EFFECTS OF AMBIENT TEMPERATURE ON LONG-TERM CAMBER OF PRECAST PRESTRESSED CONCRETE BEAMS

Ebadollah Honarvar Gheitanbaf, Graduate Research Assistant, Department of Civil, Construction, and Environmental Engineering, Iowa State University, Ames, IA
Sri Sritharan, PhD, Wilson Engineering Professor, Department of Civil, Construction, and Environmental Engineering, Iowa State University, Ames, IA
Jon M. Rouse, PhD, Senior Lecturer, Department of Civil, Construction, and Environmental Engineering, Iowa State University, Ames, IA

ABSTRACT

Measured long-term camber of 80 precast prestressed concrete beams (PPCBs) during storage revealed inconsistent trends. The variations from theory included significantly high camber at early ages and reduction or no significant increase in camber over time. The temperature gradient that develops down the beam depth due to solar radiation was suspected to be contributing to these discrepancies. If significant, the temperature gradient down the beam depth would cause construction difficulties when the PPCBs are erected and the slab elevations are set.

Considering that the thermal gradient is typically ignored in predicting the camber of PPCBs, a systematic investigation was undertaken. Twenty two different PPCBs were instrumented with string potentiometers and thermocouples to measure camber growth and surface temperature, respectively, and measurements were taken over 24 hours. The measured data indicated that camber can vary as much as 0.75 in. during the course of a day. Subsequently, this data were used to calibrate an analytical model to quantify the additional long-term camber induced by the temperature gradient. Eventually, a multiplier function was developed to take into account the increase in camber due to temperature gradient, ultimately improving accuracy of estimated camber at the time of erection.

Keywords: Temperature Gradient, Long-term Camber, Temperature Distribution, Prestressed Precast Concrete Beams, Multiplier, Camber Prediction

INTRODUCTION

Originally, a research study was undertaken to identify the potential sources of discrepancies between the predicted and measured camber of precast prestressed concrete beams (PPCBs) from release to the time of erection. The objective of this study was to improve the accuracy of camber estimation and avoid related problems in the field. To achieve the project goal and minimize the influence of uncertainties, the research involved three precast plants who supply PPCBs to bridge projects in Iowa. The mechanical properties such as modulus of elasticity, creep behavior and shrinkage of four high performance concrete mix designs were characterized through laboratory testing. Next, the investigation focused on instantaneous camber upon transfer of the prestress force to the concrete. The variables affecting the instantaneous camber were identified, and their impacts were evaluated. These variables included elastic material properties, transfer length, camber measurement techniques, friction effects, and bed deflection. The long-term camber was then analytically evaluated with due consideration to creep and shrinkage of concrete, changes in support conditions and prestress force, and temperature effects.

The investigators found several factors influencing the long-term camber[1]. The temperature gradient across the depth of the beam was one of the large influencing factors. This paper is devoted to the examination of this particular variable on the long-term camber measurement and prediction for PPCBs.

RESEARCH OBJECTIVES

Measured long-term camber of 80 PPCBs during storage exhibited inconsistent trends in data. The variations included significantly high camber at early ages and reduction or no significant increase in camber over time. The temperature gradient that develops down the beam depth due to solar radiation was suspected to be contributing to these discrepancies with theory. Considering that the thermal gradient is typically ignored in predicting the camber of PPCBs, a systematic investigation was undertaken with an objective of understanding the impact of thermal gradient on camber with due consideration to seasonal climate variations. Using a combination of field measurements and simulation, a methodology is proposed to account for this thermal effect in camber prediction.

BACKGROUND

Camber is the net deflection caused by the upward deflection due to the applied prestress force and downward deflection due to the self-weight of precast, prestressed concrete beams (PPCBs), which typically occurs from the time the prestressed is transferred to PPCBs. Camber can be referenced based on the time period when it is measured. The two most commonly referenced camber values are the instantaneous value which occurs immediately after the transfer of prestress and the long-term value at the time of erecting the beam.

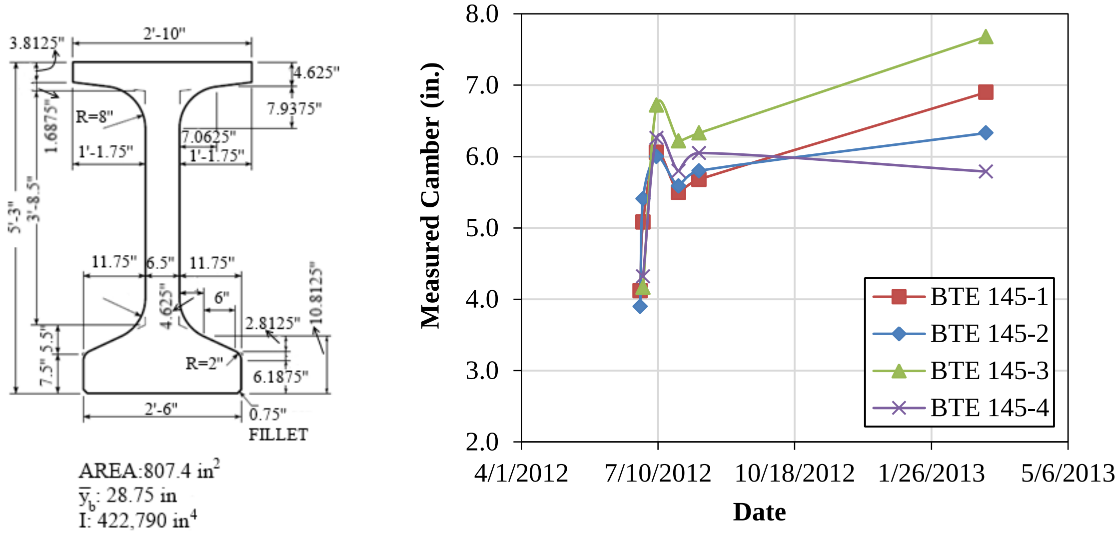
Long-term camber of PPCB's is relatively complex as it is sensitive to fabrication practices such as mix design, tolerances on prestressing forces and moisture control, bed configuration, curing procedures, and handling, storage environment, and support conditions while in storage. In addition, local aggregates, cement, and admixture supply play a significant role in creep and shrinkage behavior of concrete, which in turn can affect the long-term camber significantly. Hence, the current methods of long-term camber prediction are typically inaccurate, often leading to increased construction costs and quality control concerns. The current practice for predicting long-term camber also typically ignores the influence of the diurnal heating cycle (thermal camber) producing additional error in camber estimation.

