

## THE REALITIES OF CAMBER AND DEFLECTION PREDICTIONS FOR PRESTRESSED CONCRETE BRIDGE GIRDERS

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### ABSTRACT

*This paper presents the results of research to evaluate various methods for predicting the camber of precast, pretensioned concrete bridge girders and to recommend possible modifications to improve the predictions.*

*The effects of various factors related to girder production were examined to assess their impacts on camber. At prestress transfer, the actual concrete compressive strength was found to be an average of 25% higher than the specified transfer strength. At 28 days, the actual compressive strength was found to be an average of 45% higher than the specified 28-day strength. Camber behavior was found to vary with different girder types and curing methods. The deformation of internal void forms in box beams and cored slab girders due to the hydrostatic pressure of the fresh concrete during casting was also found to be a factor affecting camber.*

*A camber prediction method was developed that utilizes the creep factors and prestress losses based on the 2010 AASHTO LRFD Bridge Design Specifications. An approximate method based on the PCI camber multipliers was also proposed. The measured cambers of 382 prestressed concrete bridge girders were compared to the predicted values. The proposed camber prediction methods were found to provide acceptable accuracy.*

**Keywords:** Beam, Bridge, Bridge Girder, Camber, Deflection, Prestressed Concrete

## INTRODUCTION

Accurate predictions of camber and deflection often pose a difficult task for bridge engineers. Too much discrepancy between the predicted and actual camber can cause severe problems for deck construction. Many state departments of transportation have investigated some aspects of this problem<sup>1,2,3,4,5</sup> previously and have found considerable variations between the predicted and actual cambers. For example, Kelly et al.<sup>1</sup> noted that the camber for eight identical AASHTO Type IV girders that were 127 feet in length varied from 2 to 6 inches at the time of prestress transfer. Several other studies<sup>3,6,7,8,9</sup> also examined this issue relative to the use of high-strength concrete.

To predict camber accurately is difficult because camber is dependent on many variables, some of which are interdependent and change over time. Four of the most important variables are the properties of concrete, amount of creep, thermal gradients within the girder, and the actual magnitude of the prestressing force. When predicting camber at the design stage, bridge engineers by necessity typically use assumed loss of prestress and concrete properties based on specified concrete strength at various ages.

The 2010 AASHTO LRFD Bridge Design Specifications<sup>10</sup> provide both simplified and detailed methods for estimating creep, shrinkage, and prestress losses. They also require camber and deflection to be calculated, but do not provide specific procedures. The PCI Design Handbook<sup>11</sup> recommends the approximate method developed by Zia et al.<sup>12</sup> for estimating loss of prestress and provides a simplified procedure for camber and deflection calculations using multipliers, a concept originally developed by Martin.<sup>13</sup>

Other methods for predicting camber include the incremental time-steps method and the approximate time-steps method<sup>14</sup>, which more accurately account for the time-dependent behavior of creep and shrinkage of concrete, relaxation of steel, and thus the effective prestressing force and camber. The incremental time-steps method requires calculation of creep strains, shrinkage strains, and prestressing forces at numerous time intervals, and is therefore typically only justified for very long spans and segmental bridge structures. Stallings et al.<sup>3</sup> measured five AASHTO BT54 bulb-tee girders constructed with high-strength concrete with an average 28-day strength of 10 ksi. Based on the camber measurements, it was shown that the PCI multiplier method significantly overestimated the camber at the time of girder erection. Both the approximate time-steps method and the incremental time-steps method predicted camber reasonably well.

The most important factors in camber prediction are the elastic modulus and creep characteristics of the concrete, which vary with its constituents, the production process, and age. For example, Tadros et al.<sup>6</sup> showed that the stiffness of the coarse aggregate used in the concrete, which typically varies with the aggregate source, can introduce significant errors when estimating elastic modulus. They recommended the use of an adjustment factor,  $K_1$ , applied to the commonly used AASHTO equation<sup>15</sup> for elastic modulus to account for the variable aggregate stiffness. Their recommendation was subsequently adopted in the AASHTO specifications beginning with the 2005-2006 Interim Revisions.<sup>16</sup> Kelly et al.<sup>1</sup> also

noted that the actual concrete compressive strength as produced is often much higher than the specified strength. Based on their study of eight prestressed concrete girders with specified 28-day strengths of 6500 psi, they found that the average measured 28-day strength was approximately 9300 psi, more than 40% higher than the specified strength. This discrepancy results in a higher elastic modulus than would be predicted using the specified strength, consequently reducing the measured camber compared to the predicted value. Tadros et al.<sup>6</sup> also observed that it is typically assumed by the designer that the time for prestress transfer is one day after girder casting, though it is fairly common in practice to allow girders to cure over the weekend, thus delaying the prestress transfer. The extra curing time allows the elastic modulus of the concrete to become higher than the value predicted for early prestress transfer, resulting in poor predictions of initial camber. Since creep is sensitive to the strength of the concrete at the time that prestress transfer occurs, it could also lead to poor predictions of camber at later stages.

