. The strain curves not only lack an obvious plateau region, but they also exhibit several "bumps," as shown in Figure 1(a). This kind of strain profile has been repeatedly observed in essentially all of the strain profiles we have measured on prestressed concrete crossties. These bumps 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). The ambiguity in determining the plateau section (as suggested by the AMS? line in Figure 1(a)), makes it hard to implement the 95% AMS method consistently and in an unbiased manner.

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. It was also shown that for prisms, surface strain data appears to be reasonably well represented by a bilinear underlying prestressing force distribution, like that shown in Figure 1(b).

For non-prismatic members, such as concrete railroad crossties, the bumps observed in the surface strain profile preclude unambiguous identification of a strain plateau; however, the underlying prestressing force distribution does appear to exhibit a plateau behavior. Furthermore, based on a comparison between measured and predicted strain profiles, crossties have also been shown to be somewhat better represented by an exponential prestressing force distribution[11,12]. However, the simpler bilinear prestressing force distribution has the advantage of providing a well-defined and unambiguous transfer length distance and will be utilized in the analysis of experimental results presented in this paper.



(a) Automated LSI Strain Sensor (b) Future In-Plant Implementation

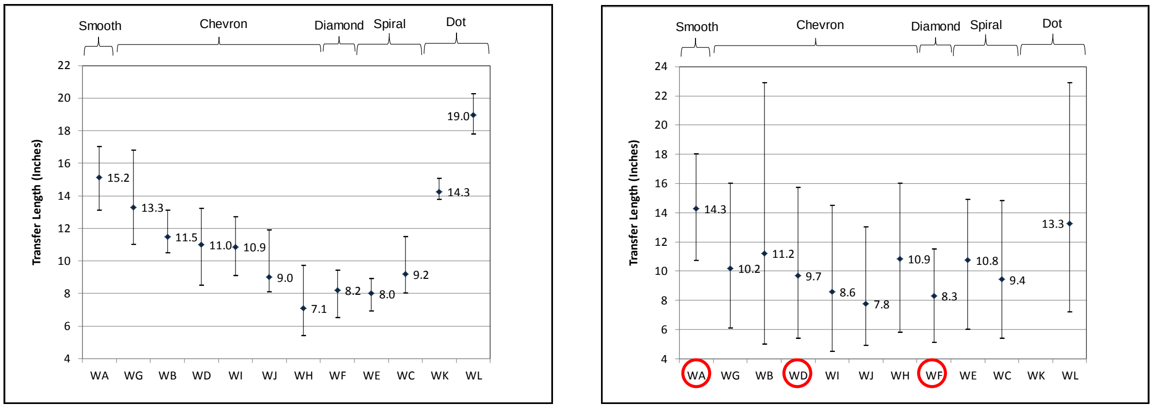
Figure 2: Fully Automated In-Plant Transfer Length Measurement System

The development of an 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. A CAD drawing of the current automated LSI system is shown in Figure 2(a), and the in-plant implementation of an automated system is shown schematically in Figure 2(b). If in-plant measurements of transfer length for use as a quality control parameter are to be realized, important issues of transfer length measurement uncertainty need to be given careful consideration.[12,13]

This paper attempts to further address the important uncertainty issues associated with reliable transfer length measurement. By means of the automated LSI system, it was possible to rapidly take data at an unprecedented resolution of 0.5 inch increments during recent extensive in-plant diagnostic testing[7,9,10,12,13]. This represents a large data base from which to extract useful additional experimental evidence on the influence that key parameters have on transfer length measurement uncertainty. The main objectives of this paper are to investigate, through the use of this in-plant transfer length data, the effect of strain measurement sampling interval, along with the applicability to crossties of theoretical transfer length measurement uncertainty analysis that was previously developed for prismatic members. A key question is what is the least number of point strain measurements required to make an accurate crosstie transfer length measurement. This has important implications associated with the development of a practical in-plant transfer length measurement system.

SELECTION OF IN-PLANT STRAIN MEASUREMENT DATA

During field trips to all six major concrete tie plants in the United States, several hundred transfer length measurements were made using strain measurements obtained using the manual Whittemore gage as well as the automated Laser-Speckle Imaging (LSI) device[7,9,10]. Most of the data were measured using the LSI device at the CXT concrete railroad tie plant in Tucson, AZ. The crossties were manufactured with many different prestressing wire types, resulting in a wide range of transfer lengths. 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.[7,8,9] Figure 4 shows a comparison between the laboratory prism test results and the in-plant transfer length measurement results.[13] The selection of transfer length data for the wire types used in the present analysis was made so as to cover a large transfer length range, and is denoted by the circled wire types in Figure 3(b). It is evident that there is a significant increase in the “scatter” associated with 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 offset due to thermal strain[13]. It should be noted, however, that on the average the transfer lengths for the prism data agree very well with the averages associated with each wire type for the in-plant measurements.[13]



(a) Laboratory Prism Measurements (b) In-Plant Crosstie Measurements

Figure 3: Transfer Length Measurements for Various Prestressing Wire Types

Three wire types were selected for the current sampling interval analysis. These are shown in Figure 4 and consist of types WA (smooth), WD (Chevron), and WF (Diamond). These correspond to the wire types identified in association with the transfer length data shown in Figure 3(b), and represent wires types that resulted in relatively long (WA Smooth), intermediate (WD Chevron) and relatively short (WF Diamond) transfer lengths. For each wire type, a sample of 7 crossties was included in the analysis, presenting 14 tie end transfer length measurements. For each of the three wire types analyzed, these crossties were selected from those located during casting in the central portion of the plant casing bed, as shown by the schematic in Figure 5.

