Accurate predictions of camber and deflection often pose a challenge for bridge engineers. Excessive discrepancy between the predicted and actual camber can cause problems for deck construction. Many state departments of transportation (DOTs) have previously investigated some aspects of this problem\(^1\) and found considerable variations between the predicted and actual cambers. For example, Kelly et al.\(^1\) noted that the camber for eight identical American Association of State Highway and Transportation Officials (AASHTO) Type IV girders that were 127 ft (38.7 m) in length varied from 2 to 6 in. (50 to 150 mm) at the time of prestress transfer. Several other studies\(^3,6-9\) also examined this issue relative to the use of high-strength concrete.

To predict camber accurately is difficult because camber depends on many random variables, some of which are interdependent and change over time. Some of the most important variables are the compressive strength and elastic modulus of concrete, amounts of creep and shrinkage, thermal gradients within the girder, and the time-dependent variations in prestressing force. When predicting camber at the design stage, bridge engineers typically calculate prestress losses and concrete properties based on the specified concrete strength at various ages because they have no knowledge of the actual concrete properties prior to manufacture. Camber is also influenced by the time history of loading and environmental conditions. Complicating
matters further is that camber is the net result of two large opposing quantities: upward deflection due to prestress and downward deflection due to dead load. Because these two quantities are each subject to some inherent variability, one cannot expect to always predict the net camber accurately.

The 2010 AASHTO LRFD Bridge Design Specifications 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: Precast and Prestressed Concrete recommends the approximate method developed by Zia et al. for estimating camber and deflection calculations using multipliers, a concept originally developed by Martin.

These PCI methods were developed more than 30 years ago, largely based on the properties of lower-strength concrete than what is typically used today and calibrated primarily against the performance of prestressed concrete building members. The specified constant multipliers account for the creep effect due to sustained load and are suitable for conventional building designs under average environmental conditions. For bridges, more detailed analysis methods are needed to account for widely varying environmental conditions and other time-dependent factors. However, many commercially available design software programs and even in-house developed design software programs used by state departments of transportation and others have used the constant multiplier method because of its simplicity. These programs are still being used today by many bridge designers in both the public and private sectors.

In 1985, Tadros et al. developed refined time-dependent multipliers for long-term deflection calculations and a refined method for estimating prestress losses. These refined approaches, unlike the PCI method, would account for the effects of various environmental conditions and the presence of nonprestressed steel reinforcement, which tends to restrain creep and shrinkage of concrete.

Other methods for predicting camber include the incremental time-step method and the approximate time-step method, which more accurately account for the time-dependent creep and shrinkage of concrete and relaxation of steel, and thus the effective prestressing force and camber. The incremental time-step method requires calculation of creep strains, shrinkage strains, and prestressing forces at numerous time intervals and is typically justified only for unusual and complex designs, such as long spans and segmental bridge structures.

The PCI Bridge Design Manual provides excellent commentaries on the complexity of estimating prestress losses and its implications on design. Methods for estimating loss of prestress prescribed by the AASHTO LRFD Bridge Design Specifications are described and illustrated by examples. The PCI Bridge Design Manual also recommends a set of multipliers for computing long-term camber and deflection but cautions that the use of the multipliers only gives “reasonable estimates of cambers at the time of erection” and “the method does not properly account for the significant effects of a large cast-in-place deck.” It also warns designers that “prestressing levels should not be increased in order to reduce or eliminate long-term downward deflection that might be predicted if the given multipliers are used.”

Stallings et al. measured the camber of five AASHTO BT54 bulb-tee girders constructed with high-strength concrete with an average 28-day strength of 10,000 psi (70 MPa). Based on the camber measurements, it was shown that the PCI Design Handbook multiplier method significantly overestimated the camber at the time of girder erection. Both the approximate time-step method and the incremental time-step method predicted camber reasonably well.

