VERIFICATION OF THERMAL STRAIN OFFSET IN PRISMS AND RAILROAD CROSSTIE PRODUCTION

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ABSTRACT

Transfer length is a key parameter used to assess the load bearing capability of prestressed concrete members, including railroad crossties. A new optical non-contact transfer length measurement technique has been developed and demonstrated on both prismatic and non-prismatic members. However, extensive measurements of transfer length for both prismatic and non-prismatic members, including in-plant crosstie measurements, have revealed a significant offset in the strain profile which appears to be related to thermal expansion effects. It has been hypothesized that this thermal effect results from a difference in the temperature of the concrete member before and after the detensioning process; however, this has never been verified experimentally. Existing algorithms have been developed to assess transfer length by including a strain offset parameter in the transfer length assessment process; however, the source of this offset has never been verified experimentally. This paper presents the results of a systematic investigation of the offset phenomena. Measurements were conducted on thermally-instrumented prismatic and non-prismatic concrete members subjected to known temperature environment both before and after detensioning. Surface strain profiles were determined using both the traditional Whittemore gauge measurement procedure and using the new multi-camera optical non-contact surface strain measurement system developed by the authors.

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

INTRODUCTION

Knowledge of the transfer length is critical for maintaining continuous production quality in 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 is developed gradually from each end of the concrete tie, and 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 inches from each end of the tie, but can range from 19.5 to 24 inches[4].

Recent research has been focused on quantifying the parameters that affect the transfer length in pretensioned concrete railroad ties[5-38], and more recently 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. Furthermore, of critical importance to 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 can be measured using various mechanical, electronic (e.g., strain gauge) devices, and more recently by using optical techniques[7,9,10,15]. The traditional method to obtain the surface strain information is to secure metal discs called “gage points” to the surface of the specimens at 50 mm (2.0 in.) spacing prior to de-tensioning the strands. The distance between the gauge points is then manually measured in a slow and rather tedious process using a mechanical Whittemore gauge.

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 an automated Laser speckle Imaging (LSI) transfer length measurement system[7,10], and this system has been used successfully to conduct literally hundreds of in-plant cross-tie measurements[9,7,10,15].

Recently a more robust new type of automated multi-camera strain profiling system has been developed and successfully demonstrated in a railroad tie manufacturing plant[33-34]. This new system was designed as a prototype for a practical system that would not only be compatible with the tie manufacturing environment, but could be used on a production basis for quality control of tie manufacturing. The overall goal is to provide the capability of measuring the 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. The most recent application of this instrument, prior to its use in the current paper, was to investigate the relative significance of lubricants on pretentioning wires and strands; specifically, their effect on the wire (or strand) bond characteristics and on the important transfer length parameter[34].

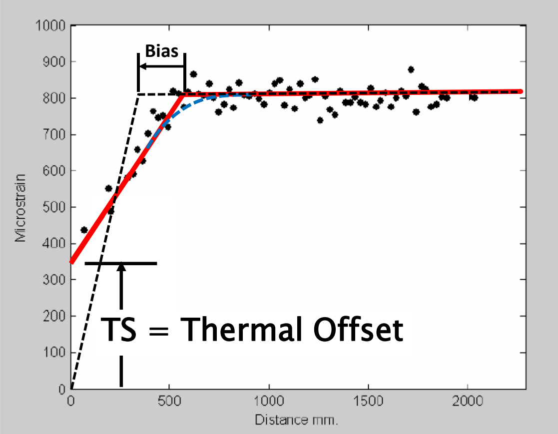


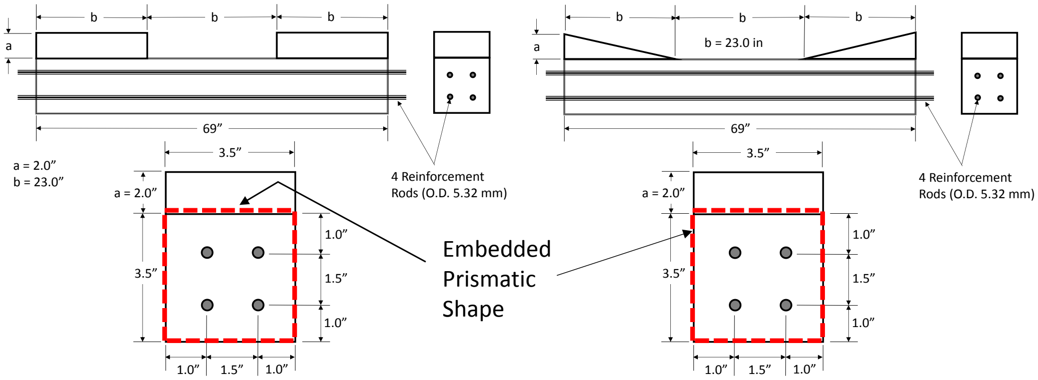
Figure 1: Hypothesized Thermal Expansion Offset for Prismatic Member

Extensive measurements of transfer length for both prismatic and non-prismatic members, including in-plant crosstie measurements, have revealed a significant displacement or offset in the strain profile, as suggested in Figure 1 for a prismatic member. This offset appears to be related to some form of thermal expansion effect. It has been hypothesized that this thermal effect results from a difference in the temperature of the concrete member before and after the detensioning process. Furthermore, algorithms have been developed to assess transfer length by including a strain offset parameter in the transfer length assessment process; however, the source of this offset has never actually been verified experimentally. Without accounting for this offset when present, the longitudinal strain profile is presumed to pass through zero strain on the ends of the crosstie. If this offset is not properly taken into account in the transfer length assessment algorithm, the result can be a bias in the transfer length, as suggested in Figure 1. This paper presents the results of a systematic investigation of the offset phenomena.

DESIGN OF NON-PRISMATIC MEMBERS FOR THERMAL TESTING

In this study, three simplified non-prismatic prestressed concrete members were cast to represent known variations in cross-section shape and prestressing wire eccentricity, in an effort to portray some of the dominant effects of shape factor on surface strain profile variation. The intent was to demonstrate with these simplified geometries the key (or most significant) influences of shape factor variation on the strain profile, and how these effects influence the offset phenomena in a controlled laboratory environment situation.

Figure 2 shows the geometries of the two non-prismatic prestressed concrete members used in the present investigation. These members contain two key geometrical features characteristic typical of railroad crosstie shapes; namely, (a) a significant reduction in cross-section in the central region of the tie, and (b) a gradual tapering of the cross-section near the end of the tie. The non-prismatic member shown in Figure 2(a) exhibits a block (or stepped) adjustment in the cross-section on each end, while the non-prismatic member shown in Figure 2(b) has a gradual linear tapering from each end of the member toward a reduced cross-section in the middle one-third region.



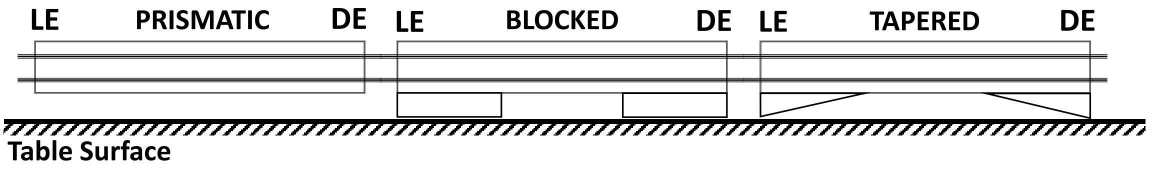
(a) Block (stepped) Design (b) Tapered Design