(a) WA (Smooth) (b) WD (Chevron) (c) WF (Diamond)

Figure 4: Selected Wire Types for Transfer Length Analysis

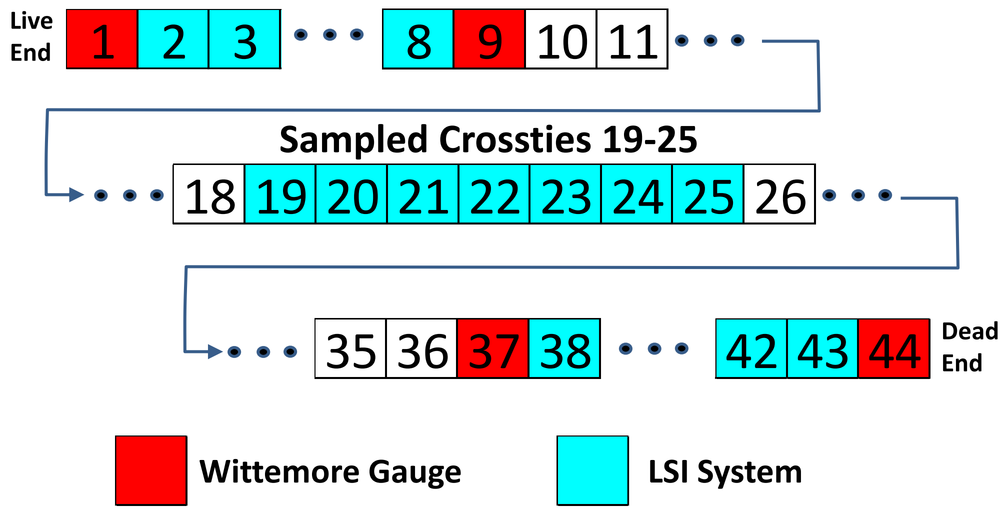


Figure 5: Plant Casting Bed Layout for Transfer Length Measurements

Selected crossties were also measured using the manual Whittemore gauge, and these are designated by the RED shading in Figure 5, whereas the ties measured using the automated LSI system are designated by the BLUE shading. The numbering shown represents the tie number from the LIVE end of the casting bed. Figure 6 shows how the measurements of transfer length for each crosstie vary from one end of the casting bed to the other. It was observed from these results that there was a tendency for the magnitude of the transfer lengths to increase near the ends of the casting bed. The reasons for this variation are not yet known. One possible explanation, although pure speculation at this point, is that it may be due to non-uniform heating of the bed. As a result of this phenomenon, it was decided to select the samples of crosstie strain measurement data from the central region of the bed comprised of crossties 19 – 25 as shown in Figure 6. It was thought that these would likely give the most unbiased set of results from which to investigate the effect of sampling interval on the uncertainty of transfer length measurement.