The most important factors in camber prediction are the elastic modulus and creep of the concrete, which vary with its constituents, the production process, and age. For example, Tadros et al. showed that the stiffness of the coarse aggregate used in the concrete, which typically varies with the aggregate source, can introduce significant variations when estimating elastic modulus. They recommended the application of an elastic modulus adjustment factor $K_{e}$ applied to the 2004 AASHTO LRFD specifications equation to account for aggregate stiffness. Their recommendation was subsequently adopted in the AASHTO LRFD specifications beginning with the 2005–2006 interim revisions. Kelly et al. also noted that the actual concrete compressive strength 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 (45 MPa), they found that the average measured 28-day strength was approximately 9300 psi (64 MPa), 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 with the predicted value. Tadros et al. 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. Because 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...
beginning of storage in the yard, prior to shipment to the bridge site, and after erection. Table 1 gives the sizes of the girders included in this study and the number of each type considered.

A simple method for measuring camber was used. The method consists of embedding a notched steel rod at each end of the girder during casting (Fig. 1). A string is pulled between the rods and tied at the notches as a reference line. 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, an initial measurement is taken as the datum.

The prestressing forces were measured for several girders before and after casting using load cells placed on the strands (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 as discussed in the following sections.

### Factors affecting the prediction of camber

Several factors related to the production of prestressed concrete 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, temperature changes in the strands after initial stressing, production schedule, and curing method.
Concrete properties

Predictions of prestress losses and camber depend 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 preapproved concrete mixture designs that will produce quality concrete with average compressive strength significantly higher than the minimum strength specified by the DOT. Therefore, the elastic modulus is generally underestimated by using the specified strength. Similarly, the prestress losses, which are also related to the concrete strength, may be 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 strength at transfer was found to be 1.24 with a range of approximately 1.0 to 2.1 (Fig. 3). Based on this result, it is recommended that the concrete strength at prestress transfer to be used for predicting camber $f_{ct}'$ be calculated using Eq. (1).

$$f_{ct}' = 1.25 f_{ct}$$  \hspace{1cm} (1)

where

$\quad f_{ct}' = \text{specified compressive strength of the concrete at prestress transfer}$

A similar analysis of the test results for 78 sets of concrete cylinders showed 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 (Fig. 4). Based on this result, it is recommended that the 28-day compressive strength to be used for predicting camber $f_{c}'$ should be calculated using Eq. (2).

$$f_{c}' = 1.45 f_{c}$$  \hspace{1cm} (2)

where

$\quad f_{c}' = \text{specified compressive strength of the concrete at 28 days}$
Two of the most common prestressed girder types used for NCDOT bridges are cored slabs and box beams. In cored slabs, heavy-duty paper tubes are used to form the round internal voids (Fig. 5). In box beams, the void is typically formed using solid blocks of expanded polystyrene foam (Fig. 6). In typical production, these form materials are semirigid, so they deform to some degree 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 effect of void deformation on camber.

Void deformation in box beams

Deformation of the expanded polystyrene 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 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 with that predicted using the original section properties. The local deformation of the voids at the hold-downs was approximately 0.25 in. (6.4 mm) 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 approximately 48 in. (1.2 m). To determine the hydrostatic deformation of the voids, the elastic modulus of the void material was taken as 170 psi (64 kPa) for expanded polystyrene having a unit weight of 1.0 lb/ft³ (16.0 kg/m³) based on manufacturers’ specifications. The material was assumed to behave linearly under the hydrostatic loads based on confirmation tests performed in the laboratory. Figure 7 illustrates the deformed shape.

The analysis revealed that void deformation could reduce the predicted camber by up to 25% for the box beam designs considered in this study. The magnitude of this discrepancy is due in part to 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, a small change to either value can have a significant effect 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 in. (13 mm) for voids that were 8 in. (200 mm) in diameter, 0.625 in. (16 mm) for voids 10 in. (250 mm) in diameter, and 0.75 in. (19 mm) for voids 12 in. (300 mm) in diameter. The analysis revealed that considering the void deformation typically reduces the predicted camber of cored slabs by 5% to 12%.