Prestressed precast concrete beams (PPCBs) are affected by daily and seasonal temperature changes during the storage at the precast yard[2]. As a result, vertical temperature gradients are developed down the beam depth due to uneven heating and cooling. Solar radiation provides heat energy most directly to the top flange of the beams. Convection to or from the surrounding atmosphere can contribute to additional heat gain or loss. Different factors such as wind speed, ambient temperature, relative humidity, weather condition (clear or cloudy), surface characteristics, the time of day, and the time of year affect the changes in the temperature[3, 4, 5]. Maximum temperature gradient can be expected when solar radiation is high and wind speed is low[2]. Conditions such as these would most likely occur in summer when solar radiation is most intense.

Beam depth mainly governs the shape of the vertical temperature gradient distribution. For shallow sections with depths smaller than a foot, the temperature distribution is nearly linear, while temperature distribution tends to be more nonlinear for depth greater than a foot[4]. The simple support conditions for the beams induced no axial or bending stresses due to thermal effects in the section. Consequently, self-equilibrating stresses were assumed to be developed in the beam from the strains induced in the member that countered the distortion of the section resulting from the nonlinear thermal strain profile. A constant curvature along the beam length can be assumed based on the resultant strain profile and can be used to calculate a theoretical camber resulting from a temperature gradient.

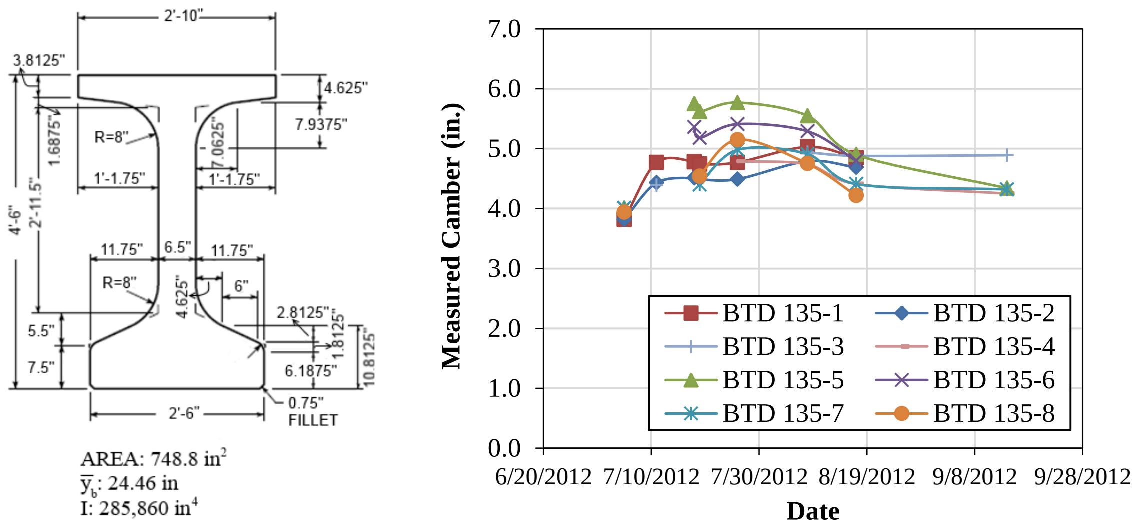
SCATTER IN LONG-TERM CAMBER

Long-term cambers of 80 various Iowa Department of Transportation (Iowa DOT) PPCBs were measured during storage at the precast plants[6]. These secondary measurements were taken between 9:00 AM and 3:00 PM in different seasons. Examination of measured long-term camber of these beams during storage revealed inconsistent trends in data, which comprised of girders cast at the same precast plant at the same time. As a representative of the entire set of measured beams, the data for two subsets of beams produced at the same time are presented here. These beams were Iowa DOT standard BTE 145 and BTD 135 beams with the span length of 145 ft and 135 ft, respectively[6].



(a) (b)

Figure 1: BTE beam: (a) Cross sectional dimensions (b) Measured long-term cambers for BTE 145



(a) (b)

Figure 2: BTD beam: (a) Cross sectional dimensions (b) Measured long-term cambers for BTD 135

The irregularities included significantly high camber at early ages with reduction or no significant increase in camber over time. The spread was more pronounced for the data collected during summer as shown in Figures 1 and 2. High camber values were observed only a few days after release of prestress for BTE 145 beams in the month of July (see Figure 1). For measured BTD 135 beams, camber generally varied little over time and even declined as depicted in Figure 2.

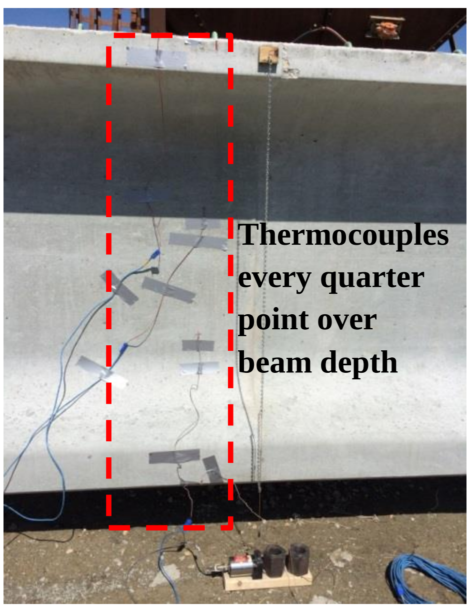
DATA COLLECTION

To further investigate the effect of solar radiation on camber, twenty two different PPCBs were instrumented with string potentiometers and thermocouples to measure thermal camber as a function of temperature over a short duration. All beams were instrumented at the mid-span with one thermocouple on the top flange, one thermocouple on the underside of the bottom flange, and one string potentiometer attached to the side of the top flange at mid-span. The beams' surface temperature and vertical deflection were monitored for a cycle of 24 hours for each beam except six BTE 155 beams that were monitored only for six hours. The measurements were taken at the Cretex precast plant in Iowa Falls, Iowa, at different times of the year to examine the impact of seasonal weather conditions on camber as a function of time. Twelve beams including six BTE 145 beams, three BTC 115 beams, and three BTD 115 beams were instrumented in summer when the solar radiation was expected to be the highest (see Figure 3). Instrumentation was performed for six BTE 155 beams in winter when temperature was below zero Fahrenheit (see Figure 4). Two BTE 155 and BTE 145 beams were instrumented in spring when moderate temperature was observed.