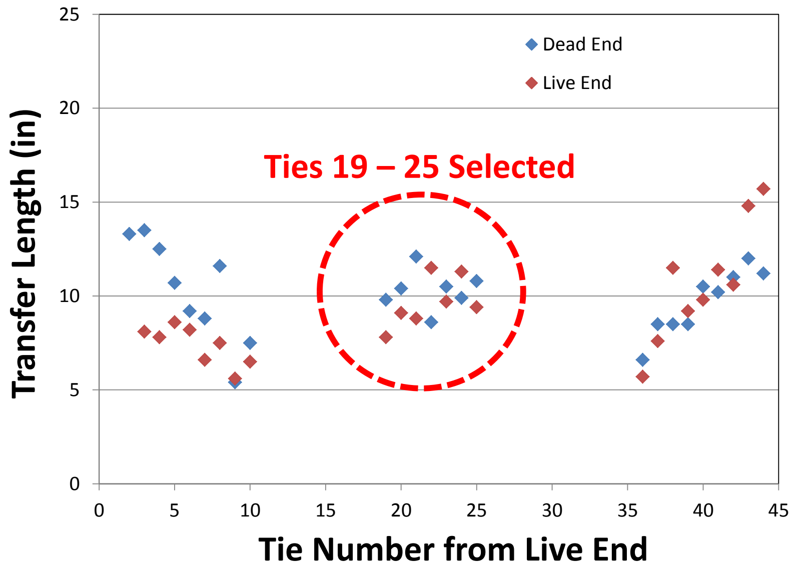
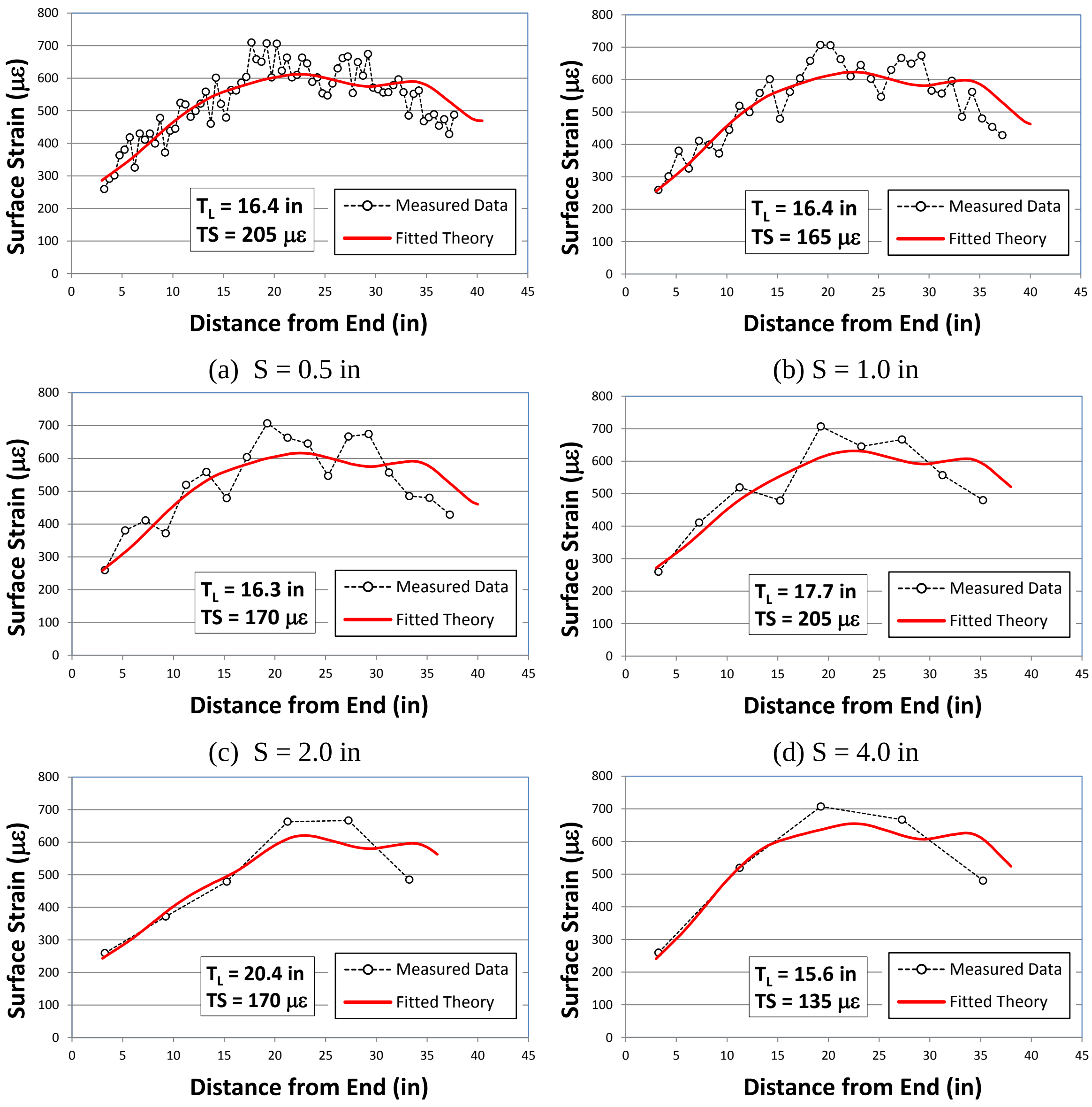


Figure 6: Typical Transfer Length Measurement Results Spanning the Full Casting Bed

EFFECT OF SAMPLING INTERVAL ON CROSSTIE STRAIN PROFILE

From the existing plant data, surface strain profiles for each crosstie selected were available to a maximum spatial resolution (i.e., sampling interval, s) of 0.5 inches. To investigate the effect of sampling interval size, s, on the resulting transfer length measurement, strain data was selectively removed from each overall crosstie sample in much the same manner as was done previously with laboratory prism data[13]. It should be noted, however, that the plant data consists of separate strain profile data for completely different crossties. The earlier sampling interval testing was obtained on a single laboratory prism, and repetitions of measurements were made on the same prism by moving the location of the starting point for LSI strain measurements. This resulted in an ideal statistically independent set of surface strain profile data with different sampling intervals obtained using the LSI system. With the current plant data, each of the centrally located crossties will be used to represent an independent sample of strain data for the same wire type. Thus, the crossties central to the casting bed (numbered 19-25) will now comprise an approximately independent sampling of strain profile data for each wire type testing. The usefulness of this in revealing the influence of sampling interval on the resulting transfer length measurement will be shown below.

Figure 7 shows some typical strain profile data for wire type WA (Smooth) data resulting from the procedure for selective removal of strain profile data described above. The procedure yields sampling intervals, s, of 0.5in, 1.0in, 2.0in, 4.0in, 6.0in, and 8.0in, as shown. The solid data points represent individual strain measurements, and the solid line represents a fit to the data using obtained using the Generalized Zhao-Lee method which uses a least-squares minimization algorithm to obtain an unbiased fit to the discrete strain profile.