The NCDOT report 19 and Storm’s thesis 20 provide the adjusted section properties for the various box beams and cored slabs considered.

### Debonding and transfer length

Partial debonding of prestressing strands near the ends of prestressed girders reduces the prestressing moment in this region and thus reduces the camber. The prestressing moment is also reduced over the transfer length at the ends of a girder. However, 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, however, for girders having partial debonding lengths of approximately 10 ft (3 m) or greater at each end, for which the error could be as high as 13%. 19,20 Based on this analysis, it is considered appropriate to include the effects...
ties and prestressing force at the time of prestress transfer
and because both of these properties are changing rapidly
during this time, the delay has the potential to affect the
predictions of both the initial and long-term cambers. In
addition, the timing for casting the composite deck often
varies greatly from project to project. Some girders are
kept in storage for several months and in extreme cases
up to a year before being shipped for installation, causing
increased uncertainty in the predicted camber at the time
of erection.

Curing method

Precast, prestressed concrete girders are typically cured
either by moist curing or by heat curing using steam
pipes. The particular curing method used was found to
significantly affect the net camber at the time of prestress
transfer, as is discussed later in this paper.

Proposed prediction methods

Based on the results of field and laboratory studies, two meth-
ods are proposed for predicting camber in prestressed concrete
bridge girders—the approximate method and the refined meth-

Figure 5. Heavy-duty paper tubes were used to form the round voids within cored-slab girders.
Figure 6. Expanded polystyrene blocks were used to form the rectangular voids within box-beam girders.

Figure 7. The hydrostatic pressure of the fresh concrete causes the expanded polystyrene void forms used in box beams to deform, altering the section properties of the girder. On the left is the section as designed, while on the right is the theoretical deformed shape. The deformation has been exaggerated slightly for illustration.
Approximate method

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

1. Calculate the net camber at prestress transfer \( \Delta_p \),

\[
\Delta_p = \Delta_{ps,i} - \Delta_{sw,i}
\]

where

\[
\Delta_{ps,i} = \text{upward deflection at transfer due to prestressing only}
\]

\[
\Delta_{sw,i} = \text{downward deflection at transfer due to girder self-weight}
\]

\[
P_i = \text{initial prestressing force after transfer, where transfer is assumed to occur one day after casting}
\]

\[
e_m = \text{eccentricity of the centroid of the strands at midspan with respect to the centroid of the gross section}
\]

\[
e_e = \text{eccentricity of the centroid of the strands at the end of the girder with respect to the centroid of the gross section; debonding is neglected (all strands are assumed fully bonded)}
\]

2. Calculate the camber at 28 days \( \Delta_{28} \).

\[
\Delta_{28} = 1.80 \Delta_{ps,i} - 1.85 \Delta_{sw,i}
\]

3. Calculate the camber at one year \( \Delta_{365} \).

\[
\Delta_{365} = 2.45 \Delta_{ps,i} - 2.70 \Delta_{sw,i}
\]

This multiplier method gives reasonable estimates for cambers at the time of erection, but it does not properly account for the significant effects of a large cast-in-place concrete deck.

Refined method

The 2010 AASHTO LRFD specifications provide a detailed method for estimating 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 uses the time-dependent loss calculations given by the 2010 AASHTO LRFD specifications.

The 2010 AASHTO LRFD specifications contain provisions for calculating the creep coefficient for any given period. Because the instantaneous camber at prestress transfer is proportional to the internal, moment-in-time stresses induced in the girder, the creep coefficients, which are typically applied to initial strains, can also be used to estimate the additional deflection (or camber) due to creep.

