111Equation Chapter 1 Section 1

THE IMPORTANCE OF CROSS-SECTION SHAPE FACTOR RESOLUTION TO ACCURATE ASSESSMENT OF TRANSFER LENGTH FOR NON-PRISMATIC RAILROAD TIES

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ABSTRACT

Non-prismatic railroad ties can have relatively complex cross-section shape variation, including tapering and scalloping along their length. The shape is commonly expressed in terms of a local shape factor parameter. Longitudinal variation in the shape factor can result in a very non-uniform longitudinal surface strain profile. This makes traditional methods of transfer length measurement, based on human judgment of a perceived "plateau region" or Average Maximum Strain (AMS), subject to large uncertainty and bias. Furthermore, manual procedures are slow, and therefore not applicable to automated in-plant transfer length diagnostics.

For automated transfer length assessment, a robust and unbiased statistical method was previously developed, known as the generalized Zhao-Lee (or ZL) method, which takes into account the shape factor variation. Thus far, transfer length for non-prismatic ties has been determined using detailed tie shape factors obtained arbitrarily every 0.50 inches (12.5 mm) along the length. The objective here is to present the results of an experimental investigation into just how detailed shape factor variation must be for accurate assessment of transfer length. Results will be presented based on actual measurements of strain profile and transfer length for ties with rather complex scalloping, and for ties which are relatively prismatic-like in shape.

Keywords: Piles, Prestressed; Research; Assessment and Monitoring

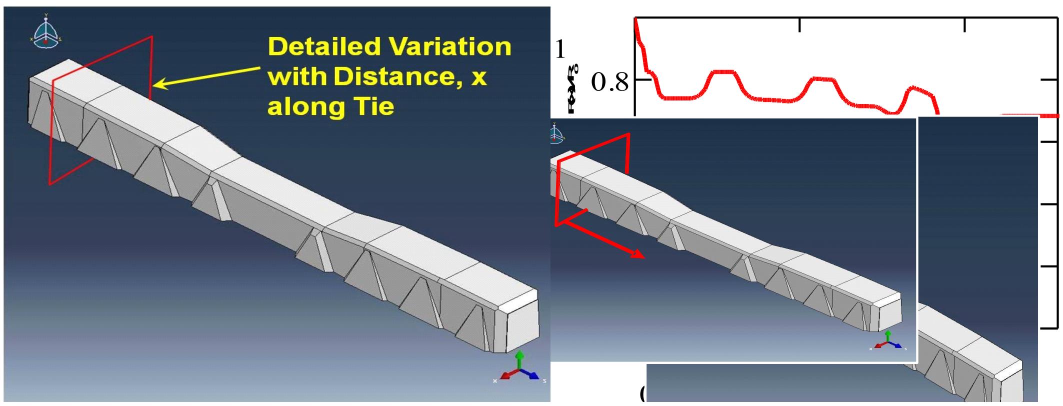
INTRODUCTION

Transfer length has been identified as a critical parameter in the assessment of the production quality associated with the modern manufacture of prestressed concrete railroad ties. 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 the ***transfer length*** [1,2,3] is defined as the length from each end of a tie required to fully develop (or transfer) the prestressing force. 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 inches from each end of the tie, but can range from 19.5 to 24 inches[4].

Research by the co-authors has focused on quantifying the parameters that affect the transfer length in pretensioned concrete railroad ties[5-49], and more recently also on an investigation of development length[35,39]. This has included not only a systematic investigation of the influence of the detailed geometrical characteristics of the prestressing steel wires[6,11,13,16-17,19,24-26], but also the study of other variables such as release strength and concrete mix. Of critical importance to the success of this research has been the development of a rapid non-contact optical method of assessing transfer length[5,7-10,14-15,20,23,27]. The goal of this work has been the practical implementation of a robust system capable of accurately measuring transfer length in the harsh in-plant environment, so that it can be used as a practical production quality control parameter.

Determination of the transfer length requires measurement of the surface strain distribution along the pre-tensioned concrete railroad ties. Surface strain have traditionally been measured using various mechanical, electronic (e.g., strain gauge) devices; however, significant improvements in the measurement of longitudinal surface strain have been achieved through the use of non-contact optical techniques[7,9,10,15,40-41,43-44]. Manual measurements are simply not practical for use on a production basis in a manufacturing plant. Practical in-plant measurements of transfer length require fast and reliable surface strain measurement, along with a rapid and reliably implemented algorithm for extracting the transfer length parameter from the railroad tie strain distribution. Considerable recent progress has been made in this area, with the development of automated Laser Speckle Imaging (LSI) transfer length measurement systems[7,10]. These systems have been used successfully to conduct literally hundreds of in-plant cross-tie measurements[9,7,10,15].

The long-range goal of the development of non-contact longitudinal surface strain measurement capability has been to facilitate the use of transfer length as a quality control parameter in the tie manufacturing process. The prototype for a practical robust new type of automated multi-camera strain profiling system has been developed and successfully demonstrated in a railroad tie manufacturing plant environment[33-34]. This new device has the potential to provide transfer length for every manufactured tie. In addition to its use for quality control, the new device, in its current portable configuration, could be used to investigate a variety of scenarios associated with the manufacture of ties, for the purpose of improving production quality. One of the most recent application of this instrument was to investigate the relative significance of lubricants on pretensioning wires and strands; specifically, their effect on the wire (or strand) bond characteristics, and on the important transfer length parameter[34]. Further developments in non-contact surface strain measurement have involved an improved dual-camera system which is capable of both continuous traversing and "jog" mode of operation. This new system has also recently been demonstrated in a plant environment, and has been shown to provide unprecedented in-plant strain measurement resolution[43]. In particular, this system has been shown to be capable of accurately identifying and resolving differences in strain profiles (and hence significant differences in transfer length) between adjacent ties manufactured in the same casting bed.