(a) S = 0.5 in (b) S = 1.0 in

(c) S = 2.0 in (d) S = 4.0 in

(e) S = 6.0 in (f) S = 8.0 in

Figure 7: Effect of Strain Data Removal for Typical Strain Profile (WA-19-D Crosstie)

It is clear from Figure 7 that in spite of the severe removal of data, the basic shape of the profile, and more importantly the basic shape of the smooth curve fit to the discrete sample of strain data, remarkably remains intact even as the data is reduced to only a few measurements. The curve fit includes compensation for a thermal strain offset parameter, TS, which is included in the algorithm for transfer length assessment. The variation of transfer length, T_L , with sampling interval associated with the data shown in Figure 7, along with the balance of the data selected for analysis in this paper, will be investigated below both experimentally and theoretically.

EFFECT OF SAMPLING INTERVAL ON CROSSTIE TRANSFER LENGTH

Following the approach used in the generalized Zhao-Lee method of transfer length assessment[13], 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) is represented as

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

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, *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. Following this same analysis, 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

$$P(x) = \begin{cases} \dfrac{x}{T_L} P_{\max} & x \le T_L \\ P_{\max} & x > T_L \end{cases} \tag{2}$$

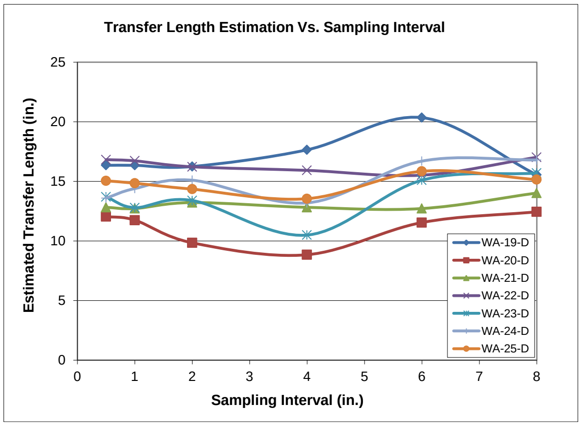
where T_L is the transfer length and P_{max} is the maximum prestressing force, as shown in Figure 1(b). The determination of the transfer length is, in essence, the problem of determining the function *P(x)*, i.e. its parameters P_{max} and T_L, given the measured strain data points.

In addition to the determination of the key parameters P_{max} and T_L, in-plant strain measurements have revealed the presence of an offset in the strain profile[13]. The existence of this offset is due to the fact that sometimes during the in-plant measurement process, considerably time lapses 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, denoted by the parameter *TS*, in the resulting strain measurements. To compensate for this effect, a thermal offset parameter, *TS*, is introduced into the expression for the measured strain as follows:

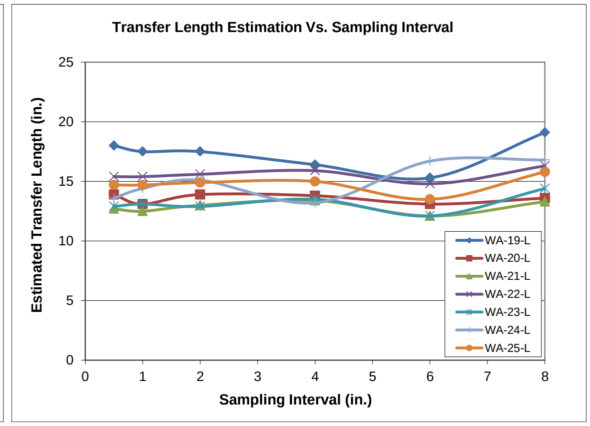
$$S_{meas}(x, P_{\max}, T_L, TS) = \frac{1}{L}\int_{x-\frac{L}{2}}^{x+\frac{L}{2}} \left[Strain(x) + TS\right] dx \tag{3}$$

where *TS* is the effective thermal strain or offset shift, and *L* is the gauge length of the LSI strain measurement system. This introduces an additional unknown parameter into the MSE minimization procedure, resulting in the following more general expression:

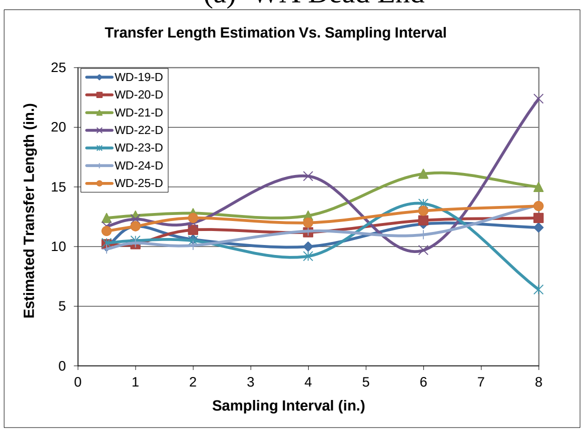
$$MSE(P_{\max}, T_L, TL) = \frac{\sum_i (S_{meas}(x_i, P_{\max}, T_L, TS) - y_i)^2}{N} \tag{4}$$