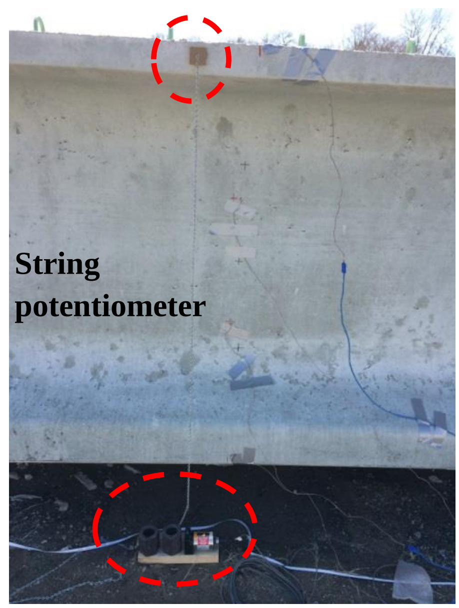
Figure 3: Instrumented PPCBs in Summer

Figure 4: Instrumented PPCBs in Winter

In addition, vertical temperature distribution over the beam depth was examined by measuring temperature at every quarter point of depth for two beams (BTE 145, BTE 155) throughout the day in spring (April). One of the beams (BTE 155) was located under shadow, while the other beam (BTE 145) was exposed to sun as demonstrated in Figure 5. Meanwhile, the vertical deflections of girders were measured by string potentiometers attached to the side of the top flange in order to correlate camber growth to temperature gradient.



(a) BTE 145



(b) BTE 155

Figure 5: Instrumented PPCBs to investigate the impact of vertical temperature distribution

OBSERVED BEHAVIOR

Figure 6 and Figure 7 show temperature variation at four points over the depth of two beams versus time. It can be seen in Figure 6 that the top flange was much warmer than at other depths for BTE 155, since those regions were under shadow. Unlike BTE 155, temperature distribution was more uniform for BTE 145 due to the exposure of the beam to sun, as exhibited in Figure 7. Additionally, the data indicate that temperature is nearly constant over the beam depth for the two beams from 8:00 PM to 8:00 AM.

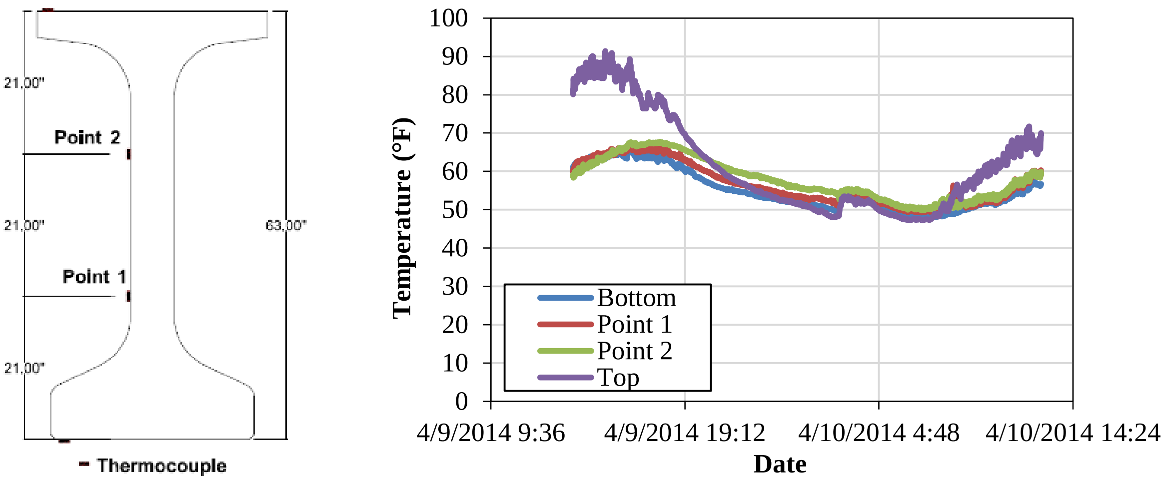


Figure 6: Temperature variation of four points over section depth of BTE 155 vs. time

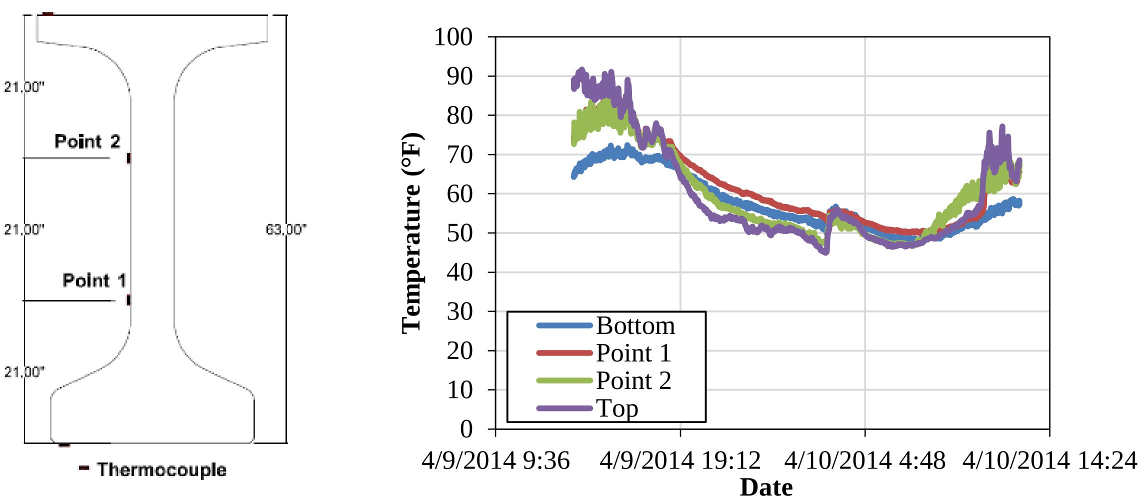


Figure 7: Temperature variation of four points over section depth of BTE 145 vs. time

The measured vertical temperature distribution over the beam depth at discrete times during the day as well as recommended vertical temperature gradient by AASHTO LRFD 2010[7] are illustrated in Figure 8 and Figure 9. It can be observed that temperature distribution is highly non-linear from noon to 6:00 PM for both beams. For the BTE 145, the measured data indicates that point 2 is cooler than point 1 since it was shadowed by the top flange of the beam (see Figure 5). Furthermore, AASHTO recommended temperature gradient over-predicted the temperature at the top of the beam as shown in Figure 8 and Figure 9.

