Enhanced camber and deflection estimation for AASHTO prestressed concrete girders

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- This study explores how the difference between specified design concrete properties and actual measured concrete properties affects camber and deflection predictions.
- Camber measurements were taken for four types of I-girders shortly after prestress transfer and at the time of erection. Concrete samples were collected during girder production and tested to determine the concrete compressive strength and modulus of elasticity.
- The measured cambers were compared with cambers calculated using two widely accepted camber prediction methods. Based on the results of the testing and analysis, an improved method for camber and deflection prediction is proposed.

In precast, prestressed concrete bridge girders, a large number of prestressing strands are placed in the bottom flange to increase the structural capacity of the girder. The concentration of the prestressing strands below the neutral axis of the girder cross section causes an upward deflection, technically termed camber. During girder fabrication, prestressing strands are tensioned between two abutments, and then concrete is placed. When the concrete achieves the required compressive strength, the strands are cut and the force from the strands is transferred to the hardened concrete. This transfer of prestressing force results in a bending moment, which creates the upward deflection.[1] Accurate prediction of camber is essential, especially during fabrication of cast-in-place concrete bridge decks. If the camber at erection is less than the design value, the deck thickness must be increased, and this adds extra weight that was not accounted for in the design. If the camber is greater than the predicted value, the top flange of the girder may interfere with the deck reinforcement. In both cases, the deck profile may have to be adjusted. This additional task can lead to changes in the construction plans, which will delay the project and increase costs.[2]

When the strands are cut (detensioned) and the prestressing force is transferred to the concrete, initial camber develops as an upward curvature along the girder. The magnitude of the initial camber depends mainly on the concrete mechanical properties, stress in the strands, girder length, and girder cross section.[3] Generally, camber increases with time. Thus, camber measured at the time of girder erection on a bridge site, or the erection camber, is larger than the initial camber. The magnitude of the erection camber depends on the magnitude of the initial camber and the growth of camber over time. The growth in camber is governed by the time-dependent deformation of concrete, typically including creep and shrinkage. Creep and shrinkage shorten the girder over time, which decreases the force in the tensioned strands, causing prestress losses. These losses in the prestressing force, along with the strand's relaxation loss, are time dependent and also affect camber growth and magnitude.[1]

Factors influencing camber and deflection are time dependent and related to each other, which makes an accurate prediction of camber challenging.[4] The initial camber is mainly influenced by the modulus of elasticity of concrete and strand stress. Camber at girder erection, on the other hand, is influenced by concrete creep, shrinkage, prestress losses, and various factors associated with the differences in quality control and storage conditions or variations in the ambient temperature and humidity. The magnitude of creep strain is also determined by the concrete strength at transfer.[5] For accurate predictions of camber and deflection, obtaining appropriate estimates for all the influential factors is necessary, and this can be a complicated task during the design stage.

An accurate prediction for camber can be obtained by using concrete properties that are representative of the concrete used to fabricate the girders.[6] Generally, concrete material properties used during design may deviate from the actual concrete properties for several reasons. These reasons include differences in the locally available materials and differences in the manufacturing and production practices. For example, the properties of the locally available coarse aggregate affect the prediction of the elastic modulus of concrete.[7,8] Concrete that contains crushed-limestone coarse aggregate has a different stiffness from concrete containing river gravel aggregate.[9] If aggregate stiffness is not considered in the modulus of elasticity calculation, the calculated elastic modulus may differ from the actual value, causing inaccurate camber prediction. The modulus of elasticity is a measure of girder stiffness that affects camber, elastic deflection, and elastic shortening losses of the girders. Differences in production practices among plants can also cause inconsistency in estimating concrete properties. Some fabricators overdesign the concrete to achieve the initial design compressive strength earlier to expedite the production process. Consequently, the concrete compressive strength at transfer and at later ages will be higher than the design strength. Concrete with a higher compressive strength will also have a higher elastic modulus, which leads to less camber and less deflection than expected. In this paper, focus is placed on evaluating the accuracy of estimating concrete properties and the effect of the estimated properties on predicting camber and deflection of bridge girders.

Literature review

The American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications* do not explicitly provide a design procedure for estimating the camber of precast, prestressed concrete girders.[10] Due to its simplicity, a multiplier method in the *PCI Design Handbook: Precast and Prestressed Concrete* is widely used to predict the long-term camber and deflection; however, the multiplier method has resulted in differences between the design camber and the actual camber.[11] In most cases, girders arrive at the bridge site with camber much less than the design value.[12] Variations in camber prediction mean the deflection is also not estimated correctly because both camber and deflection are affected by the same factors. Accurate prediction of camber and deflection is essential to prevent large deflections caused by the deck weight and long-term creep deflection. Noticeable deflection or sag in the bottom of the girders may cause serviceability issues and raise public concerns.[12]