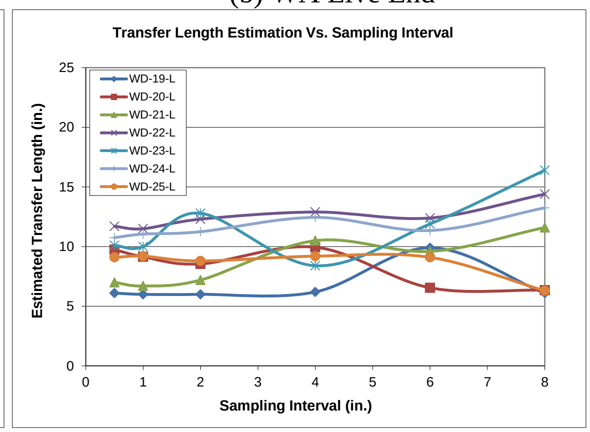
(a) WA Dead End



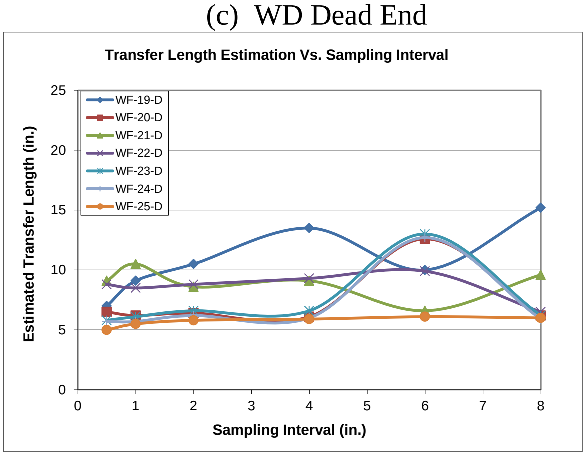
(b) WA Live End



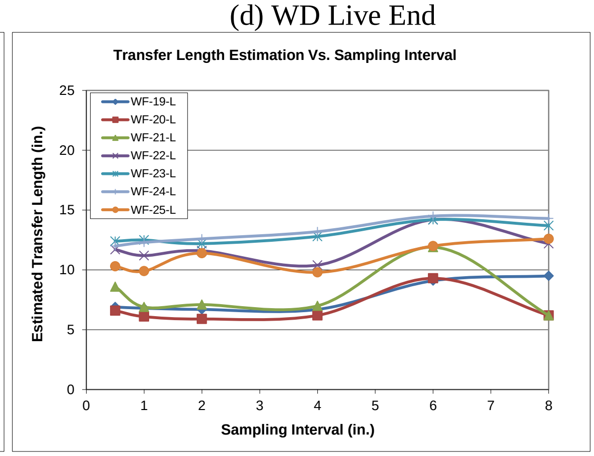
(c) WD Dead End



(d) WD Live End



(e) WF Dead End



(f) WF Live End

Figure 8: Transfer Length Estimation as a Function of Sampling Interval

Taking the random error of the typical strain sensor into account, the ith strain measurement value y_i at position x_i will be $y_i = S_{meas}(x_i, P_{\max}, T_L, TS) + \varepsilon_i$, where ε_i is the random error. The random error is typically assumed to follow a normal distribution with mean zero and standard deviation σ; $i = 1 \ldots N$. 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), $i = 1 \ldots N$, find $P_{\max}$, T_L and *TS*, so as to minimize the mean squared error (MSE) between the function $S_{meas}(x_i, P_{\max}, T_L, TS)$ and the measured y_i data. The MSE function is defined by the following:

$$MSE(P_{\max}, T_L, TS) = \frac{\sum_i (S_{meas}(x_i, P_{\max}, T_L, TS) - y_i)^2}{N} \tag{5}$$

Applying this general algorithm to strain data like that shown earlier in Figure 7, then yields the red solid line curve fit, along with the transfer length and thermal offset parameters.