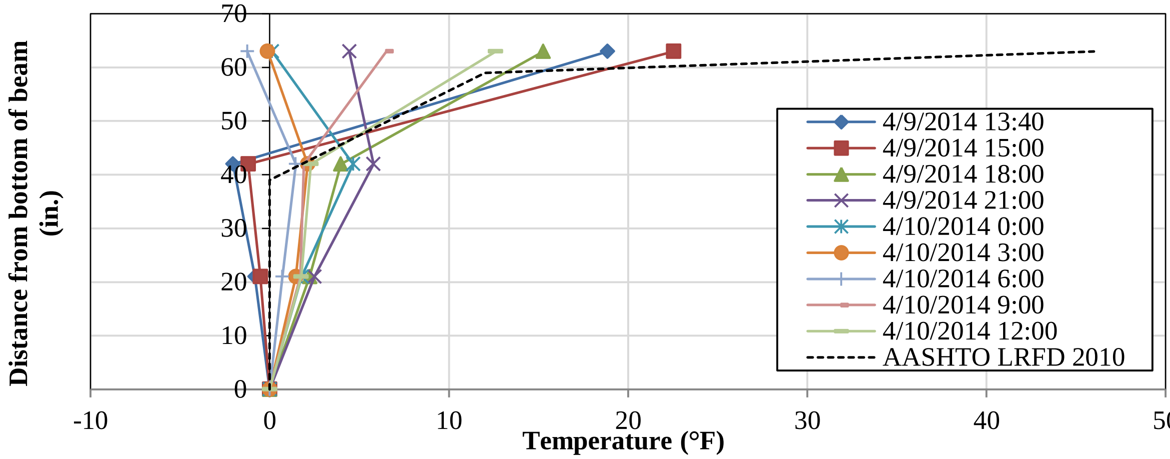


Figure 8: Temperature distribution over section depth of BTE 155 at discrete times throughout the day

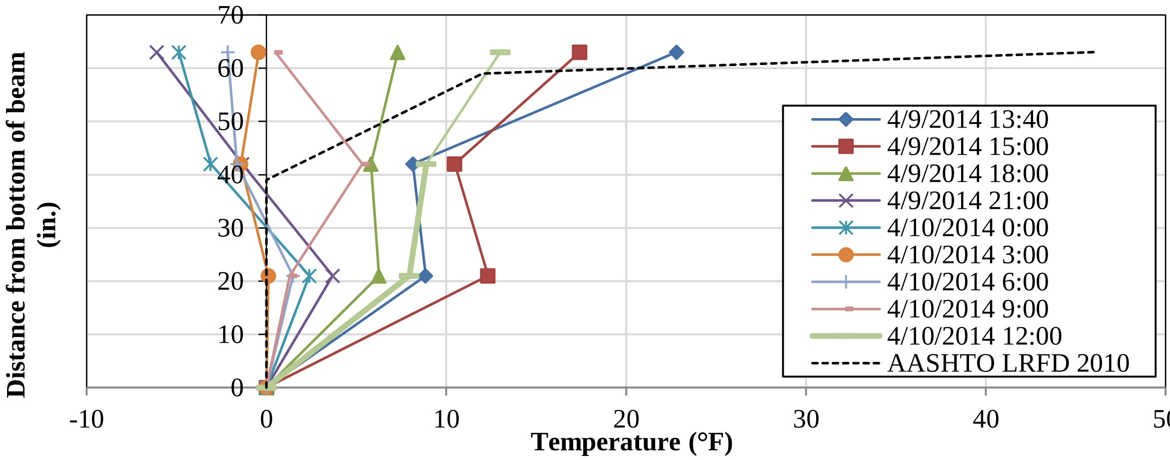


Figure 9: Temperature distribution over section depth of BTE 145 at discrete times throughout the day

Figure 10 through Figure 14 show camber growth and temperature gradient versus time in summer, winter, and spring, sequentially. The temperature gradient magnitude was taken as the temperature difference between the top and bottom flanges. The highest temperature gradient was observed in summer (July, August), while the lowest temperature gradient occurred in winter (February). As a result, thermal camber due to temperature gradient was substantially higher in summer than winter. In addition, for the girders, the maximum temperature of 128 °F and the minimum temperature of -7 °F were recorded; while, AASHTO[7] recommended value for maximum design temperature and minimum design temperature is 110 °F and -10 °F, respectively.

It can be seen in Figure 10 that the maximum temperature gradient of 29°F induced camber as high as 0.75 inches for BTE 145 girders. Thermal camber approaches zero when the temperature gradient reaches zero as shown in Figure 11. For shorter beams, the camber due to temperature gradient is smaller than for longer beams as exhibited in Figure 11, where the maximum temperature gradient of 32 °F causes thermal camber of 0.4 inches for BTC 115 girders. All the data includes time lag, which means certain time is required to attain the camber growth corresponding to the measured temperature gradient. For example, in Figure 10, temperature gradient is the highest at the beginning of the measurements, while the thermal camber is very small at the same instance. Nonetheless, the maximum thermal camber corresponding to the earlier maximum temperature gradient is reached after a few hours as shown in Figure 10.

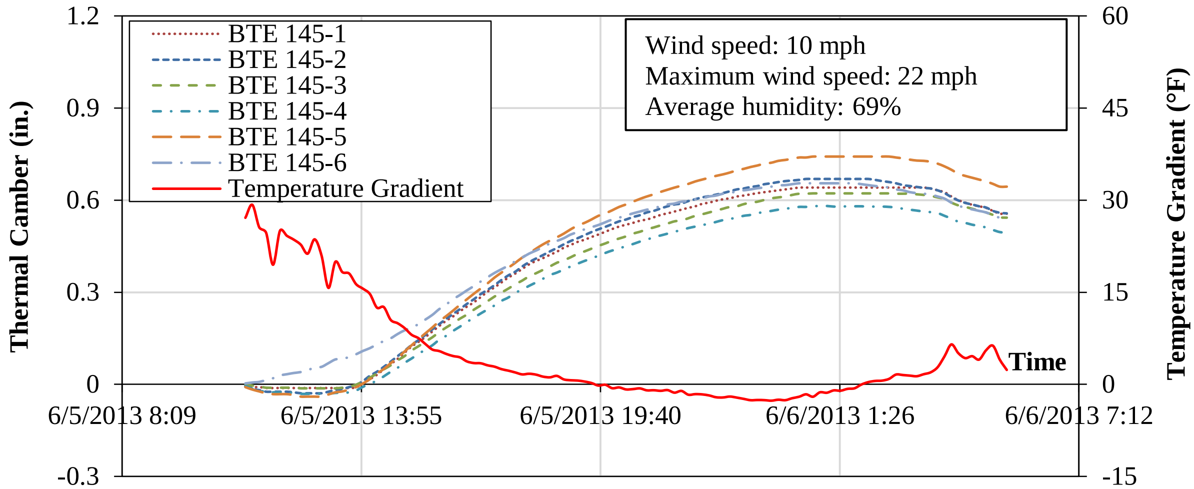


Figure 10: Thermal camber and temperature variation vs. time for BTE 145 beams in summer (June)