The prestressing force may also be affected by the thermal expansion of the prestressing strands prior to prestress transfer, caused by changes in the concrete temperature during curing. Bruce et al.<sup>7</sup> showed that, due to cement hydration during concrete curing, the temperature of the strands can increase, causing a reduction of the prestress force by as much as 11% due to thermal expansion. However, since the concrete likely bonds to the steel within six to eight hours after casting, some portion of the force would likely be regained upon cooling. They estimated that the loss of prestress due to this effect was approximately 6%.

As noted by Tadros et al.<sup>2</sup>, thermal gradients can develop through the depth of the girder due to uneven heating and cooling or due to solar effects. This gradient can temporarily cause additional camber or deflection in the girder, thereby introducing scatter into the camber measurements. Byle et al.<sup>8</sup> estimated that thermal gradient effects could produce deflections of approximately 1/2" for the U-girders that they studied, which were between 115 and 145 feet in length.

This paper presents the results of a recent study<sup>17</sup> conducted by the authors, including field and laboratory measurements, to examine the various parameters affecting the camber predictions, with particular attention to factors related to the girder production process. Based on the findings of this study, two camber prediction methods are proposed and compared with the results obtained from the field.

## **FIELD AND LABORATORY MEASUREMENTS**

Field measurements of camber taken at prestress transfer and subsequently at various other times were collected for 382 pretensioned concrete bridge girders from nine producers located in six states including Georgia, North Carolina, South Carolina, Tennessee, Virginia, and West Virginia. These producers are the frequent suppliers of bridge girders for highway projects in North Carolina. A large number of companion cylinders for each girder were also obtained from the producers to determine compressive strength, elastic modulus, and unit

weight in the laboratory at different ages. In general, camber was measured for each girder after prestress transfer, at the beginning of storage in the yard, prior to shipment to the bridge site, and after erection.

The sizes of the girders that were included in this study and the number of each type of girder considered are given in Table 1.

Table 1 Types and typical sizes of girders considered in the study.

Girder Type	Depth	Length	No. of Girders
AASHTO Type III	36"	57'	4
AASHTO Type IV	45"	43' to 104'	21
Box Beam	27", 33", 39"	44' to 100'	114
Cored Slab	18", 21", 24"	24' to 68'	194
Modified Bulb-Tee	63", 72"	73' to 142'	49

A simple and reliable method of measuring camber was developed. The method consists of placing a notched steel rod at each end of the girder during casting, as shown in Fig. 1. A string is pulled between the rods and is tied at the notches. The distance from the string to the top surface of the girder at midspan is measured, and the difference between any two consecutive measurements is the change in camber for the period between the measurements. Prior to transfer of prestress, a measurement is taken as the datum.

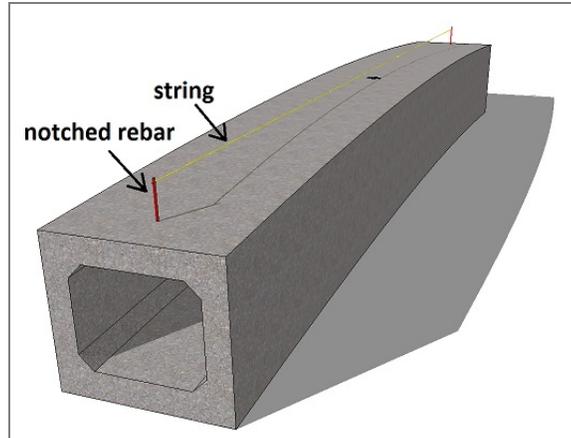


Fig. 1 Method for measuring camber.

The prestressing forces were measured for several girders before and after casting using load cells placed on the strands, as shown in Fig. 2. These measurements were used to determine the changes in the prestressing force that occur after initial stressing. During site visits to the prestressing plants, the research team also observed and documented various factors that might affect the prediction of camber. These factors are discussed in the following section.



Fig. 2 Load cell on prestressing strand.

## **FACTORS AFFECTING THE PREDICTION OF CAMBER**

Several factors related to the production process of prestressed girders were found to significantly affect the prediction of camber. These include the concrete properties, deformation of the internal voids of box beams and cored slabs during casting, strand debonding, prestress transfer length, strand temperature changes after initial stressing, production schedule of the girder, and curing method.

### **CONCRETE PROPERTIES**

Predictions of prestress losses and camber are highly dependent on the properties of the concrete being used for the girder. Important properties are the compressive strength and the elastic modulus.