(a) 3D CAD Model of Crosstie (b) Normalized Shape Factor

Figure **1**: Typical Geometry of Concrete Railroad Crosstie

In order to achieve the accuracy and reliability required for use of transfer length as a quality control parameter it has been necessary to account for the generally non-prismatic nature of the typical railroad tie geometry. Figure 1 shows the complex geometry constructed from the actual dimensions of a typical USA railroad concrete crosstie. Figure 1(a) shows a 3D (Abaqus®) model of the tie, and Figure 1(b) shows the corresponding normalized shape factor variation, which indicates the expected departures from prismatic behavior. Such strain profiles for railroad crossties can depart considerably from the ideal bilinear surface strain profile associated with a constant cross-section (prismatic) member (e.g., a turnout tie)[34]. Departure from bilinear strain behavior presents difficulties in establishing a well-defined strain plateau region and this will directly affect the accuracy of transfer length assessment. Indeed, this was the motivation for the development of the generalized Zhao-Lee (ZL) method of transfer length assessment for crossties of arbitrary non-uniform cross-section[15,20,23]. Figure 1 is an excellent example of complex "scalloped" tie geometry, which results in a strain profile that departs significantly from the ideal bi-linear strain profile associated with prismatic members.

Previous measurements of transfer length using the ZL method have revealed that a very coarse strain profile is capable of achieving accurate transfer length assessment, with as few as one local strain measurement every 6 inches is sufficient to achieve a transfer length measurement to an uncertainty of within about $\pm$ 1.5 inches. This kind of measured strain resolution is quite sufficient to resolve and monitor changes in tie performance that may take place within the manufacturing environment. The required spatial resolution in cross-sectional information, however, has not yet been investigated. If a CAD model is available, such as that shown in Figure 1, detailed cross-sectional information can be extracted. This was done initially to a resolution of about 0.50 inches, and has been in use for some time in assessing transfer length for crossties using the Zhao-Lee method. If a CAD model is not readily available, then a 3D rendering of a crosstie can be made using available 3D optical scanning hardware. Then the 3D scanned model can be sectioned at any desired spatial increment to provide the necessary cross-section and shape factor parameter information needed to apply the statistical ZL method and extract a transfer length from measured longitudinal surface strain measurements.

The main objective of the current paper is to present an initial experimental investigation into just how fine the spatial increments in cross-sectional parameters need to be in order to provide acceptable accuracy of transfer length assessment. This will be accomplished by testing different spatial increments in cross-section, using the ZL algorithm in conjunction with actual measured tie strain profile data. Available 3D CAD solid body models for two crosstie geometries, a CXT[2] tie like that shown in Figure 1 with complex scalloping and a ROCLA[3] tie geometry with relatively small departures from prismatic behavior, will be sliced to different spatial resolutions. In addition, 3D optical scanning results will be shown for these ties, along with some of the unique measurement issues associated with accurately capturing all required spatial parameters needed for transfer length assessment.

EXTRACTING CROSSTIE CROSS-SECTION PARAMETERS

Figure 2 shows the generic trapezoidal cross-section shape which is used to define the important geometrical parameters associated with an arbitrary crosstie cross-section.

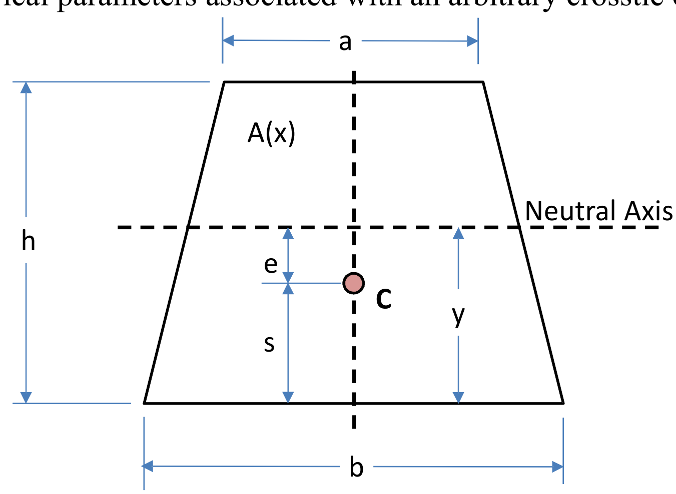


Figure 2: Trapezoidal shape defining crosstie cross sections

2 CXT® is a Registered *Trademark* of the L.B. Foster Company.
3 ROCLA refers to ROCLA Concrete Ties, Incorporated.

The location of the centroid of the wire grid is shown 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 for a CXT tie) and the centroid of the cross-section of the concrete crosstie[44]. These geometrical parameters were subsequently calculated from a 3D CAD model at 0.5 in. intervals for both the CXT tie and the ROCLA tie used in the current investigation. 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[44]

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where P(x) is the prestressing force or bond force at the location of x, E is Young's modulus and, in reference to Figure 2Figure 1, 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. The effect of the non-prismatic crosstie geometry on the local surface strain given in Equation 3 can be expressed in terms of the shape factor parameter, R(x), as follows[44]:

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where R(x) is given by

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Two distinctly different crosstie geometries are considered for the current investigation. Photographs of these ties are shown in Figure 3(a) for the CXT tie and Figure 3(b) for the ROCLA tie. The CXT tie was one of the ties taken from long-term in-track testing at the TTCI facility in Pueblo Colorado[29], so it exhibits some small amount of weathering and wear. The ROCLA tie shown was newly cast in the ROCLA manufacturing plant in Ohio[43].

(a) CXT Crosstie (b) ROCLA Crosstie

Figure 3: Photographs of CXT and ROCLA Crossties

Error: Reference source not found shows the cross-sectional parameters obtained for the CXT crosstie. The figure shows parameters extracted from both the CAD model for the tie as well as those obtained from a recent 3D optical scanning procedure using commercially-available laser-based hardware[44].