The refined method is a time-step method that uses two time steps after prestress transfer to predict camber. It is similar to the approximate time-step method described by ACI Committee 435, though the formulation is somewhat
different. An important distinction is that in the refined method, the elastic component of the deflection due to a given load is assumed to remain constant even while the elastic modulus of the concrete increases after the load has been placed. Changes in existing loads, such as the reduction in the prestressing force, are treated as new loads with an elastic deflection based on the elastic modulus of the concrete at the time the force is first applied. In the case of prestress reduction, where the change occurs over time, the average elastic modulus over the given time span is used.

This method can be used to predict camber at any time before placement of the deck or superimposed dead loads. However, because the exact date of girder erection is often not known during design, it is recommended that prestress losses and camber be estimated at transfer, at 28 days, and at one year to obtain a representative range of values.

The camber 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 2010 AASHTO LRFD specifications refined procedure using only the calculations that apply to the time prior to deck placement. Assume that the age of the concrete at the time of prestress transfer $t_i$ equals 1 day; at time of placement of composite deck or permanent superimposed dead loads $t_d$ equals 28 days and 365 days in turn; and at final time $t_f$ equals 1825 days (five years).

2. Calculate the prestressing forces after transfer $P_i$, at 28 days $P_{28}$, and at one year $P_{365}$,

$$P_i = A_p \left( f_{pj} - \Delta f_{pES} \right)$$

$$P_{28} = A_p \left[ f_{pj} - \left( \Delta f_{pES} + \Delta f_{pSR,28} + \Delta f_{pCR,28} + \Delta f_{pRE,28} \right) \right]$$

$$P_{365} = A_p \left[ f_{pj} - \left( \Delta f_{pES} + \Delta f_{pSR,365} + \Delta f_{pCR,365} + \Delta f_{pRE,365} \right) \right]$$

where

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

$A_p = $ total area of the prestressing strands

$\Delta f_{pES} = $ elastic shortening loss

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

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

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

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

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

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

3. Calculate the net camber at prestress transfer by following the procedure already defined for the approximate method (step 1).

4. Calculate the net camber at 28 days.

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

where

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

$$= A_{ps} - \left[ \frac{P - P_{28}}{E_i + E_s} \right] I_t$$

$$\times \frac{e_n L^2}{8} - \frac{\left( e_m - e_s \right) \left( \frac{L - x_S}{2} \right)^4}{6} - \frac{e_m \left( L_{ab} + L_f \right)^2}{6}$$

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

$$= \frac{1}{2} A_{sw,i}$$

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

$$= \Psi(28, t_i) \left( \frac{P_i + P_{28}}{2 I_t} \right)$$

$$\times \frac{e_n L^2}{8} - \frac{\left( e_m - e_s \right) \left( \frac{L - x_S}{2} \right)^4}{6} - \frac{e_m \left( L_{ab} + L_f \right)^2}{6}$$

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

5. Calculate the net camber at one year.

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

\[ \Delta_{ps,365} = \text{deflection due to prestressing only at 365 days} \]

\[ = \Delta_{ps,28} \left( \frac{P_{ps} - P_{ps,365}}{E_i I_f} \right) \]

\[ \times \left[ \frac{e_n L^2}{8} - \left( e_n - e_t \right) \frac{L}{6} - e_n \left( L_{eb} + L_t \right) \right] \]

\[ \Delta_{sw,365} = \text{deflection at 365 days due to self-weight only; equivalent to self-weight deflection at prestress transfer} \]

\[ = \Delta_{sw,i} \]

\[ \Delta_{cr,365} = \text{deflection due to creep at 365 days} \]

\[ = \Delta_{cr,28} + \Psi(365,28) \left( \frac{P_{ps} + P_{ps,365}}{2 E_i I_f} \right) \]

\[ \times \left[ \frac{e_n L^2}{8} - \left( e_n - e_t \right) \frac{L}{6} - e_n \left( L_{eb} + L_t \right) \right] - \Delta_{sw,i} \]

\[ \Psi(365,28) = \text{creep coefficient for the period between 28 days and 365 days due to load applied at transfer, calculated according to section 5.4.2.3.2 of the 2010 AASTHO LRFD specifications} \]

\[ = \Psi(365,t_i) - \Psi(28,t_i) \]

\[ \Psi(365,t_i) = \text{creep coefficient at 365 days due to load applied at transfer, calculated according to section 5.4.2.3.2 of the 2010 AASTHO LRFD specifications} \]