Figure 2: Non-prismatic Members used for Thermal Study

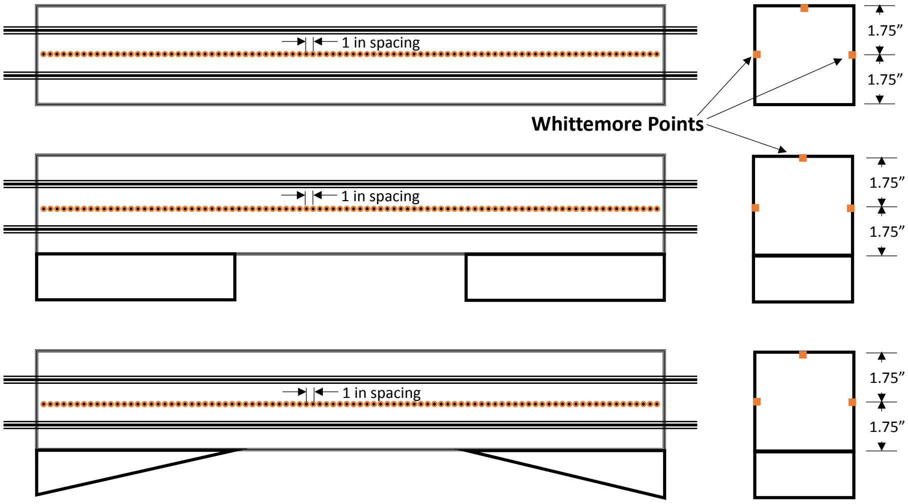
The test member features are separated into three segments each having a length of 23 in (58 cm), with the central 23 in (58 cm) section having a uniform cross-section. In addition to the non-prismatic members, a prismatic cross-section geometry was also cast for comparison with the thermal offset behavior of the non-prismatic members. The dimensions of this prismatic member were identical to those of prisms that have been used in previous investigations of the influence of wire type on transfer length[13,18]. It had a fixed square cross-section with four symmetrically placed 5.32 mm indented wire reinforcements. The cross-section of the prismatic member, and the location of its reinforcement wires, are represented by the dashed square outline in Figure 2(a) and 2(b).

CASTING OF PRESTRESSED CONCRETE MEMBERS

Figure 3(a) shows the layout of the inline casting of the three concrete test members described above. The live end (LE) associated with the tensioning and de-tensioning process is the left end of each specimen, and the dead end (DE) corresponds to the right end as shown in the Figure. Brass points were embedded as shown in Figure 3(b) on both sides of each member and also on the top surface, with a 1-in (25mm) spacing, running the entire 69 in (175 cm) span of each concrete member. Figure 4 shows a photograph of the test members aligned in the cast laboratory, with the live end on the left. Shown is the layout after tensioning and just prior to casting and subsequent de-tensioning. Note that the order of the in-line casting is slightly different from that depicted in Figure 3, but this order is arbitrary. A Sure-cure system was utilized to provide uniform and known concrete characteristics for the specimens. The wires were all tensioned to 7000 lbf (31 kN) each, for a total force of 28,000 lbf (125 kN). All members were cast in the upright configuration shown in Figure 3, with the flat surface on top. Concrete forms we constructed of plywood, and foam board was used to fill in the gaps beneath the members in order to maintain alignment of all top surfaces.



(a) In-line Casting Layout for Prestressed Concrete Test Members



(b)Layout of Embedded Whittemore Points

Figure 3: Casting of Prestressed Concrete Members and Embedded Whittemore Point Locations

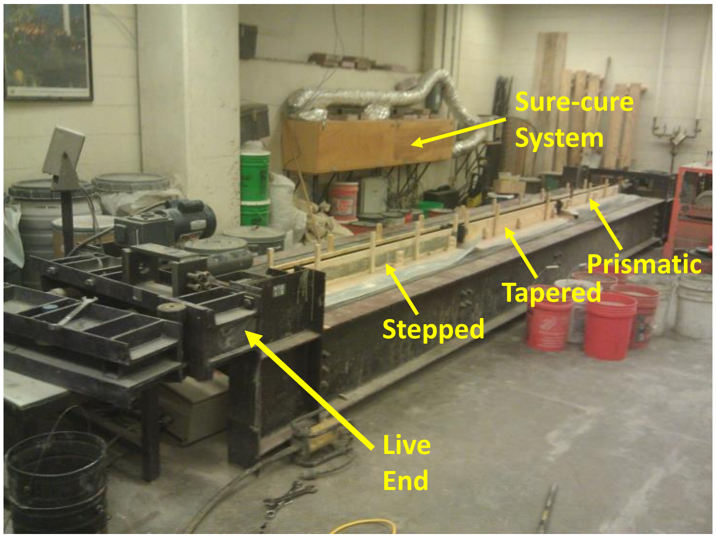
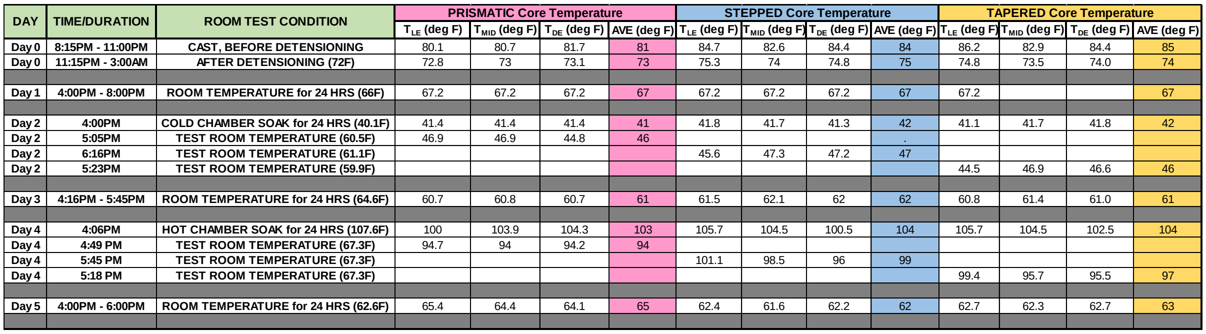


Figure 4: Photograph of Casting Bed Layout and Tensioning System

The concrete mixture used had a water-to-cement ratio of 0.32 and was similar to a mixture used by a major concrete railroad tie producer in the United States. The mixture utilized a one-inch-maximum size crushed river gravel as the coarse aggregate. The concrete was cast around 11:00 AM on April 20, 2015 and de-tensioning occurred approximately 13 hours later, when the concrete had reached a compressive strength of 8300 psi.

EXPERIMENTAL FACILITIES AND THERMAL TEST CONDITIONS

Figure 5 shows a summary of the sequence of strain measurements and associated test conditions. The casting took place on Day 0, along with the initial set of surface strain measurements which first involved measurement of surface position (baseline) prior to de-tensioning. After detensioning, measurements of surface strain were conducted on day 0 as well as under different environmental (temperature) test conditions over the next five days. Both non-contact (optical) and traditional Whittemore gauge measurement methods were used to assess surface strain. Due to the large number of processed results that come from the tests conducted, only a representative sample of test results will be presented in this paper.



DAY	TIME/DURATION	ROOM TEST CONDITION	PRISMATIC Core Temperature				STEPPED Core Temperature				TAPERED Core Temperature			
			T_{LE} (deg F)	T_{MID} (deg F)	T_{DE} (deg F)	AVE (deg F)	T_{LE} (deg F)	T_{MID} (deg F)	T_{DE} (deg F)	AVE (deg F)	T_{LE} (deg F)	T_{MID} (deg F)	T_{DE} (deg F)	AVE (deg F)
Day 0	8:15PM - 11:00PM	CAST, BEFORE DETENSIONING	80.1	80.7	81.7	81	84.7	82.6	84.4	84	86.2	82.9	84.4	85
Day 0	11:15PM - 3:00AM	AFTER DETENSIONING (72F)	72.8	73	73.1	73	75.3	74	74.8	75	74.8	73.5	74.0	74
Day 1	4:00PM - 8:00PM	ROOM TEMPERATURE for 24 HRS (66F)	67.2	67.2	67.2	67	67.2	67.2	67.2	67	67.2			67
Day 2	4:00PM	COLD CHAMBER SOAK for 24 HRS (40.1F)	41.4	41.4	41.4	41	41.8	41.7	41.3	42	41.1	41.7	41.8	42
Day 2	5:05PM	TEST ROOM TEMPERATURE (60.5F)	46.9	46.9	44.8	46				.				
Day 2	6:16PM	TEST ROOM TEMPERATURE (61.1F)					45.6	47.3	47.2	47				
Day 2	5:23PM	TEST ROOM TEMPERATURE (59.9F)									44.5	46.9	46.6	46
Day 3	4:16PM - 5:45PM	ROOM TEMPERATURE for 24 HRS (64.6F)	60.7	60.8	60.7	61	61.5	62.1	62	62	60.8	61.4	61.0	61
Day 4	4:06PM	HOT CHAMBER SOAK for 24 HRS (107.6F)	100	103.9	104.3	103	105.7	104.5	100.5	104	105.7	104.5	102.5	104
Day 4	4:49 PM	TEST ROOM TEMPERATURE (67.3F)	94.7	94	94.2	94								
Day 4	5:45 PM	TEST ROOM TEMPERATURE (67.3F)					101.1	98.5	96	99				
Day 4	5:18 PM	TEST ROOM TEMPERATURE (67.3F)									99.4	95.7	95.5	97
Day 5	4:00PM - 6:00PM	ROOM TEMPERATURE for 24 HRS (62.6F)	65.4	64.4	64.1	65	62.4	61.6	62.2	62	62.7	62.3	62.7	63

Figure 5: Summary of Strain Measurement Testing

It has been hypothesized that previously observed offset phenomena can be attributed to thermal expansion effects, which are generally not known in the typical crosstie manufacturing setting, since no provisions are typical available in a prestressed concrete tie plan to monitor internal core temperatures of the ties either before and after the de-tensioning process. It is clear, however, that some temperature difference undoubtedly does take place over this time period, and that the effects may be accented if the measurements subsequent to de-tensioning occur in an environment much different in temperature from that of the cast concrete prior to de-tensioning.