#### **Compressive Strength**

To ensure acceptance, each girder producer generally has several pre-approved concrete mix designs that will produce quality concrete with compressive strength significantly higher than the specified minimum strength by the DOT. That being the case, the elastic modulus is generally underestimated by using the specified strength. Similarly, the prestress losses, which are also related to the concrete strength, are usually overestimated. Therefore, to improve the predictions of camber and prestress losses, it is critical to have a good estimate of the actual compressive strength.

Based on the collected data for the girders included in this study, the average ratio of the measured compressive strength at prestress transfer to the specified transfer strength was found to be 1.24 with a range of approximately 1.0 to 2.1. Based on this result, it is recommended that the concrete strength at prestress transfer to be used for predicting camber be taken as:

$$f_{ci}^* = 1.25f_{ci}^* \quad 1$$

where  $f_{ci}^*$  = specified compressive strength of the concrete at prestress transfer.

A similar analysis of 200 tested concrete cylinders found that the average ratio of the measured 28-day compressive strength to the specified 28-day strength was 1.45 with a range of approximately 1.0 to 2.2. Based on this result, it is recommended that the 28-day compressive strength to be used for predicting camber should be taken as:

$$f_c^* = 1.45f_c^* \quad 2$$

where  $f_c^*$  = specified compressive strength of the concrete at 28 days.

### Elastic Modulus

To evaluate the accuracy of the AASHTO equation for estimating the elastic modulus of concrete for girders produced for NCDOT bridges, the average ratio of the measured elastic modulus to the predicted value for 153 concrete cylinders tested in the laboratory was found to be 0.85 with a range of approximately 0.62 to 1.15. Based on this analysis, it is recommended that the current AASHTO equation<sup>10</sup> be used to predict the elastic modulus for the camber predictions with the aggregate adjustment factor ( $K_1$ ) taken as 0.85 and the unit weight of concrete ( $w_c$ ) taken as 150 pcf.

$$E_c = 33K_1w_c^{1.5}\sqrt{f_c^*} \quad 3$$

It is also recommended that the concrete strength be calculated using Equation 1 and Equation 2 for the strength at transfer and at 28 days, respectively.

### VOID DEFORMATION

Two of the most common prestressed girder types used for NCDOT bridges are cored slabs and box beams. In cored slabs, paper tubes are used to form the round internal voids, as shown in Fig. 3. In box beams, the void is typically formed using solid blocks of expanded polystyrene (EPS) foam, as shown in Fig. 4.



Fig. 3 Paper tubes form the voids for cored slabs.



Fig. 4 EPS blocks form the void for box beams.

In typical production, these form materials are semi-rigid, so they deform during the casting of the concrete. This has the potential to change the geometry of the member cross-section and to affect the camber. However, design engineers typically neglect this effect in camber calculation. An analysis was performed for both of these girder types to determine the impact of void deformation on camber.

#### Void Deformation in Box Beams

Deformation of the EPS void forms in box beams involves three mechanisms. The first is the local deformation of the form at the locations of the void hold-downs due to the buoyancy of the form in the fresh concrete. The second is the upward flexural deflection between the hold-downs, and the third is the compression of the form due to hydrostatic pressure from the surrounding fresh concrete.

To determine the effect of the void deformation on camber, the section properties of the box beam with the deformed void were determined. These properties were used to calculate the camber for several sample box beams, and the resulting camber was compared to that predicted using the original section properties. The local deformation of the voids at the hold-downs was approximately 0.25 inches based on field measurements. The upward flexural deflection between the hold-downs was calculated using elastic beam formulas, where the hold-downs were spaced at 48 inches. To determine the hydrostatic deformation of the voids, the elastic modulus of the void material was 170 psi for EPS having a unit weight of 1.0 pcf based on manufacturers' specifications. The material was assumed to behave linearly under the hydrostatic loads based on confirmation tests in the laboratory. The assumed loading and deformed shape are illustrated in Fig. 5.

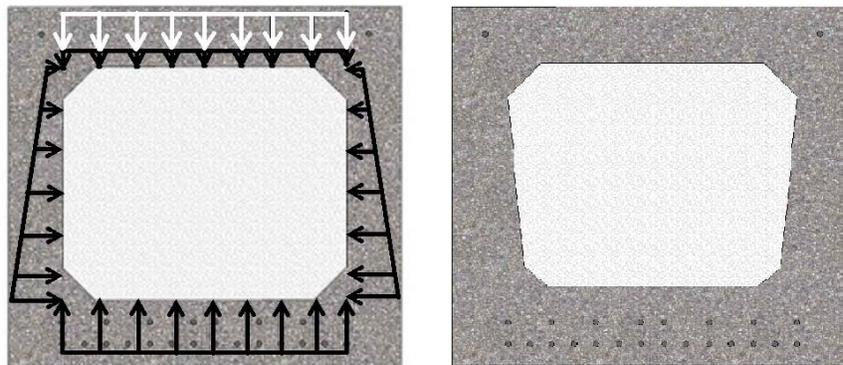


Fig. 5 Distribution of the pressures and the deformed shape of the typical EPS void in box beams.