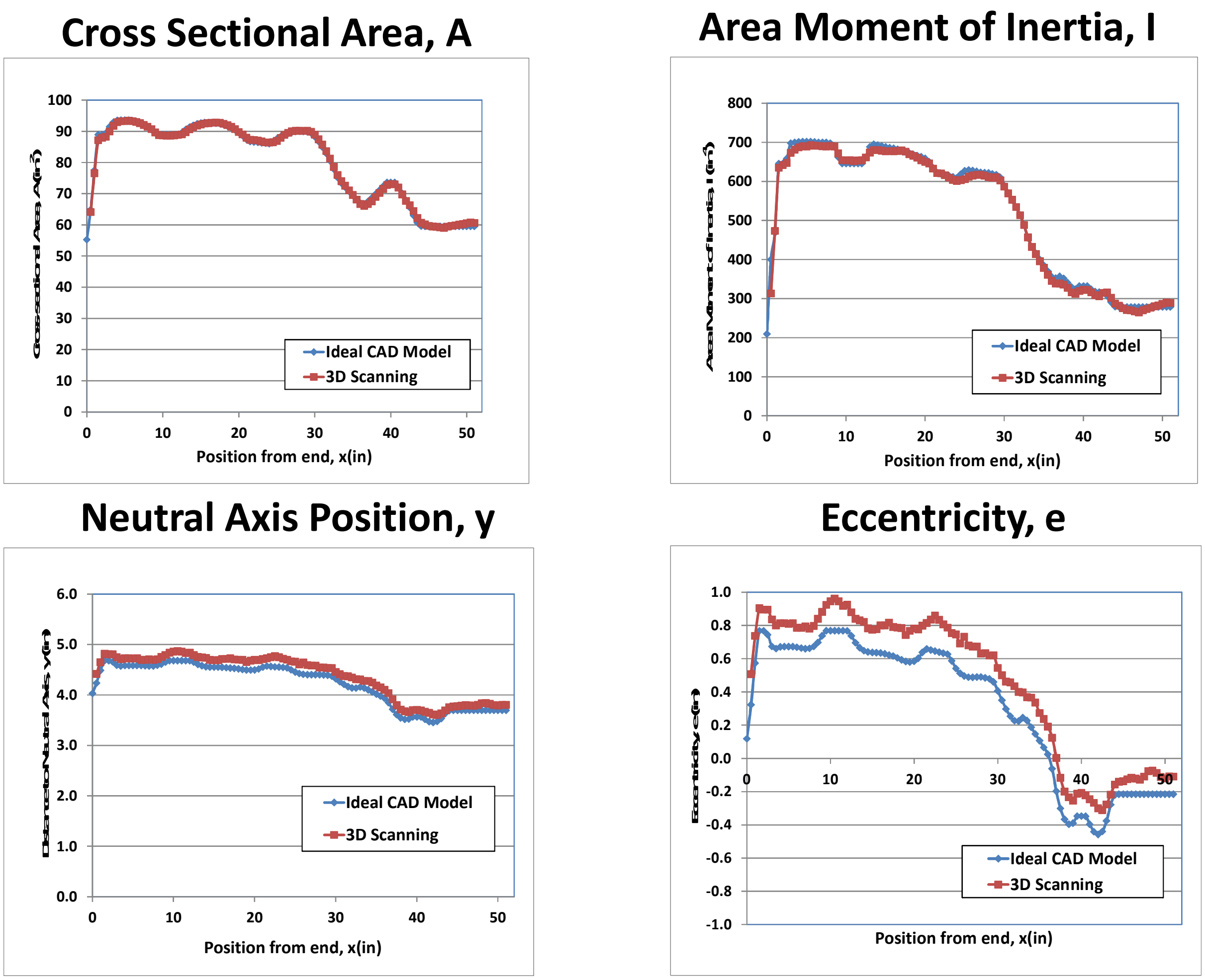
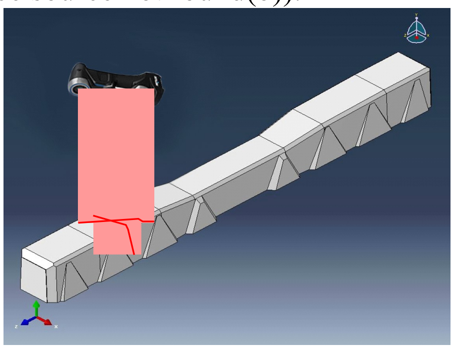


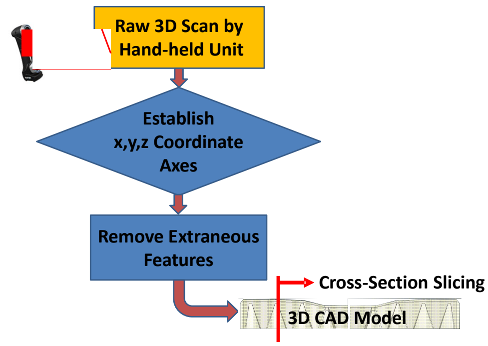
Figure 4: Cross-Sectional Parameters for the CXT Crosstie

A schematic representation of the 3D scanning procedure is illustrated in Figure 5(a) and 5(b). Initially self-adhesive retro-reflective points are applied to the tie surface, as shown in Figure 3(b). These discrete points are scanned completely over the entire tie surface, establishing a complete 3D reference grid. Then the detailed surface structure of the tie is scanned in a procedure that closely resembles the "painting of an invisible man" as the surface features are revealed. This is depicted in the screen capture image shown in Figure 5(c). It takes approximately 1-2 hours to complete the scan of a tie. The resolution of the scanning system was set to 1mm for the scans illustrated here[44], which resulted in computer storage requirements of about 3 to 5 GB per crosstie solid body model.

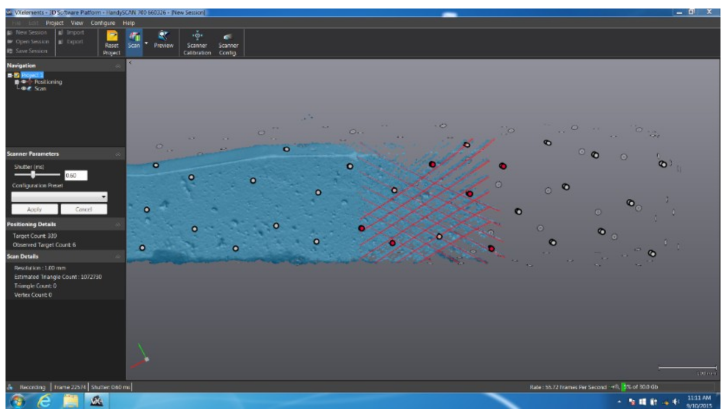
In addition to the cross-section slicing of either the CAD model or the 3D scanned rendering, it was necessary to determine the centroid of the prestressing wires. This can be accomplished in at least a couple of ways, either from directly photographing the ends of the ties and digitally (visually) extracting the centroid of the wire configuration (see Error: Reference source not found(b)), or through the use of the 3D scanned rendering (see Error: Reference source not found(b)).