To help assess the thermal offset characteristics, #20 gauge copper-constantan thermocouples were embedded along the centroid axis of the four prestressing wire, and in the middle of each of the 23 in (58 cm) regions along the test members, as shown in Figure 6. These embedded thermocouples were used to provide a registration of the internal core temperature.

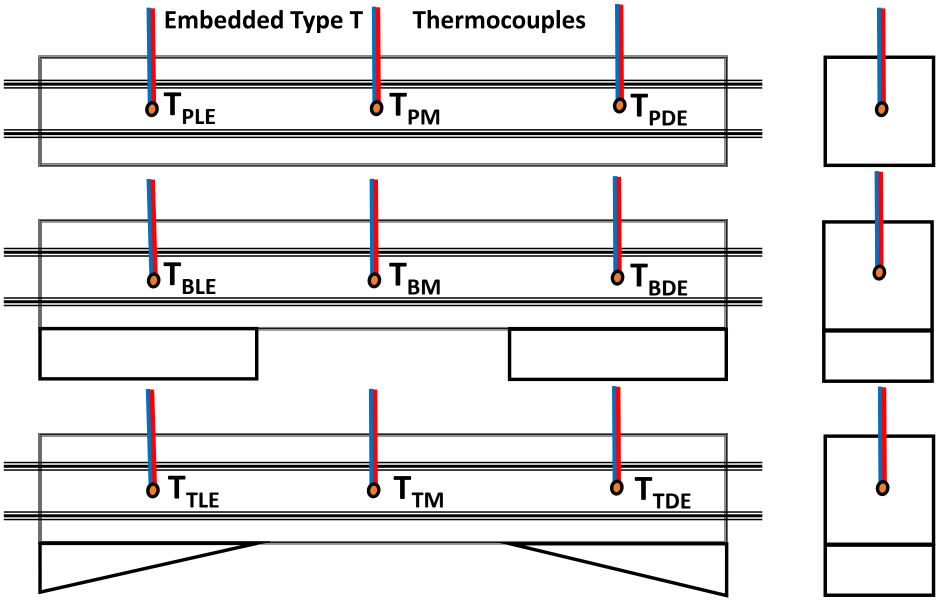


Figure 6: Location of Embedded Thermocouples for Core Temperature Monitoring

In addition, a digital infrared camera was used to provide visual and quantitative information on the surface temperature distribution of the concrete test members.

EXPERIMENTAL TEST FACILITIES AND INSTRUMENTATION

For each day of the five day testing sequence, measurements of strain were obtained for each of the geometrical configurations (PRISMATIC, STEPPED, TAPERED), using both a conventional Whittemore gauge as well as the recently developed 6-camera non-contact optical strain sensor[33,34]. Subsequent to the day of the casting and de-tensioning, Day 0, in an effort to isolate the specific effects of concrete member thermal expansion, the three concrete member geometries were immersed in different controlled environmental conditions. For the measurements that took place on Day 1, the concrete members were allowed to come to equilibrium at room temperature. The specific temperature is given in Figure 5. Prior to measurements on Day 2, the test specimens were cold-soaked in a COLD environment of approximately 40 F. The members were then allowed to return to room temperature conditions for measurements on Day 3. Prior to Day 4 measurements, the concrete members were hot-soaked in a HOT environment of just under 110 F. The last measurements conducted on Day 5 were when the members were again brought back to equilibrium at room temperature. Each new condition required approximately 24 hours for the new equilibrium conditions to be obtained. The hot and cold environments were provided by a temperature controlled environmental test chamber operated by the Institute for Environmental Research (IER) at Kansas State University.

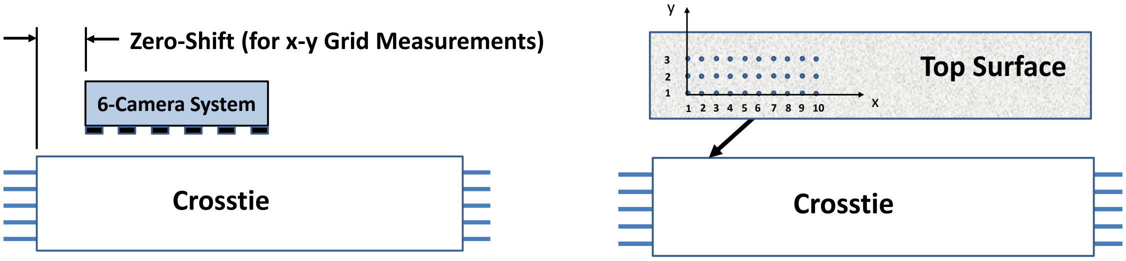
A photograph of the 6-camera system in use measuring the strain profile of one of the specimens just after de-tensioning is shown in Figure 7(a). A simple wooden platform was used to support the unit above the concrete surface under test, as shown. The positioning of the sensor is not critical and can be simply manually set in position before and after de-tensioning. The digital Infrared (IR) camera used to obtain quantitative and qualitative (visualization) of the concrete specimen surface temperature distribution is shown in Figure 7(b). It was utilized to provide images both after de-tensioning as well as after removal from the controlled hot and cold environmental chamber conditions.

(a) 6-Camera Optical System (b) Digital Infrared (IR) Camera

Figure 7: Non-contact Optical Strain Sensor and IR Camera Instrumentation

The current portable version of the 6-camera system has three-point housing support and can be easily manually positioned to any desired location for measurement. It also has large depth of focus, and large lateral high resolution image capture field, so that vertical alignment and horizontal alignment are not critical. It is sufficient to simply manually mark measurement points with a felt tip marker for system positioning alignment. Realignment of the system on this felt tip marker grid is not critical and approximate manual positioning on this grid is sufficient for accurate surface strain measurement at the 5 discrete points. The nominal strain measurement accuracy is typically about $\pm$25-50$\mu\varepsilon$, which is comparable to strain measurements using the manual Whittemore gauge.

A previously developed manual shifting technique was used to shift the unit in increments of 1.0 inches (25 mm) to provide increased spatial resolution over the fixed 6.0 inch (15 cm) camera spacing[33,34]. For the optical measurements in this paper, a single line 9-point linear shift was sufficient.