The analysis revealed that void deformation could reduce the predicted camber by up to 25% depending on the specific design of the box beam. This is a result of the fact that the upward

deflection due to prestressing and the downward deflection due to self-weight are similar in magnitude yet opposite in sign. Therefore, small changes to each value could have magnified effects on the net camber.

#### Void Deformation in Cored Slabs

A similar analysis was performed to determine the effect of void deformation on camber for cored slabs. Based on field measurements, the average upward deflection of the round void tubes due to both local deformation at the hold-down supports and flexural deflection between the supports was approximately 0.5 inches for 8-inch diameter voids, 0.625 inches for 10-inch diameter voids, and 0.75 inches for 12-inch diameter voids. The analysis revealed that considering the void deformation typically reduces the predicted camber of cored slabs by 5 to 12 percent.

The adjusted section properties for the various box beams and cored slabs considered are provided in the NCDOT report.<sup>17</sup>

#### DEBONDING AND TRANSFER LENGTH

Partial debonding of prestressing strands near the ends of prestressed girders reduces the prestressing moment and thus reduces the camber. The prestressing moment is also reduced over the transfer length at the ends of a girder. Yet both effects are typically ignored in camber calculations by the design engineers. Based on an analysis of the 382 girders in the database, considering the effects of debonding and transfer length reduced the predicted camber by less than 3% for the vast majority of the girders. The effect was more pronounced for girders having debonding lengths of 10 feet or greater at each end, for which the error could be as high as 13%. Based on this analysis, it is considered appropriate to include the effects of debonding and transfer length in camber calculation, particularly for girders with long debonding lengths.

#### TEMPERATURE OF THE STRANDS

Prior to prestress transfer, the prestressing force was found to vary according to the temperature variations in the strands after initial stressing due to thermal expansion of the strands. Significant temperature fluctuations can be caused by solar effects, by cement hydration-induced heating during the curing period, or by heat curing procedures. A theoretical analysis as well as measurements of the prestressing force showed that the prestressing force could be reduced by more than 7% due to this thermal effect.

#### GIRDER PRODUCTION SCHEDULE

When predicting camber, it is typically assumed that transfer of the prestressing force will occur one day after casting, and the elastic modulus and prestress loss calculations are based on this assumption. However, it is often the case that the girders will be cured over the weekend, with prestress transfer occurring after three days. Since creep is highly sensitive to

the concrete properties at the instant of prestress transfer, this time delay has the potential to affect the prediction of both initial and long-term cambers.

The timing for casting the composite deck often varies greatly from project to project. Some girders are kept in storage for a long time before being shipped for installation, causing increased uncertainty in the predicted camber.

## CURING METHOD

Precast, prestressed girders are typically cured either by moist curing or by heat curing using steam pipes. The particular curing method used was found to significantly impact the net camber at the time of prestress transfer, as will be discussed later when comparing the measured camber of girders cured by the two different curing methods to the predicted values.

## PROPOSED PREDICTION METHODS

Based on the results of field and laboratory studies, two methods are proposed for predicting camber in prestressed concrete bridge girders—namely, the “approximate method” and the “refined method.” Both methods include the recommendations proposed in the previous section related to the concrete unit weight, compressive strength and elastic modulus; adjusted section properties to account for void deformation in hollow girders; and consideration of the effects of debonding and transfer length.

Since the primary focus of this research was the prediction of camber at prestress transfer and at the time of deck placement, the procedures outlined below do not include the effects of superimposed dead loads applied after erection of the girder. Camber is predicted at the time of transfer (one day), at 28 days, and at one year assuming no superimposed dead loads have been applied. This provides a bilinear, one-year time-history curve for the predicted camber prior to deck placement. Given these three camber predictions, one can obtain the predicted camber at other times by interpolation.

## APPROXIMATE METHOD

The approximate method is based on the PCI multiplier method<sup>11</sup>. This method does not require calculation of the time-dependent losses. The camber prediction procedure for the approximate method is as follows:

- 1) The net camber at prestress transfer is:

$$\Delta_t = \Delta_{ps,t} - \Delta_{sw,t} \quad 4$$

where  $\Delta_{ps,t}$  = upward deflection at transfer due to prestressing only.

$$= \frac{P_t}{E_{ct}I_g} \left( \frac{a_m L^2}{8} - (a_m - a_r) \frac{(L/2 - x_r)^2}{6} - \frac{a_m (L_{db} + L_r)^2}{6} \right) \quad 5$$

$\Delta_{sw,t}$  = downward deflection at transfer due to girder self-weight.

$$= \frac{5W_g L^4}{384E_{ct}I_g} + \Delta_{diaphragm} \quad 6$$

$P_i$  = initial prestressing force after transfer, where transfer is assumed to occur one day after casting.