(a) 3D Scanning System



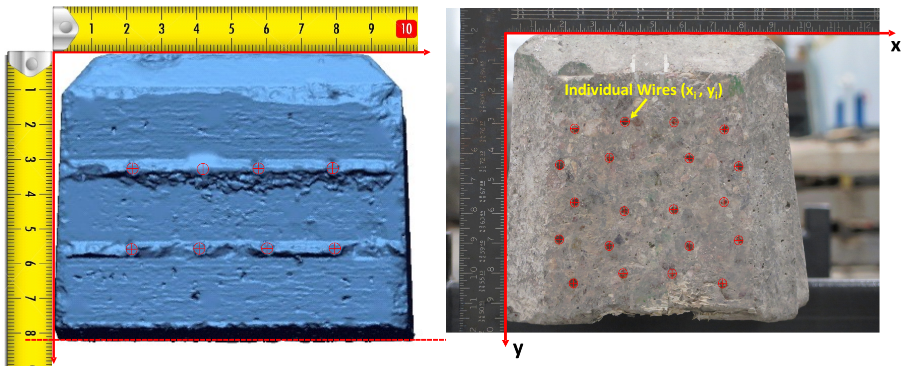
(b) 3D Model Processing



(c) Revealing of 3D Tie Surface Structure

Figure 5: The 3D Optical Scanning Procedure

End views showing the wire configurations for the CXT and ROCLA ties are shown in Error: Reference source not found(a) for the ROCLA tie and in Error: Reference source not found(b) for the CXT tie. The locations of the prestressing wires have been highlighted in each of these end views.



(a) End View 3D Scanned ROCLA Tie (b) Photograph of CXT Tie End View

Figure 6: Crosstie End Views Showing Wire Configuration

Figure 6 also shows the end cross-section dimensions, as indicated by the scales shown adjacent to the ties. It should also be noted that the crossties are both 102 inches long.

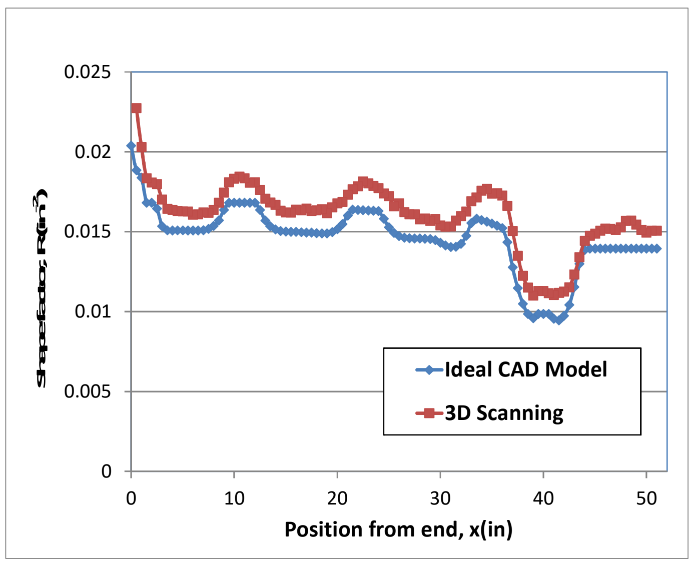


Figure 7: Shape Factor Variation for CXT Crosstie

The chief difficulty associated with the accurate extraction of the crosstie cross-sectional parameters from a 3D scanned solid body model lies mainly in accurately identifying the location of the bottom surface of the tie. From the above end views, it is clear that the process of locating the bottom of the tie has a relatively large uncertainty, perhaps on the order of 0.1 to 0.2 inches. Since this forms the reference from which the eccentricity is extracted, as shown in Figure 2, it is not surprising that the eccentricity has the largest uncertainty in comparison to all the other cross-sectional parameters, as seen in Error: Reference source not found. This further translates into a larger uncertainty in the crosstie shape factor, as suggested by the differences displayed in Figure 7 between CAD and 3D scanned rendering.

EFFECT OF COARSE RESOLUTION IN CROSSTIE SHAPE PARAMETERS

In this paper it is of specific interest to investigate how decreasing the spatial resolution of the extracted cross-section and resulting shape factor data will affect the assessment of transfer length based on the unbiased Zhao-Lee method. Following the usual Zhao-Lee procedure[15,20,23], it is assumed that *P(x)* varies linearly over the transfer length zone, according to

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where T_L is the transfer length and P_{max} is the maximum prestressing force.