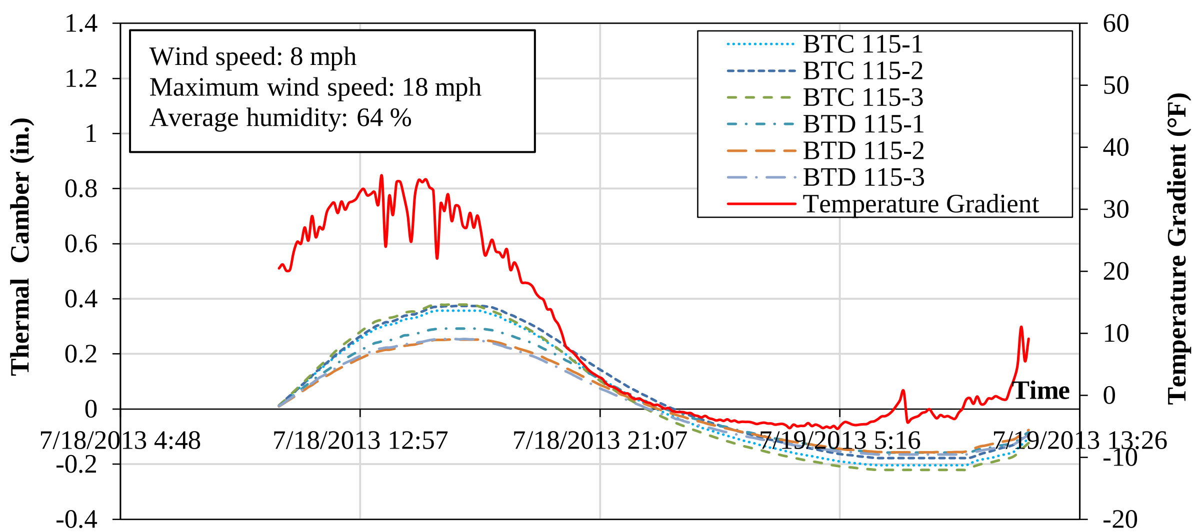


Figure 11: Thermal camber and temperature variation vs. time for BTC 115 and BTD 115 beams in summer (July)

In winter, temperature as low as -7 °F was recorded in early morning, whereas the highest measured temperature was 20 °F in the afternoon. As a result, the developed temperature gradient was relatively small in magnitude producing nearly zero thermal camber even for long beams as shown in Figure 12.

The built-up temperature gradient in spring was neither as high as summer nor as low as winter, which caused medium thermal camber as indicated in Figure 13 and Figure 14.

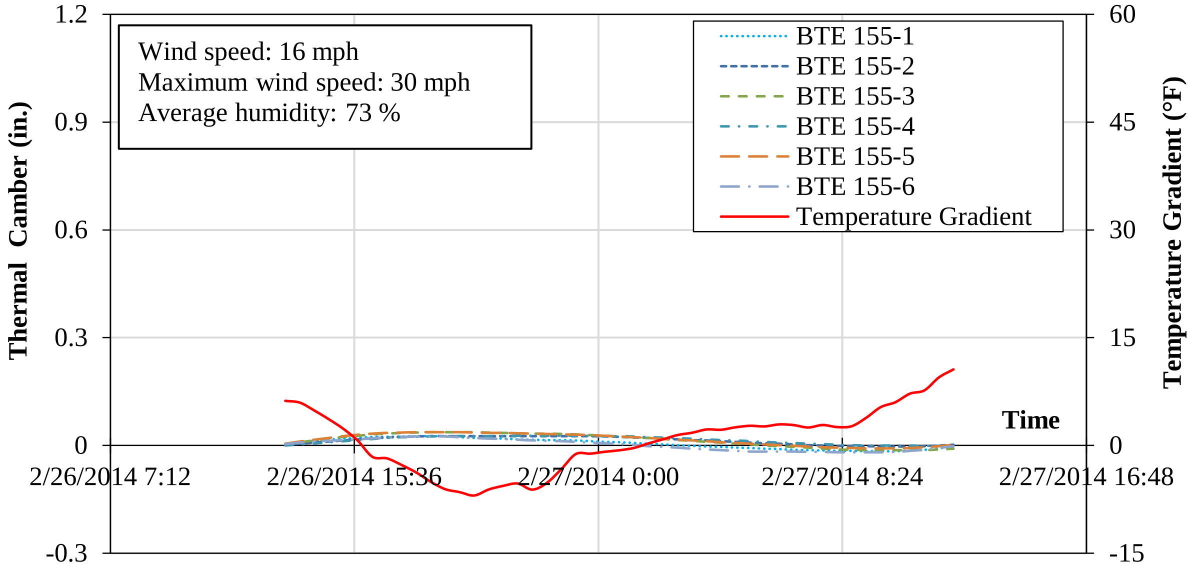


Figure 12: Thermal camber and temperature variation vs. time for BTE 155 beams in winter (February)

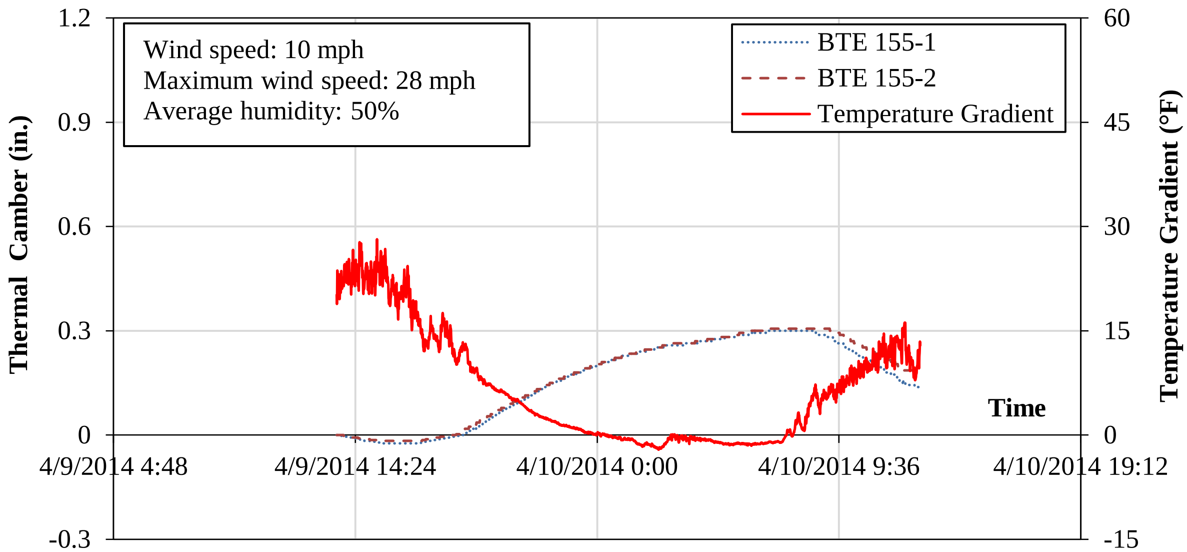


Figure 13: Thermal camber and temperature variation vs. time for BTE 155 beams in spring (April)