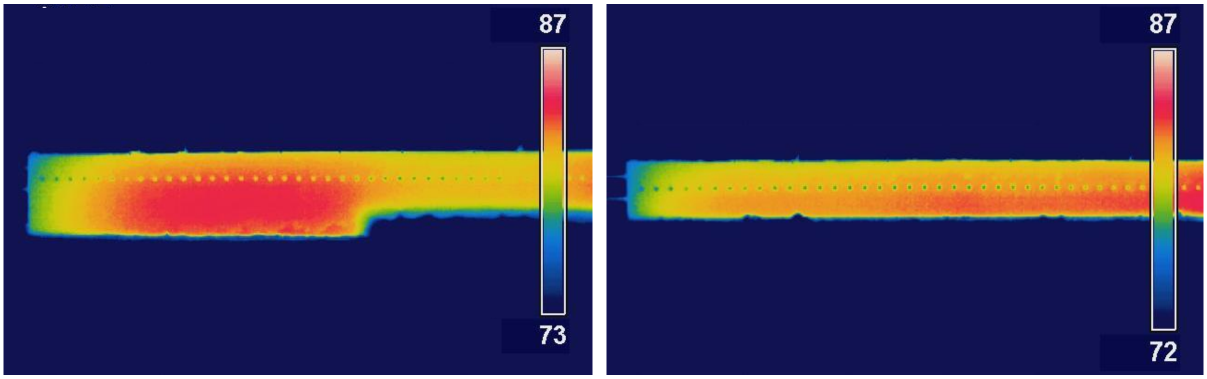
(a) Zero-Shift of 6-Camera System (b) Multi-Point x-y Grid Layout

Figure 8: Zero Shifting for High-Resolution Strain Measurement

The 6-camera system works by illuminating the concrete tie surface and capturing images of surface features or artificially introduced patterns that tag the surface deflection. For the current testing, microscopic reflective particles were dispersed as a spray paint and were bonded to the surface and used to tag surface displacement. These images were then recorded digitally at the 6 discrete measurement points along the concrete railroad tie. An initial image set was captured before de-tensioning and served as a baseline image. After de-tensioning, a second set of images was captured, and the difference in surface deflections from these two sets of images represents the strain. Measurements on each day of testing were compared directly to the original baseline image obtained on Day 0. In addition to comparisons against this absolute Day 0 reference, the captured images for the hot-soak and cold-soak conditions (Days 2 and 4) could be compared directly to achieve a "relative strain" measurement indicative of the direct thermal expansion effects resulting from the temperature change.

EXPERIMENTAL AND SIMULATED THERMAL OFFSET RESULTS

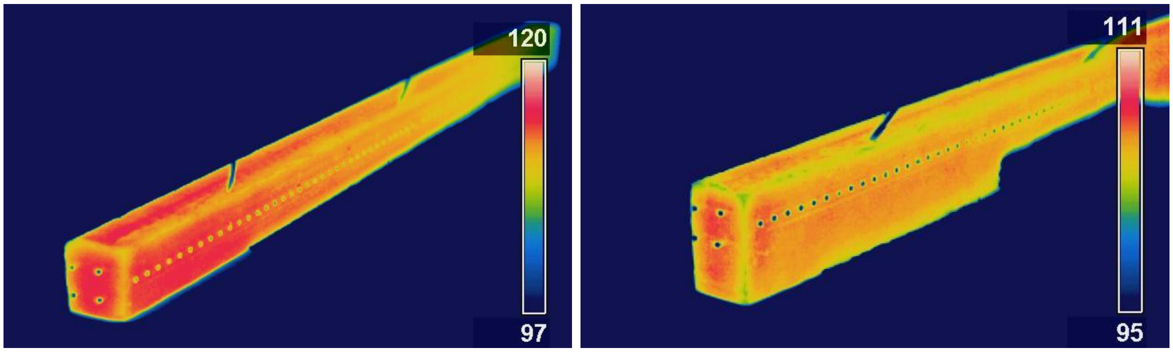
As will become evident below, in addition to directly affecting the longitudinal strain distribution, the thermal offset phenomena may also have a significant influence on the transfer length by non-uniformly altering the strain profile shape—indirectly affecting the development region characteristics associated with even prismatic members, and hence, also affecting the resulting transfer length.



(a) Stepped Concrete Member (b) Prismatic Concrete Member

Figure 9: IR Camera Images Just After De-tensioning

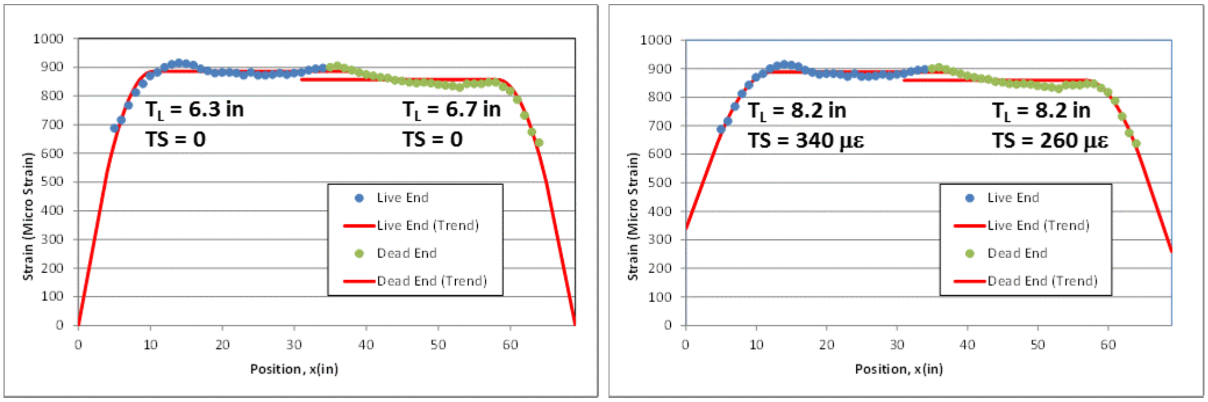
Figure 9 shows the result of typical thermal images captured by the IR camera setup shown earlier in Figure 7(b). These images were taken after de-tensioning and right after the castings were removed from plywood casting forms. The color bar shows the approximate temperature distribution for the stepped concrete member in Figure 9(a) and for the prismatic member in Figure 9(b). It is quite apparent that there is a reduction of temperature near the ends of the members and this is quite pronounced near the corners and edges where significant heat conduction "fin effect" appears to be present. This suggests a possible non-uniform thermal expansion behavior near the ends of each prestressed concrete member. Similar behavior is shown in Figure 10, which corresponds to images taken using the IR camera just after the members were removed from the hot-soak where they were brought to approximately equilibrium temperature of 107 F.



(a) Stepped Concrete Member (b) Prismatic Concrete Member

Figure 10: IR Images After Removal from Hot Environment

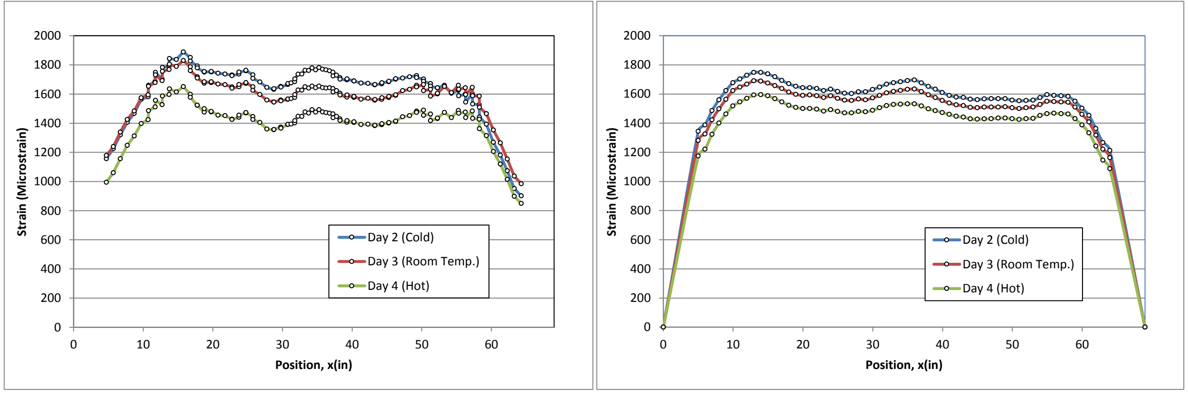
A comparison of the processing of transfer length for prismatic members, with and without a uniformly imposed thermal offset is shown in Figure 11. The data shown is 5-point averaged strain measured using the traditional Whittemore gauge. Here the transfer length was evaluated separately for each end of the concrete member. In Figure 11(a) the thermal offset parameter was set to zero, while in Figure 11(b) the Zhao-Lee transfer length algorithm[23] was allowed to evaluate the thermal offset parameter so as to provide the best fit to the measurements of strain.