In the United States, several state departments of transportation have investigated camber variability and updated their prediction methods based on research findings.[2,13,14,15] Many states have developed their own methods or modified a basic design procedure to estimate camber. Using a single design approach that quantifies camber behavior would not be accurate to predict camber for girders cast in any precast concrete plant. The reason is that camber is highly affected by concrete properties, which are affected by the local materials. Each precasting plant has unique characteristics in terms of local concrete components and production procedure. The properties of these local materials can affect concrete modulus of elasticity, shrinkage, and creep.[2,16] Moreover, concrete strength at transfer, curing time, and curing method are also different among plants and these also affect concrete properties. Even storage time and method of girder storage influence camber growth.[12]

Most of the contemporary camber prediction methods and design software use multipliers to estimate the growth in the initial camber and deflection. The idea of using multipliers came from Martin in 1977.[17] Later on, this method was adopted by the *PCI Bridge Design Manual* and also presented in the *PCI Design Handbook*,[3,4,17] as shown in Eq. (1). To estimate the erection camber, Martin suggested multiplying the initial camber due to prestressing force by 1.8 and multiplying the self-weight deflection by 1.85.[17] This method was based on general assumptions regarding concrete properties, prestress losses, and concrete age at girder erection. Martin assumed that one-half of the long-term camber, deflection, and prestress losses occur by the time of erection, which can range from 30 to 60 days after casting the girder. These assumptions resulted in differences between the proposed multiplier method and the actual camber.[12,15] Although Martin recommended using other camber prediction methods for more accurate results, many design engineers and design software still use Martin's method due to its simplicity.

$$\Delta_{erection\ camber} = 1.8\ (\uparrow\Delta_{prestress}) - 1.85\ (\downarrow\Delta_{self\text{-}weight}) \qquad (1)$$

where

$\Delta_{erection\ camber}$ = camber at time of girder erection

$\uparrow\Delta_{prestress}$ = upward component for initial camber due to prestressing force

$\downarrow\Delta_{self\text{-}weight}$ = downward component for initial deflection due to self-weight of the member

Tadros et al.[12] proposed a more detailed method to estimate the initial and long-term camber. Tadros et al. considered the effect of strand debonding, storage condition (girder overhang length), friction at girder ends, and the accuracy of the estimates for modulus of elasticity and prestress losses on the initial camber prediction. The concrete age at transfer and at deck placement were assumed to be 0.75 and 120 days, respectively. Two multipliers were proposed to predict the erection camber based on the transfer camber. The first multiplier incorporated the effect of creep on the net camber from the initial prestressing force and self-weight deflection, as shown in Eq. (2). The second multiplier includes the effect of creep on the elastic deflection due to prestress losses, as shown in Eq. (3).

$$\text{multiplier for initial prestress plus self-weight} = (1 + \psi[120, 0.75]) \quad (2)$$

$$\text{multiplier for the prestress loss} = (1 + 0.7\psi[120, 0.75]) \quad (3)$$

where

$\psi(120, 0.75)$ = creep coefficient between prestress transfer at 0.75 days and deck placement at 120 days

Tadros et al. assumed the following relationship for elastic deflection due to prestress loss.

$$\Delta_{elastic\ deflection} = (\Delta_{ip}[\Delta_{lt}/f_{pi}]) \quad (4)$$

where

f_{pi} = prestressing steel stress immediately prior to transfer

$\Delta_{elastic\ deflection}$ = elastic deflection due to long-term loss between initial time and deck placement

Δ_{ip} = initial camber due to the prestressing force

Δ_{lt} = net long-term camber before deck placement

The net long-term camber is then calculated by taking the sum of the first multiplier (Eq. [2]) times the initial camber ($\uparrow\Delta_{prestress} - \downarrow\Delta_{self\text{-}weight}$) and the second multiplier (Eq. [3]) times the elastic deflection due to prestress loss (Eq. [4]). This method requires detailed information regarding storage condition and concrete material properties that may not be available in the design stage. In addition, this method is limited to the time just before deck placement and ignores the estimated deflection due to the weight of the cast-in-place concrete deck.

Discrepancies between the measured and design camber have also been reported to Florida Department of Transportation (FDOT). Cook et al.[16] evaluated and calibrated camber prediction software for FDOT. The study involved measuring camber for 13 girders, which consisted of 78 in. (1980 mm) Florida bulb-tee girders, AASHTO Type IV girders, and AASHTO Type V girders. Camber was measured at transfer and periodically over six months. The results indicated that the design program used by FDOT at that time of the study overestimated camber by 55% for the 78 in. bulb-tee girder and by 50% for the AASHTO Type IV girder.