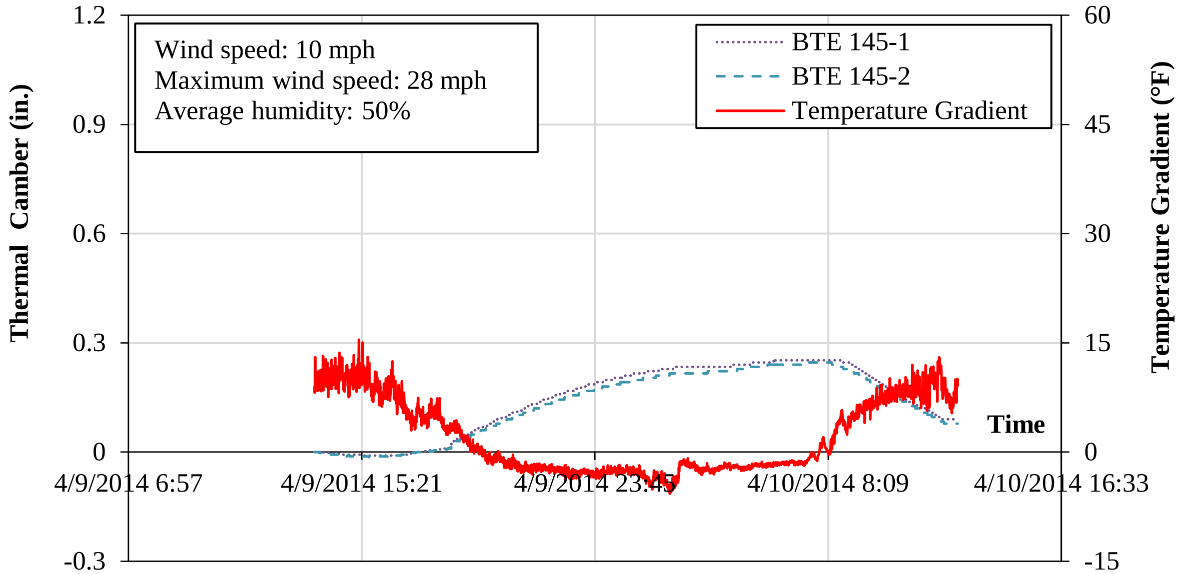


Figure 14: Thermal camber and temperature variation vs. time for BTE 145 beams in spring (April)

ANALYTICAL MODEL AND RESULTS

An analytical model was originally developed to predict camber of PPCBs from time of release to erection utilizing Finite Element Analysis[8] (FEA) without accounting for any temperature effect. Concrete modulus of elasticity was calculated according to AASHTO LRFD 2010 equation[7], using the measured initial compressive strength at time of release. Also, average creep and shrinkage curves measured at Iowa State University's structures lab in an environmentally controlled chamber were used in the model[1].

Long-term camber was compared to instantaneous camber predictions to create a power function that can provide suitable multipliers as well as a set of average multipliers to account for time-dependent effects on camber[1]. Based on the measured camber growth with time, three separate time intervals were found to be reasonable for establishing average multipliers; these time intervals were 0 to 60 days, 60 to 180 days, and 180 to 480 days. The change in camber beyond 480 days is relatively small, and precasters are not typically expected to store girders for such long periods.

Table 1 shows the recommended multipliers for bulb-tee beams with an average measured overhang length of L/30, where L is the overall beam length.

Table 1: Multiplier recommendation for long-term (erection) camber prediction including overhang effect (L/30)

0 to 60 Days	
Average Time	**Multipliers**
15	1.46±0.17
60 to 180 Days	
Average Time	**Multipliers**
115	1.59±0.10
180 to 480 Days	
Average Time	**Multipliers**
310	1.65±0.10

The proposed multipliers were used to predict long-term camber of PPCBs in this study. Then, temperature effects on camber estimation was taken into account by using temperature gradient multipliers as discussed in the following section.

VERTICAL TEMPERATURE DISTRIBUTION

Based on the measured data, it was assumed that the section is subjected to a rise of temperature which varies over the section depth in the form of a polynomial of the mth degree, in which m changes from 1 (linear) to 6. The proposed equation is presented below.

$$t_y = (\frac{y}{d})^m T \quad \textbf{(1)}$$

where, t_y is temperature at the fiber in question; y is vertical distance from bottom of section to the fiber in question; d is section depth; and T is the maximum temperature gradient in the section.

Figure 15 and Figure 16 show the comparison between the polynomial temperature distributions of different degrees and the measured temperature distribution with the maximum temperature gradient for BTE 145 and BTE 155 beams, respectively. It can be observed that the measured temperature distribution can be approximated with the second degree parabola for BTE 145 beams, while 6th degree parabola can be used to approximate the temperature distribution for BTE 155 beams. Hence, a sensitivity analysis was subsequently carried out to investigate the effects of different shape of temperature distribution on thermal camber.

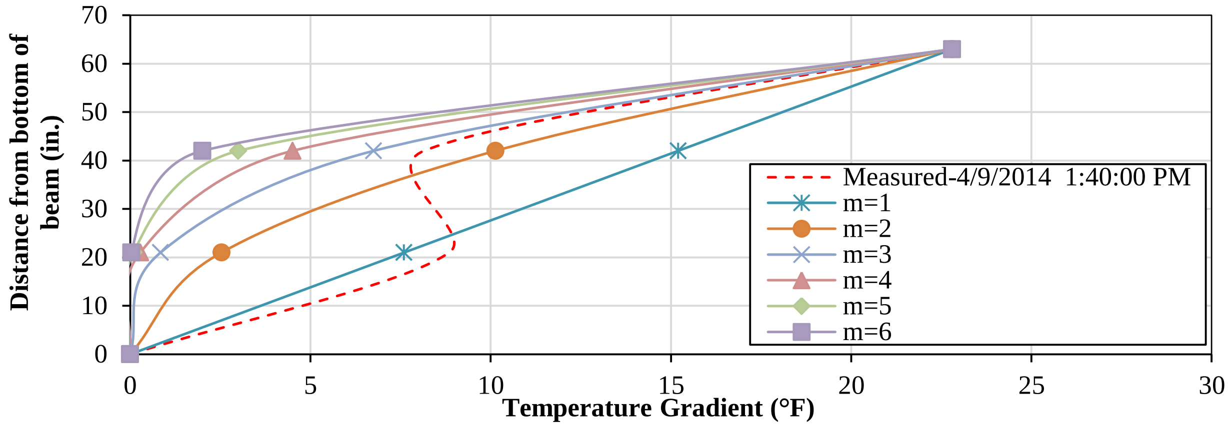


Figure 15: Comparison of mth degree polynomial temperature distribution with measured temperature distribution for BTE 145