(a) Thermal Offset Suppressed (b) With Thermal Offset Parameter

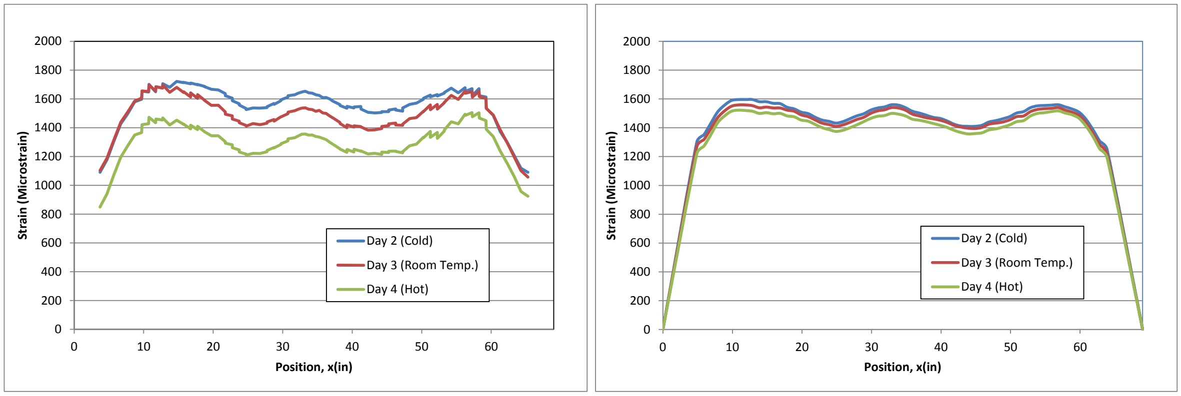
Figure 11: Prismatic Strain Profile and Transfer Length Assessment

Due to possible internal thermal gradients resulting from the internal hydration reaction of the curing concrete, the "true" thermal offset (if indeed it is due to thermal expansion effects) is probably somewhere in between the zero offset condition and the somewhat improved curve fit with the Zhao-Lee fitted thermal offset. Similar results are also shown for the other two concrete member geometries. Because of the transient nature of the hydration heating making it difficult to ascertain the real internal thermal condition, the concrete members were later subjected to known environmental temperatures for sufficient time so as to come to equilibrium. Tests conducted on Day 2 and on Day 4 represent cold-soak and hot-soak equilibrium conditions, as depicted in Figure 5. Figure 12(a) shows the result of surface strain measurements on the prismatic member obtained using the 6-camera non-contact optical strain measurement system on Day 2, Day 3, and Day 4. The strain measurements were referenced to the initial baseline on Day 0, and a 5-point smoothing was applied to the measurements to help clarify the offset. A significant thermal offset is evident in the data; however, the offset does not appear to be uniform over the length of the prism. Similar behavior is shown in Figure 12(b) for the Whittemore measurements; however, the amount of the offset is considerably less.



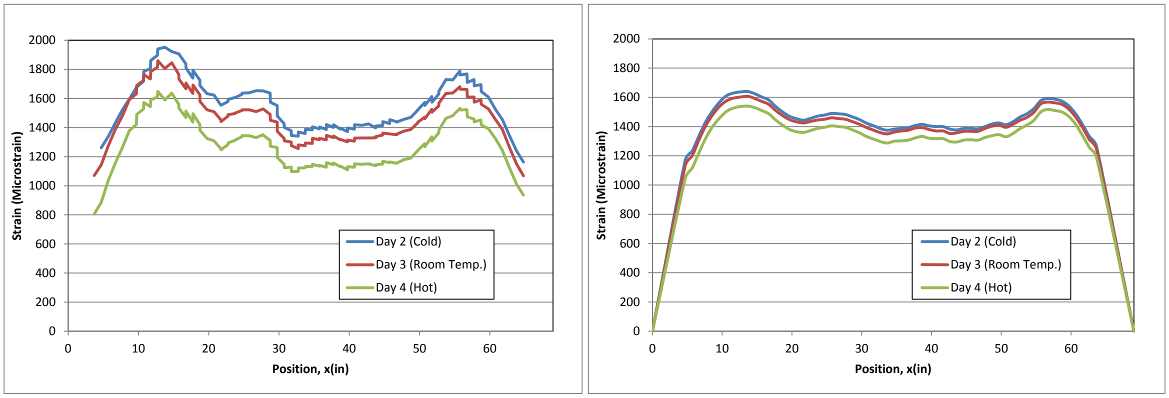
(a) 6-Camera System (b) Whittemore Gauge

Figure 12: Comparison of Observed Thermal Shift for Prismatic Member



(a) 6-Camera System (b) Whittemore Gauge

Figure 13: Comparison of Observed Thermal Shift for Stepped Member



(a) 6-Camera System (b) Whittemore Gauge

Figure 14: Comparison of Observed Thermal Shift for Tapered Member

Similar behavior is shown in Figure 13 for the stepped concrete member and in Figure 14 for the tapered concrete member. For clarify, the individual data points have been suppressed from Figure 13 and figure 14.

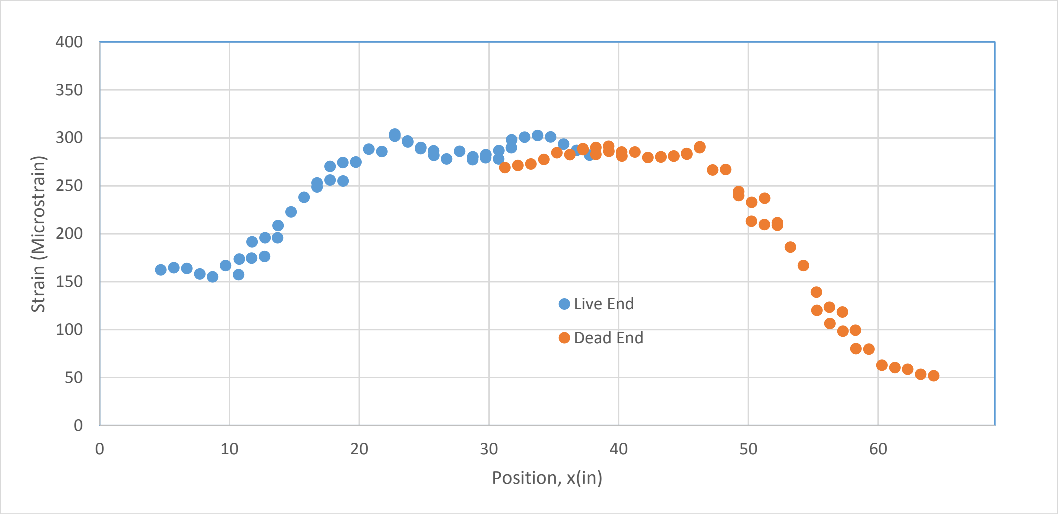


Figure 15: Direct Comparison of Prismatic Hot to Cold Environmental Thermal Shift

As an alternative to the absolute thermal offset portrayed in Figure 12 through figure 14, the optical strain sensor offers the ability to directly compare the relative thermal shift from the cold Day 2 environmental condition to the hot environmental condition on Day 4. This is accomplished by direct image correlation similar to what is done in making the strain measurements relative to the absolute baseline condition. Figure 15 shows the results of this relative shift for the prismatic member. There is a well-defined plateau with a maximum strain level of about 300 microstrain. This level of relative strain is in very good agreement with what one could expect in thermal expansion effect based on the known thermal expansion coefficient of concrete of about 5 x 10^{-6} F^{-1}. Similar peak levels of this relative strain are shown for the stepped case in Figure 16 and for the tapered case in Figure 17.

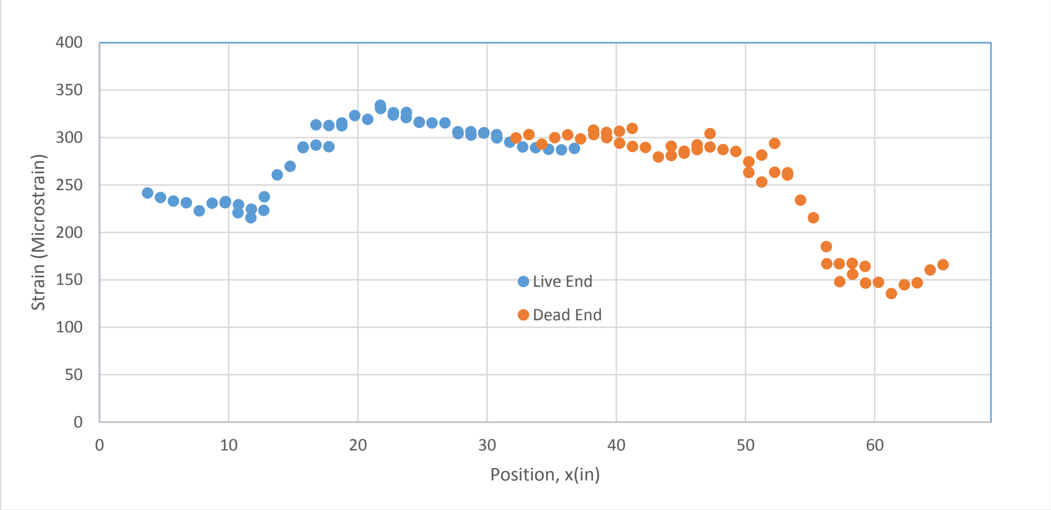


Figure 16: Direct Comparison of Stepped Hot to Cold Environmental Thermal Shift

In addition to the plateau level in Figures 15-17 being consistent with an expected level of thermal expansion offset resulting from the approximately 60 F relative temperature difference between the hot and cold chamber conditions, there appears to be a significant development region on each end of the concrete members, over which the thermal offset is not uniform but increasing from the ends of the member toward the central plateau region. This suggests that the cooling of the ends and edges of the concrete members may influence the resulting thermal expansion effect and hence the thermal offset phenomena.