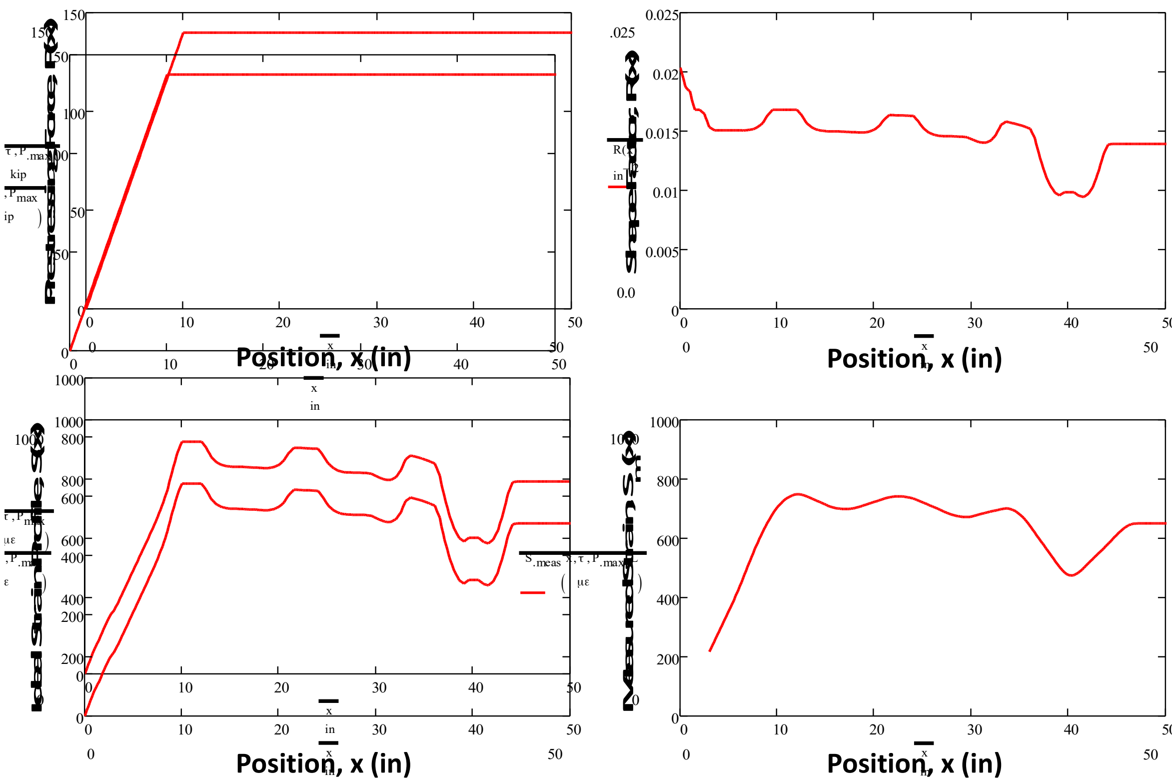

Figure 8: Typical Measured Strain Profile Development from CXT Crosstie Shape Factor

The effect of the combined CAD model CXT shape factor variation and the assumed bi-linear prestressing force distribution results in the predicted ideal CXT tie strain profile shown in the lower left-hand corner of Figure 8. The effect of a finite gauge length associated with the measured strain profile is represented by the following[44]:

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Where S_{meas} is the measured longitudinal surface strain, *TS* is the effective thermal strain or thermally induced offset, and *L* is the gauge length of the strain measurement system[44]. For the current LSI systems in use, this gauge length is 6 inches. The lower right-hand side of Figure 8 shows the smoothing influence of the shape factor, resulting in a predicted measured strain profile that significantly flattens the variations in predicted strain due to the scalloping. It should be noted that traditional methods of extracting transfer length from the measured longitudinal surface strain profile rely on the ability to establish a plateau region in strain profile in order to determine the Average Maximum Strain (AMS) level. The typical crosstie, however, is highly non-prismatic, with a rather complex cross-section shape variation along its length. This complex shape, reflected in the shape factor parameter, results in a complex strain profile which departs significantly from the simple bi-linear shape. The extent of the strain variation is very pronounced with the CXT tie, which has "scalloping" along its length. This makes it difficult to establish a meaningful AMS, since it will depend on the length of the region of strain measurement near each end of the tie. In an effort to develop a reliable and unbiased method of transfer length assessment, our approach has been to apply a general least squares curve fit to experimental measurements of longitudinal surface strain which accounts for the longitudinal variation in strain resulting from the longitudinal shape factor variation. This approach overcomes some of the difficulties noted above, since the scalloping is taken into account within the curve fitting process to yield the transfer length assessment. This approach is also required if an eventual automated transfer length procedure, capable of measuring every tie that is manufactured, is to be realized for quality control purposes.

Using the general curve fitting procedure mentioned above, the determination of transfer length is, in essence, the problem of determining the function *P(x)*, represented by the parameters P_{max} and T_L, given the measured strain data points[44]. For a general non-prismatic concrete member this can then be stated as follows: Given a set of data points,, find , and *TS*, so as to minimize the mean squared error (MSE) between the function and the measured y_i data. The MSE function is defined by the following:

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Applying this general algorithm to experimental measurements of longitudinal surface strain will yield a curve fit, along with estimates of the transfer length and thermal offset parameter.

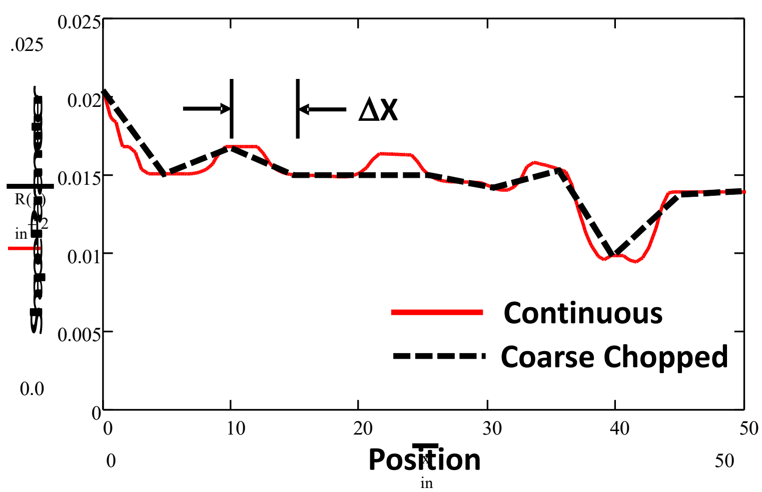


Figure 9: Coarsely chopped Crosstie Shape Factor Resolution

Variations in the manufacturing process (e.g., changes in the mix, release strength, etc.) can lead to variations in the transfer length. The problem of current interest is how detailed must the shape factor information be specified in the above algorithm to achieve an accurate assessment of transfer length? This is an important issue to resolve if transfer length is one day to be used as a quality control parameter. The crosstie cross-sectional data shown in Error: Reference source not found, Figure 7, and Figure 8 corresponds to a spatial resolution of 0.50 inches. In other words, the shape information was evaluated (either from a CAD model or a 3D scanned solid body model) every 0.50 inches along the tie, resulting in a set of cross-section parameters that appear to be nearly continuous. Figure 9 shows the result of a coarsely chopped shape factor obtained from slicing the cross-section in spatial increments of ΔX along its length. The dotted line shows a segmented shape factor function generated from this coarse increment. The specific example illustrated in Figure 9 corresponds to ΔX = 5.0 inches.