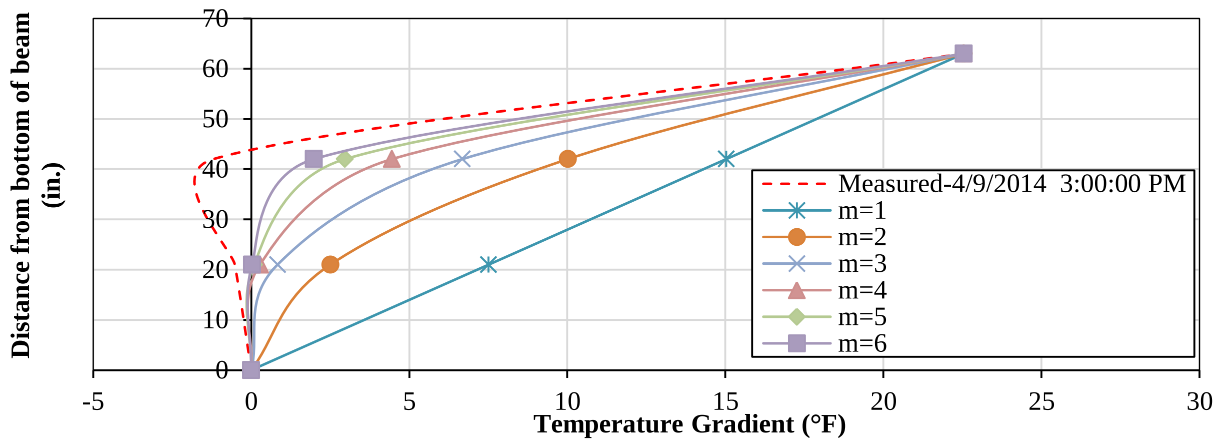


Figure 16: Comparison of mth degree polynomial temperature distribution with measured temperature distribution for BTE 155

Strain and curvature of statically determinate structures subjected to a rise of temperature with nonlinear variation over the section depth can be calculated at the centroid of the section as shown below[9].

$$\begin{Bmatrix} \Delta\varepsilon_0 \\ \Delta\psi \end{Bmatrix} = \frac{1}{E}\begin{Bmatrix} \dfrac{-\Delta N}{A} \\ \dfrac{-\Delta M}{I} \end{Bmatrix} \qquad \textbf{(2)}$$

where, $\Delta\varepsilon_0$ is the strain at the centroid of the section due to temperature rise; $\Delta\psi$ is the curvature at the centroid of the section due to temperature rise; E is the concrete modulus of elasticity; A is the cross section area; I is the section moment of inertia; and ΔN and ΔM are the axial force and bending moment due to temperature rise, respectively, which can be computed as below.

$$\Delta N = -\int E\varepsilon_T \, dA \quad \textbf{(3)}$$

$$\Delta M = -\int E\varepsilon_T \, y \, dA \quad \textbf{(4)}$$

where,

$$\varepsilon_T = \alpha_T t_y, \quad \textbf{(5)}$$

α_T is the concrete coefficient of thermal expansion; and t_y can be calculated from Equation 1. Once the curvature is calculated, the additional camber to a temperature gradient for a simply supported beam can be calculated as follows.

$$C = \frac{\psi L^2}{8} \quad \textbf{(6)}$$

where, C is the camber; L is the beam span length; and ψ is the curvature.

Additional camber induced by temperature distribution which varies in a form of a polynomial of m^{th} degree for BTE 145 beam is exhibited in Figure 17. It can be seen that camber growth is the highest when degree of parabola is one, i.e. when temperature varies linearly over member depth. Consequently, a linear temperature variation was assumed to calculate additional camber due to temperature gradient for all the beams in the proceeding analyses. It should be noted that the presumption of a linear temperature distribution would eliminate the thermal stresses, while nonlinear distribution would produce thermal stresses in a simply supported beam.

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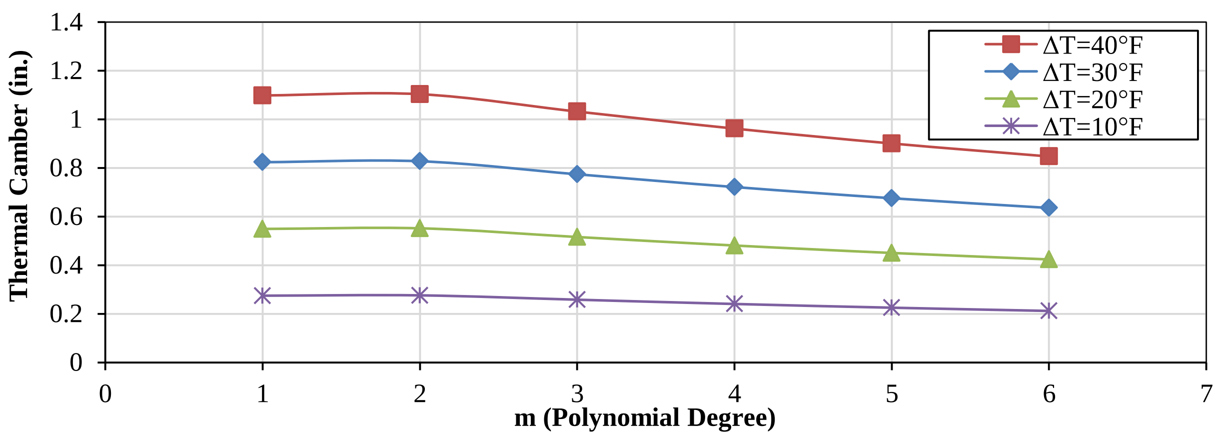

Figure 17: Thermal camber vs. degree of polynomial and temperature gradient for BTE 145

MULTIPLIER TO ACCOUNT FOR TEMPERATURE EFFECT

Using the linear temperature distribution over the member depth, additional camber due to temperature gradient was calculated for bulb-tees. This additional camber growth was added to the predicted camber by FEA to obtain the design camber with the temperature effect. Then, a multiplier is introduced as a linear function of temperature gradient that can be applied to the predicted camber to account for temperature effect. Figure 18 shows the multipliers for different bulb-tee beams. As shown, multipliers are nearly identical for different beams, thus one multiplier function can be used for all the beams.