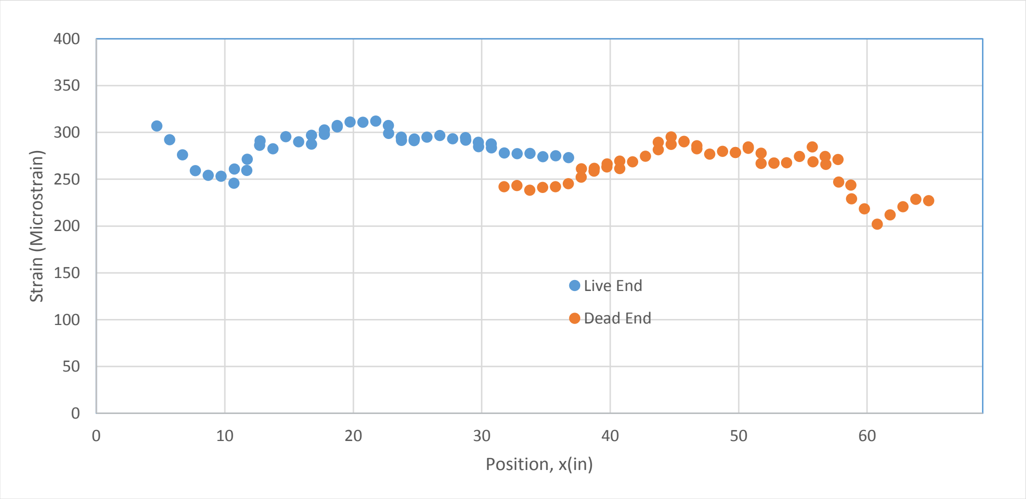
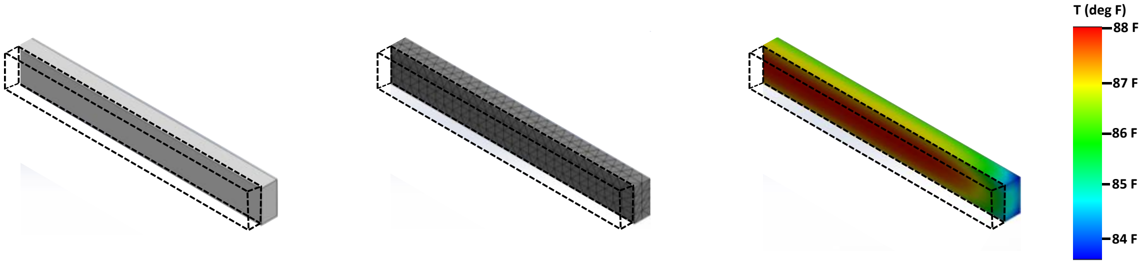


Figure 17: Direct Comparison of Tapered Hot to Cold Environmental Thermal Shift

Comparing the surface strain measurements obtained using the Whittemore gauge with those of the optical sensor reveals an apparent reduction in the magnitude of the observed thermal offset phenomena. This observed reduction in offset with the Whittemore gauge appears to be due to the manner in which the manual gauge is prepared (calibrated) against a standard gauge block prior to conducting the measurements. The usual approach is to allow the calibration block to come to equilibrium on the surface of the concrete member prior to making the calibration zero check. In the case of the current concrete members, however, the surface temperature is not as representative as the internal core temperature and in fact an appreciable temperature drop will occur from the interior to the surface for the hot-soak condition in particular. In effect, this reduces the amount of strain observed by the mechanical gauge, resulting in a smaller effective thermal shift. This new observation may prove to be of further importance in future situations where appreciable thermal effects are likely to be encountered when using the Whittemore gauge.

To further investigate the above thermal offset phenomena, a relatively simple transient numerical thermal conduction simulation was developed using SolidWorks software. The sectional view of the transient simulation is shown in Figure 18 for a half-length prism. The results correspond to the thermal condition after about 30 minutes of exposure to room temperature conditions starting from an elevated temperature of about 110 F. This approximates the Day 4 hot-soak conditions.



(a) Prismatic Geometry (b) Numerical Mesh (c) Temperature Contours

Figure 18: Transient Thermal Simulation for Prismatic Member

The simulation shows the same observations of appreciable cooling near the ends of the prismatic member, suggesting possible development of a non-uniform thermal expansion and hence likely producing a strain profile similar to the measured relative strain shown in Figure 15. This same numerical result was used to compare predicted core temperatures to the observed core temperatures. From the observed (measured) core temperature data shown in Figure 19, the observed temperatures correspond to a cooling time between about 10-30 min from initial exposure to the ambient room temperature environment, which is very similar to the nominal time of measurement on each end of the concrete members. Of course, this transient simulation depends on the specific convection conditions imposed on the model; however, the magnitudes indeed strongly suggest correspondence with the observed cooling effect.

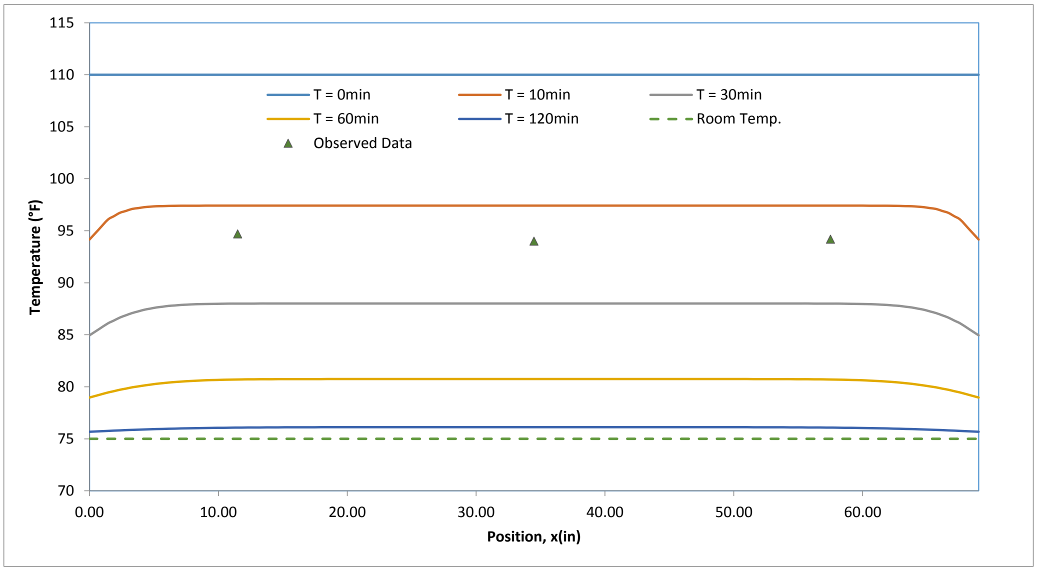


Figure 19: Simulated and Measured Core Temperatures for Prismatic Member

The transient effects noted above could affect the manner in which we evaluate the thermal offset in the existing Zhao-Lee transfer length algorithm, and as a result may affect the transfer length value itself by altering (effectively increasing) the length of the strain development region near the end of each member. Some form of monitoring of the thermal condition of the concrete member may be necessary in some situations for reliable and repeatable transfer length assessment.