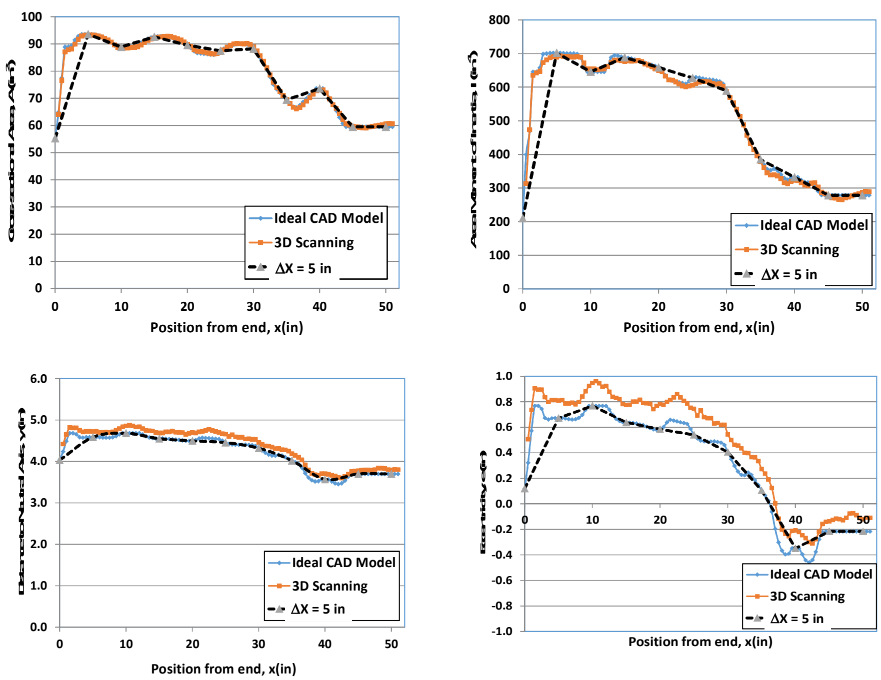


Figure 10: CXT Crosstie Coarsely Chopped Profile

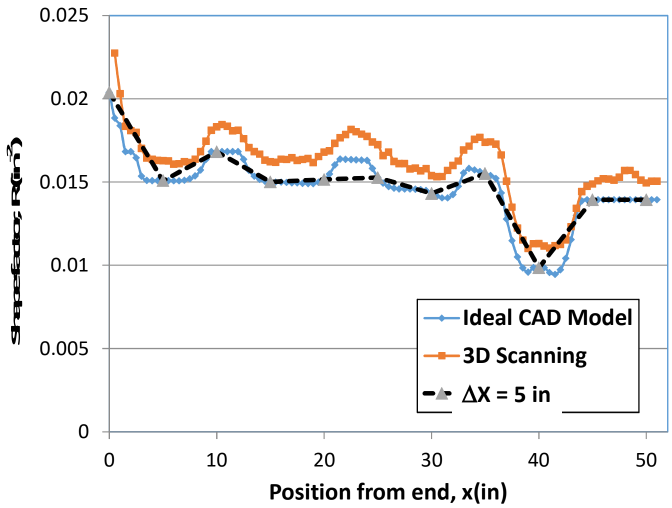


Figure 11: CXT Shape Factor Chopped Resolution

Figure 10 shows the result of this ΔX = 5.0 inch chopping resolution for all of the basic cross-sectional parameters that comprise the shape factor for the CXT tie. For this initial investigation, the chopping was applied to only the CAD model; however, the 3D scanned parameters are shown for comparison on each of the plots in Figure 10. Figure 11 shows the resulting shape factor for the CXT tie, with the coarse resolution chopping again applied to only the CAD model representation. It should be noted that for all these characteristic cross-sectional parameters, even though this coarse chopping represents about ten times less detail in the original 0.50 inch profile slicing resolution, it appears that there is sufficient detail to capture the major trend of the shape variations.

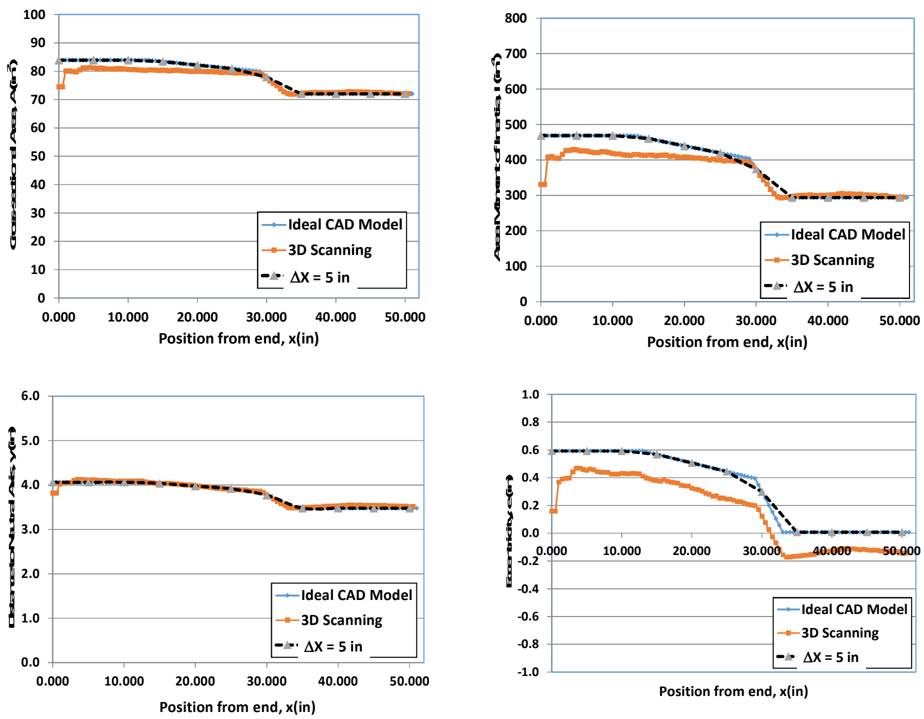


Figure 12: Coarse Chopping of ROCLA Tie Cross-Section Parameters

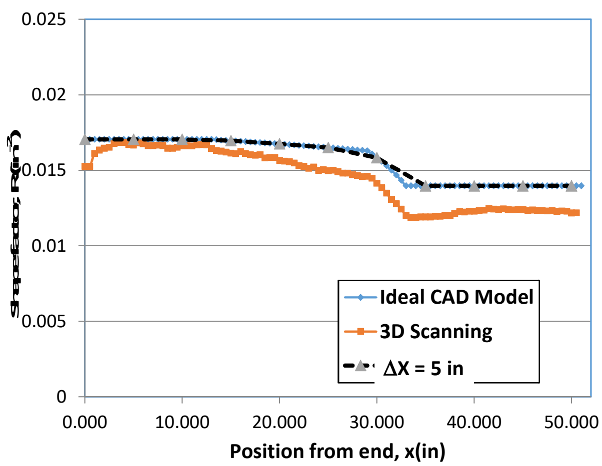


Figure 13: Coarsely Chopped ROCLA Tie Shape Factor

A similar coarse chopping of the crosstie profile data was applied to the CAD model data for the ROCLA tie, with both CAD profile and 3D optically scanned cross-section data shown in Figure 12 for comparison purposes. Figure 13 shows this same coarse chopping applied to the ROCLA tie shape factor. Again, the basic shape effects are fairly well captured even with this very coarse $\Delta X = 5.0$ inch slicing resolution.