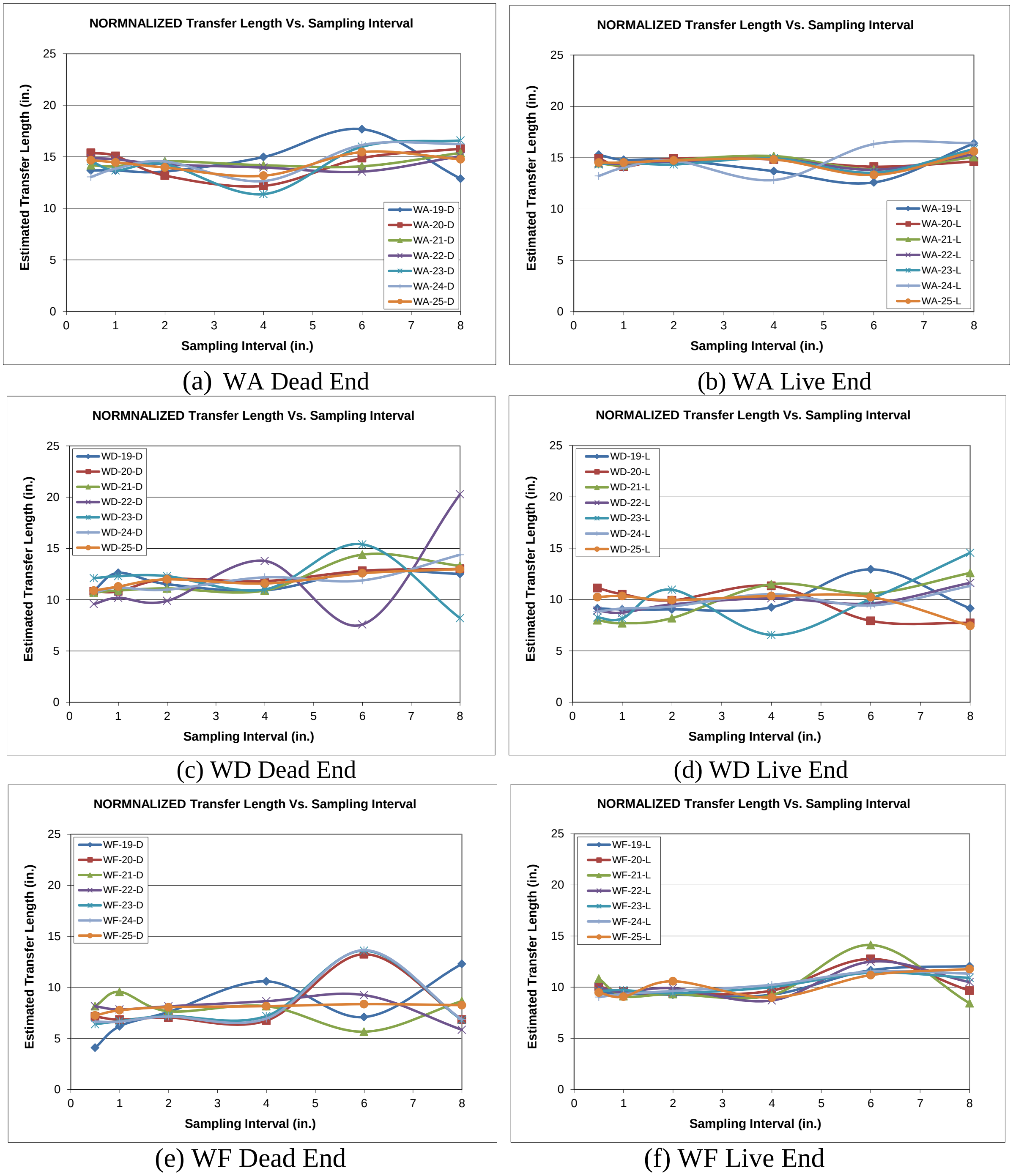
Figure 8 shows a comparison of the calculated transfer length as a function of the sampling interval for the crossties associated with the three different wire types WA, WD and WF. The separate Live-End and Dead-End measurements are also shown. Two completely different, but identically designed, LSI strain measurement systems were used to take the in-plant strain measurements, which greatly speeded up the collection of data. This was especially important for the baseline measurements taken prior to the detensioning and cutting operation. From the result in Figure 8, it is clear that there is variation in the transfer length as the amount of measured data is reduced in size, effectively reducing the sampling interval. However, it is also apparent that there is bias in the measurements from one crosstie to another. This may be due to individual crosstie differences, or due in part to differences in the two LSI measurement system uncertainties. It is particularly interesting to note that the variations from crosstie to crosstie are about the same as the variations resulting from the different sampling intervals.

EFFECT OF SAMPLING INTERVAL ON TRANSFER LENGTH VARIATIONS

To further investigate the effect of sampling interval, and distinguish this effect from the apparent bias variations associated with individual crosstie behavior, the transfer length measurements were normalized. The procedure is a common statistical normalization process[14] which removes the variations between crossties and adjusts the individual variations in transfer length around a common average transfer length according to the following:

$$T_L \leftarrow T_L - \left(\overline{T_{Li}} - \overline{\overline{T_{Li}}}\right) \tag{6}$$

where $\overline{T_{Li}}$ is the mean of the transfer length measurements using various sampling intervals for a given crosstie, and $\overline{\overline{T_{Li}}}$ represents the mean of the transfer length measurements for all the investigated crossties in the particular sample. Initially, the process was applied to the Live-End and Dead-End data separately, in case this might reveal some differences between the different LSI systems. Comparing the normalized results shown in Figure 9 with the original un-normalized and biased data shown in Figure 8, clearly indicates that the normalization process has reduced much of the bias associated with the individual crosstie measurements.