$e_m$  = eccentricity of the centroid of the strands at midspan with respect to the centroid of the gross section.

$e_e$  = eccentricity of the centroid of the strands at the end of the girder with respect to the centroid of the gross section. Debonding is neglected.

$L$  = girder length.

$E_{ct}$  = elastic modulus of the concrete at transfer.

$I_g$  = moment of inertia of the girder cross section.

$W_g$  = uniformly distributed girder self-weight.

$x_h$  = distance from harp point to center of span.

$L_{db}$  = average debonded length of the debonded strands.

$L_t$  = transfer length; assumed to be 36 inches.

$\Delta_{diaphragm}$  = deflection due to internal diaphragms in hollow girders; diaphragms are treated as point loads; deflection depends on number and location; zero for solid girders.

2) The camber at 28 days is:

$$\Delta_{28} = 1.80 \Delta_{ps,t} - 1.85 \Delta_{sw,t} \quad 7$$

3) The camber at one year is:

$$\Delta_{365} = 2.45 \Delta_{ps,t} - 2.70 \Delta_{sw,t} \quad 8$$

## REFINED METHOD

The 2010 *AASHTO LRFD Bridge Design Specifications*<sup>10</sup> provide detailed calculations to estimate the prestress losses at any given time. However, they do not specify a procedure to predict camber. Therefore, this paper introduces a detailed method for predicting camber that utilizes the time-dependent losses calculations given by the 2010 AASHTO specifications.

The 2010 AASHTO specifications contain provisions for calculating the creep coefficient for any given period. Since the instantaneous camber at transfer due to prestressing and self-weight is proportional to the internal stresses induced in the girder at that time, the creep coefficients, which are applied to initial strains, can also be used to estimate the additional deflection due to creep.

The refined method is a time-step method that uses two time-steps after prestress transfer at which to predict camber. It is similar to the approximate time-steps method described by the ACI Committee 435<sup>14</sup>, although the formulation is somewhat different. An important

distinction is that the elastic component of the deflection due to a given load is assumed to remain constant unless the load itself changes, even though the elastic modulus of the concrete increases after the load has been placed.

This method can be used to predict camber at any time before placement of the deck or superimposed dead loads. However, since the time of girder erection is not known during the design stage, it is recommended that losses and camber be estimated at transfer, at 28 days, and at one year without the deck or any superimposed dead loads.

The prediction procedure for the refined method is as follows:

- 1) Estimate the prestress losses at transfer, at 28 days, and at 365 days according to the AASHTO 2010 “refined” procedure using only the calculations that apply to the losses prior to deck placement. Assume that  $t_i$  equals 1 day,  $t_d$  equals 28 days, and  $t_f$  equals 1825 days (five years).
- 2) The prestressing forces after transfer, at 28 days, and at one year, respectively, are:

$$P_i = A_{ps}(f_{sj} - \Delta f_{RES}) \quad 9$$

$$P_{28} = A_{ps}(f_{sj} - [\Delta f_{RES} + \Delta f_{SR,28} + \Delta f_{CR,28} + \Delta f_{RE,28}]) \quad 10$$

$$P_{365} = A_{ps}(f_{sj} - [\Delta f_{RES} + \Delta f_{SR,365} + \Delta f_{CR,365} + \Delta f_{RE,365}]) \quad 11$$

where  $P_i$  = initial prestressing force after transfer.

$P_{28}$  = prestressing force at 28 days.

$P_{365}$  = prestressing force at 365 days.

$f_{sj}$  = stress in the strand after jacking, taken as 75% of the nominal strength.

$A_{ps}$  = total area of the prestressing strands.

$\Delta f_{RES}$  = elastic shortening loss.

$\Delta f_{SR,28}$  = shrinkage loss between transfer and 28 days.

$\Delta f_{SR,365}$  = shrinkage loss between transfer and 365 days.

$\Delta f_{CR,28}$  = creep loss between transfer and 28 days.

$\Delta f_{CR,365}$  = creep loss between transfer and 365 days.

$\Delta f_{RE,28}$  = relaxation loss between transfer and 28 days.

$\Delta f_{RE,365}$  = relaxation loss between transfer and 365 days.