In Minnesota, O'Neill and French investigated the overestimation in the measured camber for bridge girders.[2] The study included collecting historical data for compressive strength, camber at transfer, and camber at erection from two precast concrete plants. The changes in camber were monitored for 14 girders from strand transfer to girder shipment. O'Neill and French proposed different multipliers to predict the long-term camber based on field measurements and the collected camber values.

Rosa et al.[13] proposed a refined camber design method for the Washington State Department of Transportation. The study included material testing and analysis of field measurements. Concrete compressive strength, elastic modulus, creep, and shrinkage were measured on representative samples. Camber was measured at transfer and during storage for eight girders. A computer program was developed to predict camber over time. The design software did not quantify the deflection of the girder due to the cast-in-place concrete bridge deck.

Research significance

The goal of this study is to improve the accuracy in predicting long-term camber and deflection of AASHTO I-section prestressed concrete girders and determine the sources of error in camber design. The experimental part of the study consisted of concrete materials testing and field measurements for camber and deflection. Concrete specimens were sampled at two precasting plants during the casting of several girders. Camber and deflection were measured to identify trends and potential causes of the differences between the design and the actual camber and deflection. The analytical part of the study evaluated the accuracy of existing camber prediction models and developed an improved method for predicting erection camber. The study also evaluated the accuracy of predicting the camber at transfer.

Experimental program

The experimental program consisted of testing the concrete compressive strength and modulus of elasticity for several full-scale prestressed concrete girders and monitoring camber and deflection. Several types of girders, including AASHTO Types II, III, IV, and VI, were examined in this study. For each girder type, the number of girders investigated depended on the measurements conducted. Concrete was sampled during the casting of 21 girders: six each of Types II, III, and VI girders and three of Type IV girders. The initial camber was measured for each of those girders plus 21 additional girders that were cast a day or two earlier. The erection camber and the deflection were measured on a total of 94 girders. The AASHTO Types II, III, and VI girders were fabricated at one prestressing plant, and the AASHTO Type IV girders were cast at another prestressing plant. These girders were used in the construction of three bridges in Arkansas. Girder details are available in **Table 1**, and more details are available in Almohammedi et al.[18]

Initial camber measurements

Camber was measured during all stages of the construction process to collect data for the study. As mentioned, camber is affected by production practices, ambient temperature, relative humidity, and support conditions.[12,19,20] Therefore, camber for a particular girder can vary depending on its age and the time of day. In this study, the research team was careful to perform all measurements for camber at conditions that were as identical as possible, especially for girders of the same type.

A rotary laser level system was used to measure the camber and deflection for all girders. The laser unit was stationed at the end of each girder, and three readings were taken along the girder span. The manufacturer-stated accuracy for the level was ±1⁄16 in. (1.5 mm) for each 100 ft (30.5 m) distance between the level and the laser receiver. A laser detector was attached to a wooden rod with a scale on both sides to record the elevations. The rod had three locations that must be in contact with the concrete when measuring elevations. Two points were in contact with the web to keep the rod vertical, and the third point ensured that the rod was sitting on the bottom flange. The rod was held perpendicularly to the top flange surface using a bubble level attached to the side of the rod. Two readings were taken at the girder ends and one at the girder midspan. Camber was then calculated by averaging the end readings and subtracting that value from the midspan reading. **Figure 1** shows the level and the rod used for measurements.

Studies have found that the friction between the girder ends and the steel prestressing bed prevents the initial camber from reaching its full potential.[15,21] Given those findings from previous studies, camber measured on the bed should be less than that measured after moving the girders to the storage yard. In this study, camber was first measured after prestress transfer, when the girders were still on the prestressing bed. Camber was measured again immediately after moving the girders to a storage yard. The camber measured at the storage yard was always greater than or equal to that measured when the girders were still on the steel prestressing bed. The camber measured at the storage yard was reported as the initial camber. For determining the girder camber while on the prestressing bed, the midspan of the girder was located. The distance between the bed chamfer edge and the edge of the girder at midspan was measured using a tape measure (**Fig. 2**). This distance represents the instantaneous camber.

Erection camber measurements

At the bridge construction site, the erection cambers were measured after setting up the stay-in-place deck forms but before installing the reinforcement for the deck. It would not have been accurate to take camber readings on the top of the bridge because the top flange surfaces of the girders were inconsistent. In addition to that, the follow-up readings would not have been possible once the deck was cast. Instead, readings for the erection camber were conducted under the bridge, on the bottom flange of each girder. A rotary laser level was used for the measurements (**Fig. 3**). Because the bridges were about 30 ft (9.1 m) off the ground, it was not possible to record accurate elevations by physically touching the bottom surface of the girder with the conventional scaled rod. Therefore, a laser distance device was used to record the distance to the bottom of the girder. The laser distance device was attached to the receiver, and both were mounted on an aluminum prism pole (Fig. 3). Each elevation was recorded by adjusting the receiver vertically until it detected the laser. This was done while maintaining the prism pole perpendicular to the instrument's line of sight using the bubble level. Three elevations were recorded for each girder, one at midspan and one at each end. Camber was then calculated by averaging the end elevations and subtracting that value from the midspan elevation. The elevations were taken relative to reference marks set earlier on the piers.