(a) WA Dead End (b) WA Live End

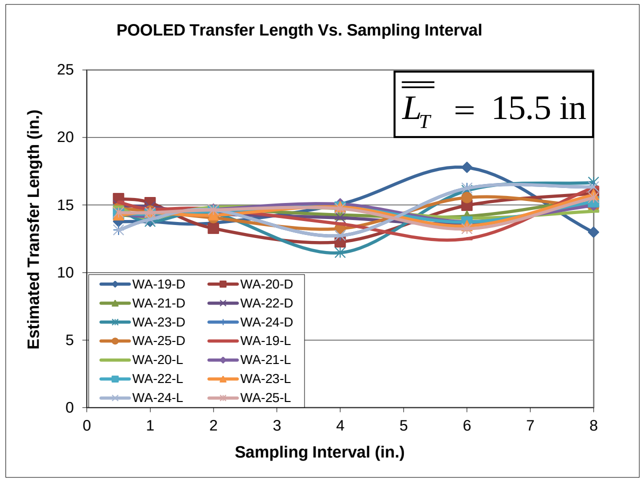
(c) WD Dead End (d) WD Live End

(e) WF Dead End (f) WF Live End

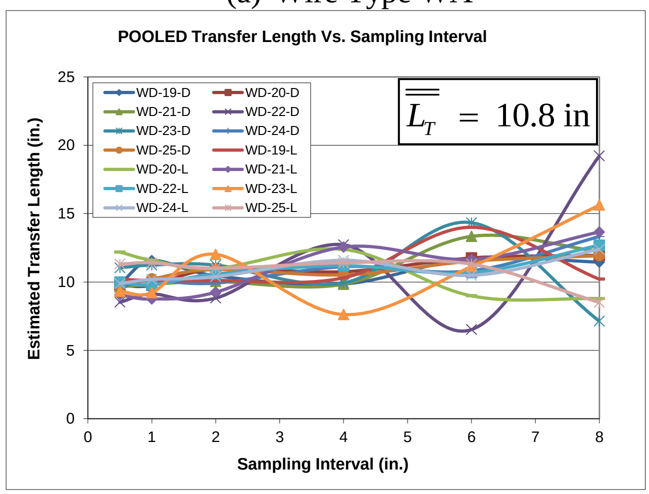
Figure 9: Normalized Transfer Length vs. Sampling Interval

There is a clear trend appearing to come into view indicating some apparent increase in the scatter as the sampling interval is increased. However, the extent of the trend is somewhat obscured by the small sample size of only 7 tests per crosstie. In an attempt to further extract information regarding the quantitative trend of the effect of sampling interval on the variation in crosstie transfer length, the Live-End and Dead-End data was pooled into a single set of measurements for each wire type, following the same normalization procedure indicated in

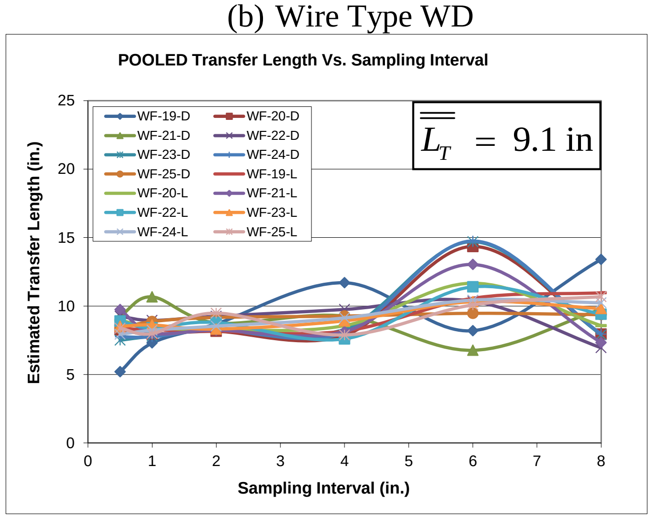
Equation (6). The results of this pooling procedure are shown in Figure 10 for each of the wire types.



(a) Wire Type WA



(b) Wire Type WD



(c) Wire Type WF

Figure 10: Effect of Sampling Interval on Pooled Transfer Length Data

STATISTICAL ANALYSIS OF SAMPLING INTERVAL EFFECT

To further reveal the effect of sampling interval, and better distinguish this effect from the apparent bias variations discussed above, the statistical characteristics of the standard deviation of the transfer length will be compared to the known influence of parameters associated with prisms. A well-developed analysis of the uncertainty has been presented previously for prismatic members.[15] According to this theoretical analysis, the uncertainty in the measured transfer length, U_{L_T}, can be expressed as follows:

$$U_{L_T} = \pm \frac{2U_{LSI}\sqrt{sL_T}}{S_{\max}} \tag{7}$$

where,

U_{LSI} = Uncertainty of the LSI strain sensor

L_T = Transfer length

S_{max} = Average maxmum strain

Equation (7) shows that the transfer length uncertainty is approximately proportional to the square root of the sampling interval, s. Equation (7) can be recast in terms of the standard deviation of the measured transfer length, yielding

$$\sigma_{L_T} = \pm \frac{2\sigma_{LSI}\sqrt{sL_T}}{S_{\max}} \tag{8}$$

where σ_{L_T} is the standard deviation of the measured transfer length, and σ_{LSI} is the standard deviation of the LSI strain sensor measurements.