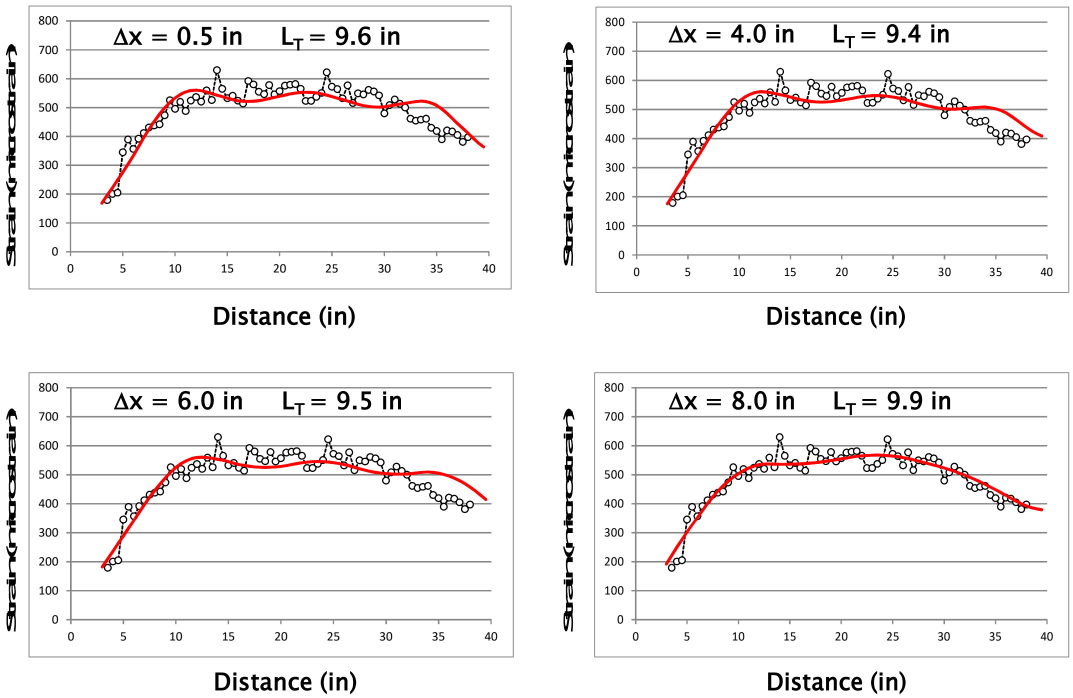


Figure 14: Effect of Slicing Resolution on Transfer Length Assessment for CXT Tie Data

The effect of applying these coarse shape factor renderings to actual experimental strain data for the extraction of transfer length is shown in Figure 14 for some typical CXT tie data.

CXT CAD Tie

Δx (in)	L_T (in)
0.5	9.6
1.0	9.6
2.0	9.6
4.0	9.4
5.0	10.0
6.0	9.5
7.0	9.3
8.0	9.9

Figure 15: Effect of Reduced Slicing Resolution on Transfer Length Assessment (CXT Tie)

The resolution of shape factor shown here varies from the original high resolution 0.50 inch level down to as low as one slice of shape factor data every 8.0 inches along the tie. The resulting variations in evaluated transfer length associated with these different levels of coarseness are given in Figure 15, where it is observed that the effect is remarkably small. Even less variation in transfer length takes place for the case of the ROCLA tie, as shown graphically in Figure 16 on some typical experimental strain profile data, and in tabular form in Figure 17, where the slicing increment shows minimal variation in transfer length over range of slicing increments ranging from the original 0.50 inch case to the very coarse case of one slice of shape factor data every 8.0 inches along the tie.

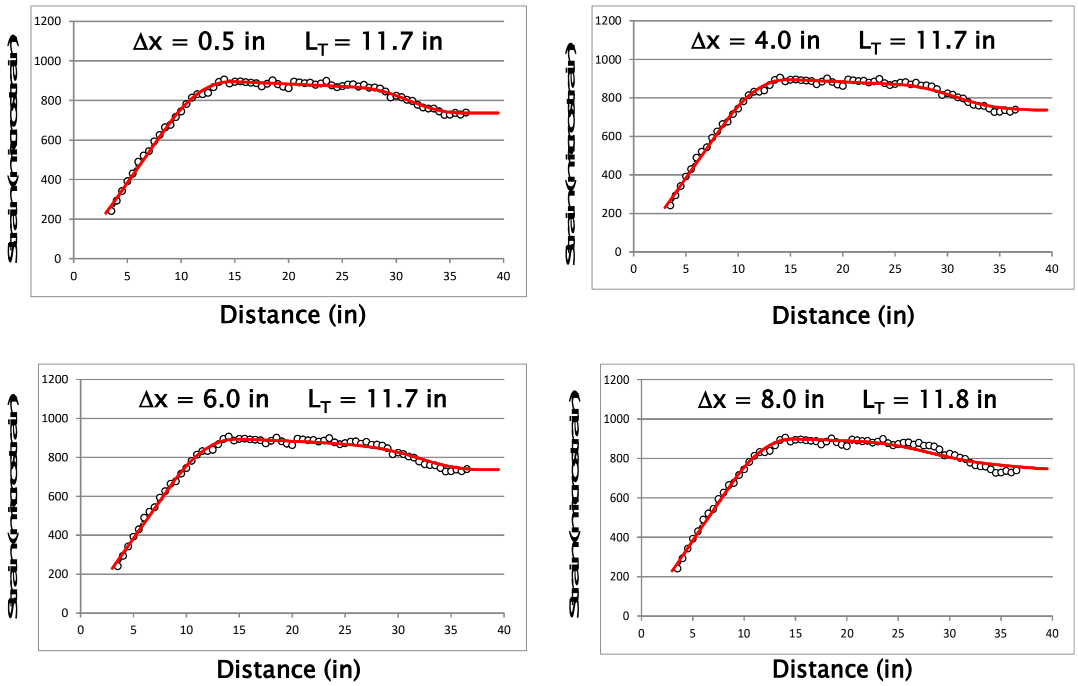
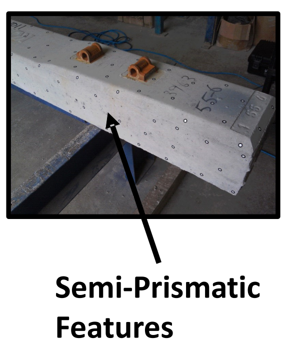