CONCLUSIONS

Extensive measurements of transfer length for prismatic as well as non-prismatic members, including in-plant crosstie measurements, have often revealed a significant offset in the strain profile which appears to be related to thermal expansion effects. It has been hypothesized that this thermal offset results from a difference in the temperature of the concrete member before and after the de-tensioning process; however, this has never been verified experimentally. Furthermore, existing algorithms used to assess transfer length have included a strain offset parameter for the purpose of improving the evaluation process. However, the source of this offset, and the applicability of assuming a uniform thermal offset parameter in assessing transfer length, has also never been verified experimentally.

This paper has presented the results of a systematic investigation of the observed offset phenomena. Measurements were conducted on thermally-instrumented prismatic members as well as non-prismatic members subjected to known temperature environments both before and after de-tensioning. The concrete members tested included a stepped member and a tapered member, the features of which are somewhat representative of the main features encountered in typical actual railroad crosstie geometry. Surface strain profiles were determined using both the traditional Whittemore gauge measurement procedure and using the new multi-camera optical non-contact surface strain measurement system developed by the authors.

As a first step in a systematic experimental investigation of the thermal offset phenomena, experimentally measured surface strain profiles have been presented here when the concrete members were immersed in known hot and cold environmental conditions and allowed to come to equilibrium before initiating the strain measurements. Two simplified non-prismatic prestressed concrete members were cast to represent known variations in cross-section shape and prestressing wire eccentricity, so as to demonstrate any effect of the geometry on surface strain profile variation and likewise on the thermal offset phenomena. These two non-prismatic shapes were an abrupt stepped (or block) geometry and a tapered geometry, each of which captures one of the dominant geometrical features associated with commercially produced railroad crossties.

The strain measurements presented in this paper have revealed that the source of the offset phenomena does indeed appear to be associated with thermal expansion. The observed plateau in relative thermal shift when comparing strain measurements under hot to cold conditions is consistent with thermal expansion for the measured temperature change. In addition, there appears to be a strong indication of a non-uniform thermal expansion effect resulting from localized cooling near the ends of the concrete members. This has been further established by direct infrared camera images of surface temperature contours, and also by means of a conduction simulation model. While this non-uniformity clearly will depend on the mass of the concrete member under test, it suggests that under certain circumstances the non-uniformity in thermal offset may manifest itself in the form of a modified strain development region, essentially altering the slope of the strain development zone near the ends of prismatic members, and likely also affecting non-prismatic members to an extent as well.

More analysis of the influence of the thermal offset behavior and its influence on transfer length, and transfer length uncertainty in particular, 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 measurement requirements needed for reliable in-plant automated transfer length assessment if it is to be used for in-plant quality control.

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REFERENCES

1. Peterman, R. J., J. A. Ramirez, and J. Olek, “Influence of Flexure-Shear Cracking on Strand Development Length in Prestressed Concrete Members”, PCI Journal, V. 45, No. 5, September–October 2000, pp. 76–94.
2. Gross, Shawn P., and Ned H. Burns, “Transfer and development length of 15.2mm (0.6 in.) diameter prestressing strand in high performance concrete: results of the Hobitzell-Buckner beam tests”, Research report FHWA/TX-97/580-2, Center for transportation Research, The University of Texas at Austin, June 1995.
3. Kaar, P., and D. Magura., “Effect of Strand Blanketing on Performance of Pretensioned Girders”, PCI Journal, V. 10, No. 6, December 1965, pp. 20–34.
4. Murphy, Robert L., “Determining the Transfer Length in Prestressed Concrete Railroad Ties Produced in the United States”, M.S. Thesis, 2012, Kansas State University, Manhattan, Kansas, USA.
5. Wu C.-H., Zhao W., Beck T. and Peterman R. "Optical Sensor Developments for Measuring the Surface Strains in Prestressed Concrete Members" Journal of Strains, 47, Supp. 1, pp. 376-386, (2011), DOI: 10.1111/j.1475-1305.2009.00621.x.
6. Mark Haynes, John C.-H. Wu, B. Terry Beck, and Robert J. Peterman "Non-Contact Measurement of Wire Indent Profiles on Prestressing Reinforcement Steel" Proceedings of the 2012 AREMA Conference, Sept. 16-19, 2012, Chicago Illinois, USA.
7. Weixin Zhao, Terry Beck, Robert Peterman, John Wu, Rob Murphy and John Bloomfield, Grace Lee. “An Automated Transfer Length Measurement System for use on Concrete Railroad Ties,” The 2012 PCI Convention and National Bridge Conference, September 29 - October 3, 2012.

8. Weixin Zhao ; B. Terry Beck ; Robert J. Peterman and Chih-Hang J. Wu, "A Portable Modular Optical Sensor Capable of Measuring Complex Multi-Axis Strain Fields", Proceedings *of the SPIE* 8466, Instrumentation, Metrology, and Standards for Nanomanufacturing, Optics, and Semiconductors VI, 84660Q (October 11, 2012); doi:10.1117/12.929931.
9. Weixin Zhao, Kyle Larsan Robert J. Peterman,B. Terry Beck, and C.-H.John Wu, "Development of a laser-speckle imaging device to determine the transfer length in pretensioned concrete members" PCI Journal Winter 2012, pp. 135-143.
10. Weixin Zhao, Robert L Murphy, Robert J Peterman, B. Terry Beck, Chih-Hang John Wu, Pelle Duong, "A Non-Contact Inspection Method to Determine the Transfer Length in Pre-tensioned Concrete Railroad Ties," ASCE, Journal of Engineering Mechanics, Journal of Engineering Mechanics, Volume: 139, Issue: 3, March 2013, pp. 256- 263.
11. Mark Haynes, John C.-H. Wu, B. Terry Beck, Naga N.B. Bodapati, and Robert J. Peterman "Prestressing Steel Reinforcement Wire Bond Index Number," Proceedings of the 2013 Joint Rail Conference, JRC2013-2422 April 15-18, 2013, Knoxville, Tennessee, USA. DOI: 10.1115/JRC2013-2422.
12. Matthew L. Arnold, Robert J. Peterman, Naga N.B. Bodapati, B. Terry Beck and John C.-H. Wu "Development of A Standard Bond Test For Indented Prestressing Wires," Proceedings of the 2013 Joint Rail Conference, JRC2013-2461 April 15-18, 2013, Knoxville, Tennessee, USA. doi: 10.1115/JRC2013-2461
13. Naga N.B. Bodapati, Weixin Zhao, Robert J. Peterman, John C.-H. Wu, B. Terry Beck, Mark Haynes and Joseph R. Holste, "Influence Of Indented Wire Geometry and Concrete Parameters on the Transfer Length in Prestressed Concrete Crossties," Proceedings of the 2013 Joint Rail Conference, JRC2013-2463 April 15-18, 2013, Knoxville, Tennessee, USA. doi: 10.1115/JRC2013-2463
14. Weixin Zhao, B. Terry Beck, Robert J. Peterman, and John C.-H. Wu, "Development Of A 5-Camera Transfer Length Measurement System For Real-Time Monitoring Of Railroad Crosstie Production," Proceedings of the 2013 Joint Rail Conference, JRC2013-2468 April 15-18, 2013, Knoxville, Tennessee, USA. doi: 10.1115/JRC2013-2468.
15. Weixin Zhao, B. Terry Beck, Robert J. Peterman, Robert Murphy, John C.-H. Wu, and Grace Lee, "A Direct Comparison Of The Traditional Method And A New Approach In Determining 220 Transfer Lengths In Prestressed Concrete Railroad Ties," Proceedings of the 2013 Joint Rail Conference, JRC2013-2469 April 15-18, 2013, Knoxville, Tennessee, USA. doi: 10.1115/JRC2013-2469.
16. Mark D. Haynes, Chih-Hang J. Wu, B. Terry Beck, Robert J. Peterman (2013), "3D Non-contact Profilometry For Reinforcement Steel Quality Control," *Proceedings of the Industrial and Systems Engineering Research Conference (ISERC)*, May 2013, San Juan, Puerto Rico.
17. Mark D. Haynes, Chih-Hang J. Wu, B. Terry Beck, Robert J. Peterman (2013), "Automated Real-Time Search and Analysis Algorithms for a Non-Contact 3D Profiling System," *Proceedings of the SPIE, Volume 8791, id. 87911G 12 pp.* Munich, Germany.
18. Naga Bodapati, R.J. Peterman, W. Zhao, T. Beck, C.-H. Wu, J. Holste, M. Arnold, R. Benteman, R. Schweiger, "Transfer-Length Measurements On Concrete Railroad Ties Fabricated With 15 Different Prestressing Reinforcements," 2013 PCI Convention and