- 3) The net camber at prestress transfer is determined by following the procedure defined for the approximate method, Eqs. 4-6.
- 4) The net camber at 28 days is:

$$\Delta_{28} = \Delta_{ps,28} - \Delta_{sw,28} + \Delta_{cr,28} \quad 12$$

where  $\Delta_{ps,28}$  = deflection at 28 days due to prestressing only.

$$= \Delta_{ps,t} - \frac{P_t - P_{28}}{\left(\frac{E_{ct} + E_c}{2}\right) I_g} \left( \frac{a_m L^2}{8} - \frac{(a_m - a_e) \left(\frac{L}{2} - x_h\right)^2}{6} - \frac{a_m (L_{db} + L_p)^2}{6} \right) \quad 13$$

$\Delta_{sw,28}$  = deflection at 28 days due to self-weight only; equivalent to self-weight deflection at transfer.

$$= \Delta_{sw,t}$$

$\Delta_{cr,28}$  = deflection at 28 days due to creep.

$$= \Psi(28, t_i) \left( \frac{(P_t + P_{28})}{E_{ct} I_g} \left( \frac{a_m L^2}{8} - \frac{(a_m - a_e) \left(\frac{L}{2} - x_h\right)^2}{6} - \frac{a_m (L_{db} + L_p)^2}{6} \right) - \Delta_{sw,t} \right) \quad 14$$

$\Psi(28, t_i)$  = creep coefficient at 28 days due to loading applied at transfer, calculated according to section 5.4.2.3.2 of the 2010 AASTHO LRFD Bridge Design Specifications.

5) The net camber at one year is:

$$\Delta_{365} = \Delta_{ps,365} - \Delta_{sw,365} + \Delta_{cr,365} \quad 15$$

where  $\Delta_{ps,365}$  = deflection at 365 days due to prestressing only.

$$= \Delta_{ps,28} - \frac{P_{28} - P_{365}}{E_c I_g} \left( \frac{a_m L^2}{8} - \frac{(a_m - a_e) \left(\frac{L}{2} - x_h\right)^2}{6} - \frac{a_m (L_{db} + L_p)^2}{6} \right) \quad 16$$

$\Delta_{sw,365}$  = deflection at 365 days due to self-weight only; equivalent to self-weight deflection at transfer.

$$= \Delta_{sw,t}$$

$\Delta_{cr,365}$  = deflection at 365 days due to creep.

$$= \Delta_{cr,28} + \Psi(365, 28) \left( \frac{(P_{28} + P_{365})}{E_{ct} I_g} \left( \frac{a_m L^2}{8} - \frac{(a_m - a_e) \left(\frac{L}{2} - x_h\right)^2}{6} - \frac{a_m (L_{db} + L_p)^2}{6} \right) - \Delta_{sw,t} \right) \quad 17$$

$\Psi(365, 28)$  = creep coefficient for the period between 28 days and 365 days due to loading applied at transfer, calculated according to section 5.4.2.3.2 of the 2010 AASTHO LRFD Bridge Design Specifications.

$$= \Psi(365, t_i) - \Psi(28, t_i) \quad 18$$

$\Psi(365, t_i)$  – creep coefficient at 365 days due to loading applied at transfer, calculated according to section 5.4.2.3.2 of the 2010 AASTHO LRFD Bridge Design Specifications.

## EVALUATION OF THE PROPOSED PREDICTION METHODS

To evaluate the accuracy of the proposed methods for predicting camber, the predicted cambers from both methods were compared to the field measurements for all the girders in the database. Linear interpolation between the predicted cambers at each time-step was used to determine the predicted camber at the time each measurement was taken. Since the camber grows quickly in the early days after prestress transfer and since the rate of increase slows over time, the linear interpolation is expected to significantly underestimate the camber between roughly 3 days and 24 days for any given method, even if the method itself is accurate. Therefore, only measurements taken either at the time of prestress transfer or at ages greater than 24 days were used to evaluate the prediction models.

The camber data were grouped by girder type, by curing method, and by the time at which camber was measured.

To compare the predicted camber to the measured camber, the difference between the predicted and measured camber was determined for each camber measurement. The mean of these values was then determined for each group of data and each prediction method. The mean relative percent error of the predictions for each group of data was determined by comparing the mean difference of the group to the mean measured camber of the group.

The analysis of the camber data collected in the database for the 382 girders studied revealed significant scatter in the camber prediction accuracy. This was due primarily to the random variability of the concrete properties and the effect of thermal gradient in the girder, as well as other factors. However, since the number of girders studied was large, the mean relative percent error can be used to compare the prediction methods.

## CAMBER AT PRESTRESS TRANSFER

The calculation of the camber at prestress transfer is identical for both methods. It can be observed from Fig. 6 that the effect of the curing method on the camber at prestress transfer is significant. For cored slabs and box beams, the mean relative percent error of the camber predictions is approximately 65% to 75% for the heat-cured girders, while it is less than 20% for moist cured girders of the same types. For Type IV girders, the difference in the percent error between moist cured and heat cured girders is approximately 20%. For modified bulb-tees, there is not a significant difference in the prediction error between curing methods. Since the predicted camber value is always the same for moist cured and heat cured girders, the measured camber at transfer must be significantly less for heat-cured girders than for moist cured girders. This discrepancy may be caused by the presence of a thermal gradient

within the concrete at transfer due to uneven heating and cooling for heat-cured members or by the reduction in the prestressing force due to the thermal expansion of the strands.