Figure 16: ROCLA Strain Profiles for Coarsely Sliced Tie Shape Parameters



Rocla CAD Tie

Δx (in)	L_T (in)
0.5	11.7
1.0	11.7
2.0	11.7
4.0	11.7
5.0	11.7
6.0	11.7
7.0	11.7
8.0	11.8

Figure 17: Effect of Coarse Shape Resolution on Transfer Length Assessment

It was quite remarkable and unexpected that reducing the crosstie resolution to as coarse as ΔX = 8.0 inches would result in such a minimal effect on the resulting transfer length. The reason appears to be associated with the fact that the overall gross variation in cross-section parameters is still well-represented by the coarse resolution. This was especially unexpected for the case for the CXT ties, where the scalloping would seemingly introduce significant detailed variation in the local strain profile. Another factor to consider is the averaging (or smoothing) effect of the finite 6.0 inch gauge length associated with the strain measurement instrumentation. This tends to significantly reduce the detail introduced by scalloping associated with the CXT tie shape, as shown by the development of the generalized measured strain profile in Figure 8. In contrast with the CXT tie behavior, the ROCLA tie, which has a much more prismatic cross-sectional shape variation, exhibited an even smaller effect of the reduced slicing resolution on transfer length than did the CXT tie case. It should be noted that these results are somewhat preliminary and further investigation is needed to formulate a more sound theoretical basis for this unexpected experimental behavior, in terms of an analysis of the transfer length uncertainty like that previously developed for prismatic ties[14]. It is important to point out, however, that the apparent lack of sensitivity to detailed resolution in the shape factor for a given tie does not imply that knowledge of the shape factor is unimportant. It simply indicates that the unbiased statistical ZL transfer length processing algorithm focusses mainly on the gross or overall variation in the cross-section shape (and associated experimental data) and not on the fine spatial detail such as that associated with scalloping on a CXT tie.

CONCLUSIONS

This paper has presented the results of an initial experimental investigation into the effect of crosstie cross-section shape resolution on the assessment of transfer length. This work was conducted in the spirit of an earlier investigation of the effect of strain profile sampling resolution, which ultimately led to the development of a prototype multi-camera optical strain measurement system intended for in-plant quality control.

The non-prismatic nature of railroad crossties motivated the development of the generalized Zhao-Lee (ZL) transfer length processing algorithm, which takes into account the non-prismatic cross-section profile information. This was shown to be necessary in order to properly account for the significant departures from bi-linear strain profile behavior that had been observed during in-plant testing of crossties—in particular, transfer length measurements for the complex CXT tie with highly scalloped geometry. Previously this cross-section information had been obtained exclusively from available CAD models, the CXT tie being a particular example. However, more recently it has been shown to be possible to extract similar high-resolution cross-section parameters from 3D optical scanning.

The initial 0.50 inch resolution CAD profile data for the CXT tie was extracted earlier from a CAD model, and this high-resolution profile information has been in use for some time in conjunction with the ZL method for measurement of transfer lengths in literally hundreds of crossties. As a first step in the investigation of the importance of cross-section resolution, the cross-section resolution was successively reduced from every 0.50 inch to as coarse as every 8.0 inches along the length of the tie. Clearly this significantly reduced the level of detail captured in the cross-section parameters. Similar reduction in cross-section resolution was imposed on the ROCLA tie geometry, which has a much more prismatic-like profile characteristic shape and exhibits no complex scalloping.

In spite of the severe reduction in cross-section resolution imposed, the level of detail remaining in the cross-section parameters, and in particular the important shape factor parameter which characterizes the basic shape of the resulting strain profile, was shown to sufficiently capture the basic shape of the strain profile and the resulting transfer length remarkably well. This was demonstrated through direct comparisons with experimental longitudinal surface strain measurements for both the CXT tie and the ROCLA tie. Although more investigation is warranted, one reason for this unexpected behavior may be that for the most part only the overall dominant cross-section shape, and its influence on the shape factor, significantly affect the ability of the statistical ZL algorithm to extract the transfer length parameter. This may be due in part also to the averaging or smoothing that results from the finite 6-inch gauge length associated with the optical strain profiling system in use. In summary, only the dominant geometrical features associated with commercially produced railroad crossties appear to be of major importance when using the unbiased ZL transfer length algorithm.

It is important to note that the lack of sensitivity to coarseness of tie cross-section information does not imply that taking into account the cross-section shape is not important. Without considering shape effects, the departures from bi-linear strain profile are still significant and prevent accurate assessment (or even definition) of a strain plateau (average maximum strain, or AMS). However, it appears that much of the high-level detail, such as the complex scalloping associated with the CXT tie, may not be of major importance to accurate transfer length assessment with the unbiased ZL method.

Clearly, more concrete theoretical and experimental analysis of the influence of coarseness in cross-section data on the assessment of transfer length is needed if transfer length is to be used eventually as a production quality control parameter. However, the results presented in this paper represent one more positive step toward an understanding of the system requirements needed for reliable in-plant automated transfer length assessment. The goal is that transfer length measurement will eventually take an important role as a routinely measured parameter for in-plant quality control.

ACKNOWLEGMENTS

The authors would like to gratefully acknowledge the Federal Railroad Administration (FRA) for providing the major source of funding for this research.

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