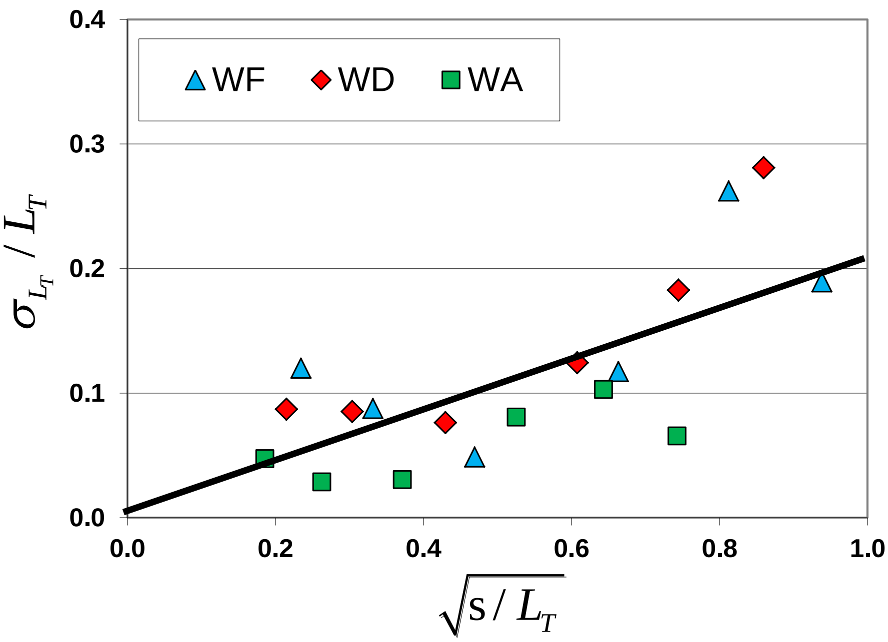


Figure 11: Effect of Sampling Interval on Pooled Transfer Length Data

Equation (8) can be further rearranged to yield

$$\frac{\sigma_{L_T}}{L_T} = \frac{2\sigma_{LSI}}{S_{\max}}\sqrt{\frac{s}{L_T}} \tag{9}$$

which indicates a simple dimensionless theoretical relationship between the standard deviation of the transfer length measurements and the sampling interval. Figure 11 shows a plot of this theoretical result compared with the entire set of experimental data for all three wire types WA, WD and WF. Note that the pooled transfer length data associated with each wire type has a separate pooled average transfer length corresponding to the values indicated on Figure 10 for each wire type WA, WD and WF. The fact that this relationship represents the measured standard deviation of the transfer length measurements indicates that the essential features developed for prisms[15] still appear to be largely true, in spite of the non-prismatic crosstie behavior. The slope of the line fit shown in Figure 11 is given theoretically from Equation (9), and has an approximate value of

$$Slope = \frac{2\sigma_{LSI}}{S_{\max}} \cong 0.2 \tag{10}$$

Substituting a nominal value for the average maximum strain of about $S_{\max} \cong 600\mu\varepsilon$ from Figure 7 yields a nominal standard deviation for the LSI measurement system of about $\sigma_{LSI} \cong 60\mu\varepsilon$, which is comparable with the level of scatter observed in the measured strain data. The in-plant random scatter was somewhat larger than the scatter associated with laboratory prism data, as evidenced by the larger scatter in the measurements of transfer length shown in Figure 3(b). However, this scatter does appear to be largely random scatter since the averaged in-plant measurements and the laboratory measurements of transfer length agree very well. Hence, the statistics in the present paper have revealed that the effect of sampling interval for crossties is essentially the same as that established earlier both experimentally and theoretically for prismatic members[15]. It is important to note that this is the first time this type of statistical comparison has been attempted with actual in-plant experimental results. More detailed analysis is needed to establish this empirical relation on a more firm theoretical foundation.

CONCLUSIONS

This paper has presented statistical and theoretical analysis of in-plant crosstie transfer length measurements that were previously obtained using an automated Laser Speckle Imaging (LSI) strain sensor system developed by the first four co-authors for rapid in-plant crosstie transfer length assessment. Through the use of selected samples of this in-plant data, the effect of strain measurement sampling interval on the resulting transfer length was investigated both theoretically and experimentally, and compared with results developed earlier for prisms.

Samples of crossties manufactured using prestressing wire types WA (smooth), WD (Chevron), and WF (Diamond) were selected for the current sampling interval analysis. These wire types had produced crossties with relatively long (WA Smooth), intermediate (WD Chevron) and relatively short (WF Diamond) transfer lengths. For each wire type, a sample of 7 crossties was included in the analysis, representing 14 tie end transfer length measurements. For each of the three wire types analyzed, strain data was selected for crossties located during casting in the central portion of the plant casing bed.

The strain measurements were analyzed using the generalized Zhao-Lee transfer length algorithm, which accounted for the non-prismatic crosstie characteristics, and also compensated for the presence of thermal strain offset. The resulting transfer length data was pooled and normalized so as to reveal the effect of sampling interval on the statistical scatter in the data. It was shown that, for the three different levels of transfer length tested (associated with the three prestressing wire types), the standard deviation of the measured transfer length correlated very well with a simple theory developed to estimate the uncertainty of transfer lengths for constant cross-section prismatic members. Although more analysis of the influence of non-prismatic behavior on transfer length uncertainty is needed, the results presented in this paper lend further support to the concept, developed on the basis of prism transfer length analysis, that only a few discrete surface strain measurements are required to achieve accurate and reliable in-plant transfer length assessment. This represents one more positive step toward an understanding of the system requirements needed for reliable in-plant automated transfer length assessment as an eventual in-plant quality control parameter.

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