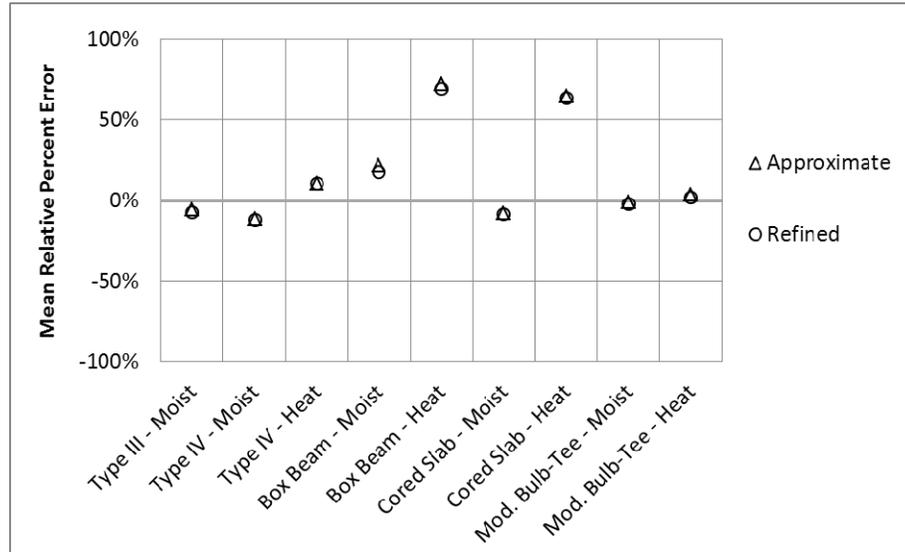


Fig. 6 Mean relative percent error of the camber predictions for measurements taken at prestress transfer.

#### CAMBER AT 24 DAYS AND LATER

The data for camber measurements taken at 24 days or more after casting provide the best means to evaluate the prediction methods since the focus for this research is to improve the prediction of camber at the time of girder erection, which typically occurs at least four weeks after casting.

The analysis indicates that both the approximate method and the refined method provide reasonably accurate camber predictions, although the refined method is more accurate for most of the girder types and curing methods, as shown in Fig. 7. When the refined method is used, the average error is less than 10% for most of the data groups. When the approximate method is used, the error is between approximately 10% and 20% for most of the data groups.

It should be noted that the proposed methods improved the predictions of camber by reducing the average prediction error compared to the current NCDOT method, for which the error was between roughly 20% and 90% depending on the member type and curing method used. However, since the current NCDOT method is unique and not widely used by other agencies, it is not included in this paper.

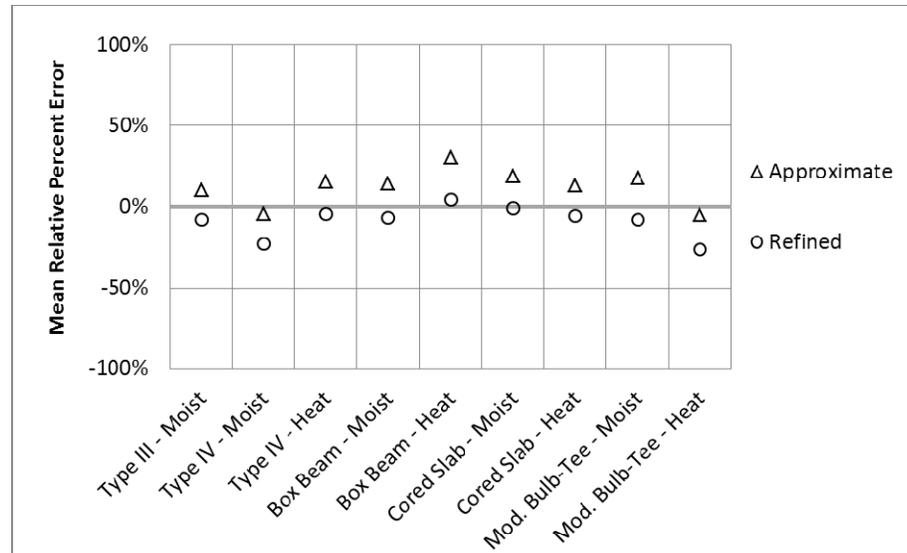


Fig. 7 Mean relative percent error of the camber predictions for measurements taken at 24 days or later.