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 with the field measurements for all of 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. Because the camber grows quickly in the early days after prestress transfer and because 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, curing method, and the time at which camber was measured. To compare the predicted camber with the measured camber, the difference between the predicted and measured camber was determined for each camber measurement using each prediction method. The mean difference was then determined for each category of girders and each prediction method. The mean relative error of the predictions for each girder category was then determined by dividing the mean difference of each category by the mean measured camber of the category.

Camber at prestress transfer

The calculation of the camber at prestress transfer is identical for both methods. Figure 8 shows that the effect of the curing method on the camber at prestress transfer is significant. For cored slabs and box beams, the mean relative error of the camber predictions is approximately 70% for the heat-cured girders, while it is only approximately 20% or less for moist-cured girders of the same types. For Type IV girders, the error is approximately -12% for moist-cured members compared with +11% for heat-cured members. Because the predicted camber value is always equal for moist-cured and heat-cured versions of the same girder, it follows from the graph that the average measured camber at transfer for most girder types was significantly less for the heat-cured versions than for the moist-cured versions. This discrepancy may be caused by at least two factors that are potentially significant in heat-cured girders: the presence of a thermal gradient within the concrete at transfer due to uneven cooling and the reduction in the prestressing force due to the thermal expansion of the strands. For modified bulb tees, the curing method did not seem to affect the camber at transfer as significantly as it did the other member types. This could be due to a potentially less substantial thermal gradient effect in the modified bulb tee because its unique shape and greater depth result in a different thermal profile during cooling.
The data for camber measurements taken at 24 days after casting or later provide the best means to evaluate the prediction methods. 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, though the refined method is more accurate for most of the girder types and curing methods (Fig. 9). 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.

**Conclusion**

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:

- The camber predictions should account for the typically higher concrete strength at prestress transfer and at 28 days compared with the specified values.
- The coefficients in Eq. (1) and (2), developed from this study based on concrete materials normally provided for NCDOT, should be validated or determined for concrete supplied from other localities and regions. However, these coefficients are simply the averages of a widely varying value and therefore should not be viewed as anything more than an estimate.
- 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.
- 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.
- The camber of girders at the time of prestress transfer can be significantly affected by the curing method

**Figure 8.** Heat-cured box beams and cored slabs exhibited significantly less camber at the time of prestress transfer than moist-cured versions of the same girders, causing the camber prediction error to be high for the girders at this stage.
used. Heat-cured girders—especially box beams and cored slabs—tend to have significantly less camber at transfer than moist-cured girders, though 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.

- 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.

- The refined method provides the most accurate camber predictions for most girder types and curing methods. The approximate method generally overestimates camber at erection slightly, but it is suitable for preliminary estimates and rough by-hand calculations.

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Notation

\[ A_{ps} = \text{total area of the prestressing strands} \]

\[ E_c = \text{elastic modulus of concrete} \]

\[ E_{ci} = \text{elastic modulus of the concrete at prestress transfer} \]

\[ e_c = \text{eccentricity of the centroid of the strands at the end of the girder with respect to the centroid of the gross section; debonding is neglected (all strands are assumed fully bonded)} \]

\[ e_m = \text{eccentricity of the centroid of the strands at midspan with respect to the centroid of the gross section} \]

\[ f_c = \text{measured compressive strength of the concrete at 28 days} \]

\[ f_{ci} = \text{specified compressive strength of the concrete at 28 days} \]

\[ f^*_{ci} = \text{recommended compressive strength of the concrete at 28 days for use in camber predictions} \]

\[ f_o = \text{specified compressive strength of the concrete at prestress transfer} \]
\( f_{ci} \) = recommended compressive strength of the concrete at prestress transfer for use in camber predictions