National Bridge Conference, September 21 – 24 at the Gaylord Texan Resort in Grapevine, Texas.
19. Mark Haynes, Levi DeLissa, Chih-Hang John Wu, B. Terry Beck, and Robert J. Peterman, "Design of a Non-Contact Surface Profilometry System for Automated Geometrical Dimensioning and Tolerancing," *International Journal of Engineering Inventions* 2013 e-ISSN2278-7461, p-ISSN: 2319-6491, Vol. 3, Issue 2, Sep. 2013, PP: 15-19.
20. Weixin Zhao, B. Terry Beck, Robert J. Peterman, John C.-H. Wu, Grace Lee, and Naga N.B. Bodapati, "Determining Transfer Length In Pre-Tensioned Concrete Railroad Ties: Is Anew Evaluation Method Needed?" Proceedings of the 2013 ASME Rail Transportation Division Fall Technical Conference, RTDF2013-4727 October 15-17, 2013, Altoona, Pennsylvania, USA.
21. Joseph R. Holste, Robert J. Peterman, Naga, N.B. Bodapati, B.Terry Beck, and C.-H. John Wu, "Transfer Bond Test User to Predict Transfer Length of Concrete Railroad Ties," Proceedings of the 2013 ASME Rail Transportation Division Fall Technical Conference, RTDF2013-4726 October 15-17, 2013, Altoona, Pennsylvania, USA.
22. Naga N.B. Bodapati, Weixin Zhao, Robert J. Peterman, John C.-H. Wu, B. Terry Beck, Mark Haynes and Joseph R. Holste, "Effect of Concrete Properties on Transfer Lengths in Concrete Rail-Road Ties," Proceedings of the 2014 Joint Rail Conference, JRC2014-3859 April 2-4, 2014, Colorado Springs, Colorado, USA.
23. Weixin Zhao, B. Terry Beck, Robert J. Peterman, John C.-H. Wu, Naga N.B. Bodapati, and Grace Lee, "Reliable Transfer Length Assessment For Real-Time Monitoring Of Railroad Cross-Tie Production," Proceedings of the 2014 Joint Rail Conference, JRC2014-3830 April 2-4, 2014, Colorado Springs, Colorado, USA.
24. Mark Haynes, John C.-H. Wu, B. Terry Beck, Naga N.B. Bodapati, and Robert J. Peterman, "Prestressing Steel Reinforcement Wire Measurement Protocol," Proceedings of the 2014 Joint Rail Conference, JRC2014-3800 April 2-4, 2014, Colorado Springs, Colorado, USA.
25. Joseph R. Holste, Mark Haynes, Robert J. Peterman, B. Terry Beck, John C.-H. Wu, "Tensioned Pullout Test used to Investigate Wire Splitting Propensity in Concrete Railroad Ties," Proceedings of the 2014 Joint Rail Conference, JRC2014-3799 April 2-4, 2014, Colorado Springs, Colorado, USA.
26. Mark Haynes, John C.-H. Wu, B. Terry Beck, Naga N.B. Bodapati, and Robert J. Peterman, "An Investigation into Non-Linear Search Modifications for Minimizing Objective Function Computations," Proceedings of the 2014 Industrial & Systems Engineering Research Conference (ISERC) Conference, ISERC2014-I393 May 31-June 3 2014, Montréal, Canada.
27. B. Terry Beck, Weixin Zhao, Robert J. Peterman, Chih-Hang John Wu, Joseph Holste, Naga Narendra B. Bodapati, Grace Lee, "Effect Of Surface-Strain Sampling Interval On The Reliability Of Pretensioned Concrete Railroad Tie Transfer Length Measurements," 2014 PCI Convention and National Bridge Conference, September 21 - 24 at the Gaylord National Resort in Washington, D.C.
28. Joseph Holste, Mark Haynes, Robert Peterman, B. Terry Beck, Chih-Hang John Wu, "Application Of Tensioned Pullout Tests To Investigate The Effect Of Prestressing Wire Indent Geometry On Bond And Splitting Characteristics," 2014 PCI Convention and

National Bridge Conference, September 21 - 24 at the Gaylord National Resort in Washington, D.C.
29. Naga Narendra B. Bodapati, Robert J. Peterman, Weixin Zhao, B. Terry Beck, PhD, Chih-Hang John Wu, Joseph R. Holste, Matthew L. Arnold, Ryan Benteman, Robert Schweiger, "Long-Term Transfer-Length Measurements On Pretensioned Concrete Rail Road Ties," 2014 PCI Convention and National Bridge Conference, September 21 - 24 at the Gaylord National Resort in Washington, D.C.
30. Russell, B. W., and N. H. Burns., "Design Guidelines for Transfer, Development and Debonding of Large Diameter Seven Wire Strands in Pretensioned Concrete Girders", Report number 1210-5F., 1993, Austin, TX: Center for Transportation Research, University of Texas at Austin.
31. Lutch, Russell H., "Capacity optimization of a prestressed concrete railroad tie", M.S. Thesis, Civil and Environmental Engineering Department, Michigan Technological University, May 2010 (Open Access Theses & Dissertations. http://digitalcommons.mtu.edu/etds/254).
32. Yu, H., Jeong, D., "Railroad Tie Responses to Directly Applied Rail Seat Loading in Ballasted Tracks: A Computational Study", Proceedings of the ASME/ASCE/IEEE 2012 Joint Rail Conference, April 17-19, 2012, Philadelphia, Pennsylvania, USA.
33. Beck, B. Terry, Peterman, Robert J., Wu, Chih-Hang (John), and Bodapati, Naga Narendra B., "In-Plant Testing of a New Multi-Camera Transfer Length Measurement System for Monitoring Quality Control of Railroad Crosstie Production," Proceedings of the 2015 Joint Rail conference, March 23-26, 2015, San Hose, CA, USA.
34. B. Terry Beck, Robert J. Peterman, John C.-H. Wu, Steve Mattson, "Experimental Investigation of the Influence of Surface Contaminants on the Transfer Length of Smooth and Indented Prestressing Reinforcements Used in the Manufacture of Concrete Railroad Ties, Paper Number: JRC2015-5751, Proceedings of the 2015 Joint Rail Conference, San jose, CA, March 23-26, 2015.
35. Amir Farid Momeni, Robert J. Peterman, B. Terry Beck, Chih-Hang John Wu, Naga Narendra B. Bodapati, "Effect of Prestressing Wire Indentation Type on the Development Length and Flexural Capacity of Pretensioned Concrete Crossties," Paper Number: JRC2015-5739, Proceedings of the 2015 Joint Rail Conference, San Jose, CA, March 23-26, 2015.
36. Mark Haynes, Chih-Hang John Wu, Naga Narendra B. Bodapati, B. Terry Beck, Robert J. Peterman, "Modeling the Behavior of Prestressed concrete Railroad Ties," Paper Number: JRC2015-5703, Proceedings of the 2015 Joint Rail Conference, San Jose, CA, March 23-26, 2015.
37. B. Terry Beck, Naga Narendra B. Bodapati, Robert J. Peterman, Amir Farid Momeni, Chih-Hang John Wu, "Transfer length Measurements in Pretensioned Concrete Railroad Ties Under Rail Loads," Paper Number: JRC2015-5690, Proceedings of the 2015 Joint Rail Conference, San Jose, CA, March 23-26, 2015.
38. Robert J. Peterman, Naga Narendra B. Bodapati, B. Terry Beck, John C.-H. Wu, "Long-Term End-Slip Measurements and Corresponding Transfer lengths in Pretensioned concrete Railroad Ties fabricated with 15 Different Reinforcements," Paper Number: JRC2015-5678, Proceedings of the 2015 Joint Rail Conference, San Jose, CA, March 23-26, 2015.

39. Amir Farid Momeni, Robert J. Peterman, B. Terry Beck, Chih-Hang John Wu, Naga Narendra B. Bodapati, "Effect of Concrete Release Strength on the Development Length and Flexural capacity of Members Made with different Prestressing Wires Commonly Used in Pretensioned concrete Railroad Ties," Paper Number: JRC2015-5736, Proceedings of the 2015 Joint Rail Conference, San Jose, CA, March 23-26, 2015.