## CONCLUSIONS

Based on the field measurements of camber for 382 pretensioned concrete bridge girders taken at prestress transfer and at several later stages as well as observations regarding the production process, two methods for predicting camber are proposed. The following conclusions can be drawn:

- 1) The camber predictions should account for the typically higher concrete strength at prestress transfer and at 28 days compared to the specified values.
- 2) Deformation of the internal voids for box beams and cored slabs caused by the hydrostatic pressure of the fresh concrete and by the buoyancy of the voids during casting can lead to overestimation of the camber by as much as 25%. Camber predictions can be improved by modifying the section properties to account for this deformation. The use of stiffer void materials would reduce this effect.
- 3) The camber predictions should consider the reduced curvature at the ends of the girder due to debonding and transfer length, especially for girders with long debonding lengths.
- 4) The camber of girders at the time of prestress transfer can be significantly affected by the curing method used. Heat-cured girders—especially box beams and cored slabs—tend to have significantly less camber at transfer than moist cured girders, although there was not a significant difference in the camber at later stages between girders cured using either method. This suggests that the discrepancy could be due to the temporary thermal gradient caused by uneven heating and cooling for heat cured

- girders or by temporary reductions in the prestressing force caused by thermal expansion of the strands during curing.
- 5) Due to production variables, the measured camber can vary significantly among girders that are identical in their design even if the girders are cast at the same time on the same casting bed, in part because multiple batches of concrete are typically used for a single casting.
  - 6) The refined method provided the most accurate camber predictions for most girder types and curing methods. The approximate method generally overestimated camber slightly, although the predictions were still reasonable.

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## REFERENCES

1. Kelly, D., Bradbury, T., and Breen, J., *Time-Dependent Deflections of Pretensioned Beams*, Center for Transportation Research, University of Texas, Austin, TX, 1987.
2. Tadros, M. K., Fawzy, F., and Hanna, K., "Precast, Prestressed Girder Camber Variability," *PCI Journal*, Vol. 56, No. 1, Winter 2011, pp. 135-154.
3. Stallings, J. M., and Eskildsen, S., *Camber and Prestress Losses in High Performance Concrete Bridge Girders (Research Report ALDOT 930-373)*, Highway Research Center, Auburn University, Auburn, AL, 2001.
4. Cook, R. A., Bloomquist, D., and Sanek, J. E., *Field Verification of Camber Estimates for Prestressed Concrete Bridge Girders*, Final Report No. BD-545 RPWO#7, Florida Department of Transportation, Tallahassee, FL., April 2005, 129 pp.

5. Rosa, M. A., Stanton, J. F., and Eberhard, M. O., *Improving Predictions for Camber in Precast, Prestressed Concrete Bridge Girders*, Final Report No. WA-RD669-1, Washington State Department of Transportation, Olympia, WA, March 2007, 134 pp.
6. Tadros, M. K., Al-Omaishi, N., Seguirant, S., and Gallt, J., *Prestress Losses in Pretensioned High-Strength Concrete Bridge Girders (NCHRP Report No. 496)*, National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, DC, 2003.
7. Bruce, R. N., Russell, H. G., Roller, J. J., and Hassett, B. M., *Implementation of High Performance Concrete in Louisiana Bridges (Report No. 310)*, Louisiana Transportation Research Center, Baton Rouge, LA, 2001.
8. Byle, K. A., Burns, N. H., and Carrasquillo, R. L., *Time-Dependent Deformation Behavior of Prestressed High Performance Concrete Bridge Beams*, Center for Transportation Research, University of Texas, Austin, TX, 1997.
9. Al-Omaishi, N., Tadros, M. K., and Sequirant, S. J., "Estimating Prestress Loss in Pretensioned, High-Strength Concrete Members," *PCI Journal*, Vol. 54, No. 4, pp. 132-159.
10. AASHTO, *AASHTO LRFD Bridge Design Specifications (5th ed.)*, American Association of State Highway Transportation Officials, Washington, DC, 2010.
11. PCI, *PCI Design Handbook (6th ed.)*, Precast/Prestressed Concrete Institute, Chicago, IL, 2004.
12. Zia, P., Preston, H. K., Scott, N. L., and Workman, E. B., "Estimating Prestress Losses," *Concrete International*, Vol. 1, No. 6, June 1979, pp. 32-38.
13. Martin, L. D., "A Rational Method for Estimating Camber and Deflection of Precast Prestressed Members," *PCI Journal*, V. 22, No. 1, Jan.-Feb. 1977, pp. 100-108.
14. ACI Committee 435, *Control of Deflection in Concrete Structures (ACI 435R-95)*, American Concrete Institute, Farmington Hills, MI, 1995.
15. AASHTO, *AASHTO LRFD Bridge Design Specifications (3rd ed.)*, American Association of State Highway Transportation Officials, Washington, DC, 2004.
16. AASHTO, *2005-2006 Interim Revisions to the AASHTO LRFD Bridge Design Specifications*, American Association of State Highway and Transportation Officials, Washington, DC, 2006.
17. Rizkalla, S. H., Zia, P., and Storm, T. K., *Predicting Camber, Deflection, and Prestress Losses in Prestressed Concrete Members*, Final Report No. FHWA/NC 2010-05, North Carolina Department of Transportation, Raleigh, NC, July 2011, 174 pp.