\( f_{ci} \) = measured compressive strength of the concrete at the time of prestress transfer

\( f_{pj} \) = stress in the strand after jacking, taken as 75% of the nominal strength

\( I_g \) = gross moment of inertia of the girder cross section

\( K_1 \) = local aggregate adjustment factor for elastic modulus of concrete

\( L \) = girder length

\( L_{db} \) = average debonded length of the debonded strands measured from the girder end

\( L_T \) = transfer length

\( P_{28} \) = prestressing force at 28 days

\( P_{365} \) = prestressing force at 365 days

\( P_i \) = initial prestressing force after transfer, where transfer is assumed to occur one day after casting

\( t_d \) = age of concrete at time of placement of composite deck or permanent superimposed dead loads

\( t_f \) = age of concrete at final time

\( t_i \) = age of concrete at time of prestress transfer

\( w_c \) = unit weight of concrete

\( w_g \) = uniformly distributed girder self-weight

\( x_h \) = distance from strand harping point to mid-span

\( \Delta_{28} \) = net camber 28 days after casting, before application of composite deck or superimposed dead loads

\( \Delta_{365} \) = net camber 365 days after casting, before application of composite deck or superimposed dead loads

\( \Delta_{r,28} \) = deflection due to creep at 28 days

\( \Delta_{r,365} \) = deflection due to creep at 365 days

\( \Delta_{\text{diaphragms}} \) = deflection due to internal diaphragms in hollow girders

\( \Delta_i \) = net camber immediately after prestress transfer

\( \Delta_{ps,i} \) = upward deflection at transfer due to prestressing only

\( \Delta_{ps,28} \) = deflection due to prestressing only at 28 days

\( \Delta_{ps,365} \) = deflection due to prestressing only at 365 days

\( \Delta_{sw,i} \) = downward deflection at transfer due to girder self-weight only

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

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

\( \Delta_{fpCR,28} \) = creep loss between transfer and 28 days

\( \Delta_{fpCR,365} \) = creep loss between transfer and 365 days

\( \Delta_{fs,ES} \) = elastic shortening loss

\( \Delta_{fpRE,28} \) = relaxation loss between transfer and 28 days

\( \Delta_{fpRE,365} \) = relaxation loss between transfer and 365 days

\( \Delta_{fs,SR,28} \) = shrinkage loss between transfer and 28 days

\( \Delta_{fs,SR,365} \) = shrinkage loss between transfer and 365 days

\( \Psi(28,t_i) \) = creep coefficient at 28 days due to load applied at transfer

\( \Psi(365,t_i) \) = creep coefficient at 365 days due to load applied at transfer

\( \Psi(365,28) \) = creep coefficient for the period between 28 days and 365 days due to load applied at transfer
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Abstract

This paper presents the results of research to investigate factors related to prestressed concrete girder production that could affect the camber and to recommend camber prediction methods.

At prestress transfer, the actual concrete compressive strength was found to be an average of 25% higher than the specified transfer strength, thus affecting the camber predictions. 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 among 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 found to significantly affect camber. In addition, strand debonding and transfer length were found to be non-negligible when predicting camber for some girders.

A refined camber prediction method was developed that uses creep coefficients and prestress losses based on the 2010 AASHTO LRFD Bridge Design Specifications. An approximate method based on PCI Design Handbook: Precast and Prestressed Concrete camber multipliers was also proposed. The measured cambers of 382 prestressed concrete bridge girders were compared with the predicted values. The proposed methods were both found to provide reasonable estimates of camber, though the refined method was more accurate for the majority of girders.

Keywords

Beam, bridge, camber, deflection, girder.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute’s peer-review process.

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