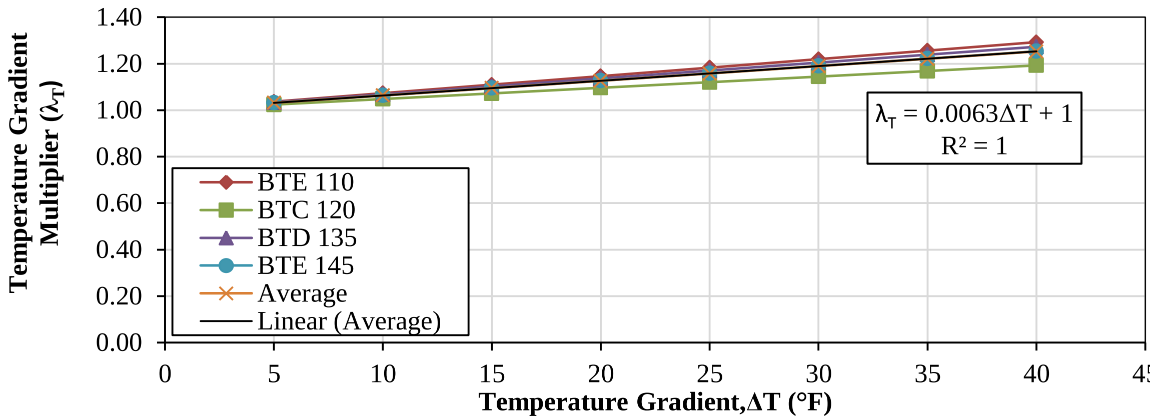

Figure 18: Temperature gradient multiplier vs. temperature gradient for bulb-tees

The proposed multiplier was utilized to perform a sensitivity analysis on temperature gradient, ΔT to determine at what temperature gradient the error between the measured and predicted camber is the smallest. The average ratio of measured to predicted camber versus temperature gradient for bulb-tee beams is presented in Figure 19. The results indicate that the ratio of measured to predicted camber is nearly one when the temperature gradient is 15°F.

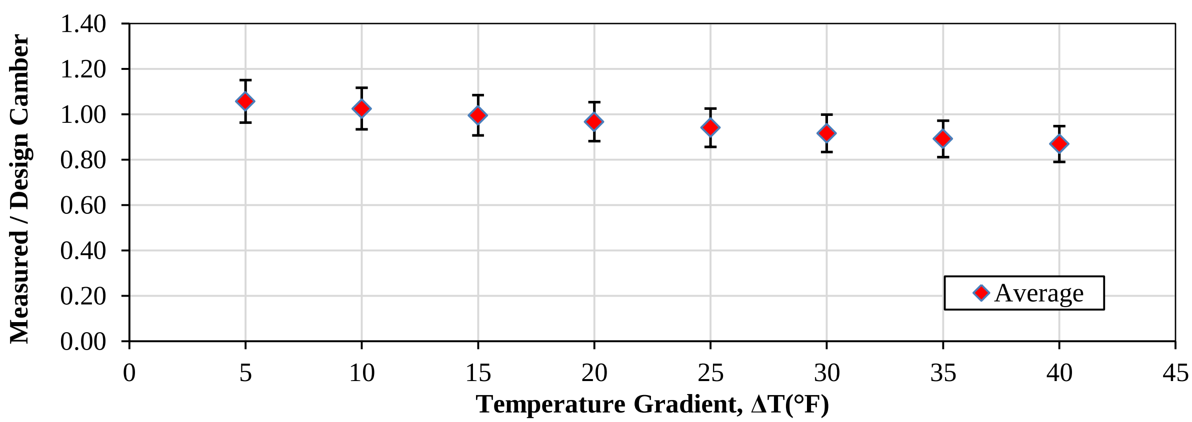

Figure 19: Ratio of measured to design camber vs. temperature gradient for bulb-tees

The presented work was based on the Iowa DOT PPCBs and Iowa weather, thus the applicability of the results should be considered within that context.

SUMMARY AND CONCLUSIONS

Temperature gradient developed over the section depth due to solar radiation can induce significant thermal camber for PPCBs. The maximum temperature gradient is expected to occur between 9:00 AM and 6:00 PM during hot, sunny summer days. The measured data indicated that the temperature gradient can reach as high as 32 °F in July, and the corresponding increase in camber can reach as much as 0.75 inches. Also, the vertical temperature distribution over the section depth changes throughout the day and can be highly non-uniform and nonlinear according to the measurements. However, a sensitivity analysis on the shape of vertical temperature distribution using a polynomial of m^{th} degree showed that linear temperature distribution would cause the maximum thermal camber compared to non-linear distributions. Hence, it can be conservatively assumed that temperature varies linearly over the section depth to perform the analysis.

Using a linear temperature distribution, a temperature gradient multiplier was proposed to account for the additional camber due to temperature gradient for bulb-tee beams, which can be applied to the predicted camber value. It was also observed that the error between the measured and predicted camber is minimum when 15 °F is used as a temperature gradient to conduct the analysis.

ACKNOWLEDGEMENTS

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REFERENCES

1. E. Honarvar Ghietanbaf, J. Nervig, W. He, S. Sritharan and J. M. Rouse, "Improving Accuracy of the Camber Predictions for Precast Prestressed Concrete Bridge Girders," Draft Report, Institute of Transportation Iowa State Univeristy, Ames, Iowa, 2014.
2. K. A. Byle, Ned H. Burns, and Ramón L. Carrasquillo, "Time-Dependent Deformation Behavior of Prestressed High Performance Concrete Bridge Beam," Report, Center for Transportation Research Bureau of Engineering Research the University Of Texas at Austin, October 1997.
3. Potgiester and W. Gamble, "Nonlinear Temperature Distributions in Bridges at Different Locations in the United States," *PCI Journal*, pp. 80-103, 1989.
4. M. Radolli and R. Green, "Thermal Stresses in Concrete Bridge Superstructures under Summer Conditions," *Transportation Research Board*, pp. 23-36, 1975.
5. M. Priestly, "Design of Concrete Bridges for Temperature Gradients," *ACI Journal*, pp. 209-217, 1978.
6. Iowa Department of Transportation, "Index of Beam Standards," 26 4 2011. [Online]. Available: http://www.iowadot.gov/bridge/standards/english/EnglishBeams.pdf. [Accessed April 2014].

7. AASHTO, LRFD Bridge Design Specifications, Washington D.C.: American Association of State Highway and Transportation officials , 2010.
8. MIDAS Civil 2013 Software Analysis Reference.
9. A.Ghali, R. Favre and M. Elbadry, Concrete Structures- Stresses and Deformation, Spon Press, 2002.