Table 1. Testing matrix

AASHTO girder	Number of girders			Girder length, ft	Precast concrete plant
	For concrete testing	For initial camber measurements	For erection camber measurements		
Type II	6	12	15	42	1
Type III	6	12	16	63	1
Type IV	3	6	24	94	2
Type VI	6	12	39	109	1

Note: AASHTO = American Association of State Highway and Transportation Officials. 1 ft = 0.305 m.

Figure 1. Rotary laser level and receiver rod used to measure camber.

Figure 2. Initial camber measured on the casting bed.

Figure 3. Deflection measurement devices.

Deflection measurements

Some studies that aimed at improving camber prediction did not consider the reduction in the camber due to the deflection caused by the self-weight of the deck.[2,14,15] It is important to have a proper estimate for the elastic deflection to determine the remaining camber after applying all the dead load. An accurate value for remaining camber after the elastic deflection is necessary to compensate for the long-term deflection and prevent noticeable sag. As mentioned, the girders were used in the construction of three bridges in Arkansas. The elastic deflection was measured for AASHTO Types II, III, and VI girders. During the erection camber measurements, the elevations of the bottom surface of the girders at midspan were recorded. After placing the concrete deck, the elevations of the bottom surfaces of the girders were recorded again. For each girder, the difference between the two midspan elevations recorded before and after deck placement represents the elastic deflection.

Preparing the concrete testing specimens

Due to the many reasons mentioned, concrete properties measured at jobsites often differ from those used in design.[2,15] These differences cause errors in camber and deflection estimations and must be evaluated. In this study, the researchers were present during the manufacturing of the 21 girders that included AASHTO Types II, III, IV, and VI. For each type of girder, the research team chose one or two castings from which to collect concrete for material property tests. Fresh and hardened concrete tests were conducted using the plant laboratory equipment. At later concrete ages, tests were conducted at the Engineering Research Center at the University of Arkansas.

During girder castings, 20 to 25 concrete cylinders with dimensions of 4 × 8 in. (100 × 200 mm) were prepared from the concrete used to cast each type of the AASHTO I-section girders. Concrete was collected from each girder on the prestressing bed when possible and from at least three different mixers. This practice aimed at collecting necessary specimens that were representative of the concrete cast in each girder. In both plants, concrete was sampled according to ASTM C172/C172M-17.[22] The specimens were placed beside the girders to cure so that they could experience the same curing conditions as the girders (**Fig. 4**). Before opening the forms, the concrete cylinders were collected and kept in the molds until the test day. Whenever concrete was sampled, the researcher stayed in the plant until the transfer time to measure the initial camber of the girders.

Compressive strength and modulus of elasticity testing

Sixteen to twenty hours following casting, the laboratory technician tested three cylinders to ensure that the compressive strength of the concrete met the specified transfer design strength before detensioning the strands. If the concrete had not achieved the transfer strength, the technician would wait an hour then test additional cylinders. It is important to point out that the transfer of the prestressing strands occurred four to five hours after the required compressive strength was achieved. Therefore, the actual compressive strength at transfer was higher than that tested by the plant laboratory technician. This additional time was required for removing the tarps and opening the side forms. Also, the plant staff was not authorized to open the forms until the transfer strength met the design value. In this study, the research team tested the compressive strength and the modulus of elasticity at the time of strand transfer rather than recording the strength from the technician data sheet. The increase in compressive strength between when the cylinders were first tested by the laboratory technician and when the strands were detensioned ranged from 525 to 1050 psi

Figure 4. Concrete specimens stored under the tarps during curing for Types III and VI girders.

(3.62 to 7.24 MPa). The compressive strength and the modulus of elasticity were tested according to ASTM C39/C39M-18 and ASTM C469/C469M-14, respectively.[23,24]

Results and discussion

Compressive strength of concrete

Test results indicated that the measured compressive strength for all girders was higher than the design strength. At plant 1, the concrete compressive strengths at transfer for the Types II, III, and VI girders were 27% to 73% higher than the design value. For the Type IV girders that were cast at plant 2, the measured concrete compressive strength at transfer was 59% higher than the design strength. The compressive strength at transfer directly affects the initial and the erection camber. **Figure 5** shows a comparison between the design and measured compressive strength at transfer for each girder type. At 28 days of age, on average, the measured compressive strength was 69% higher than the design strength for all girders (**Fig. 6**).

The study found that both precasting plants produced concrete with much higher compressive strengths than the design values. Precast concrete producers tend to obtain the required design strength as early as possible. This practice allows the producers to detension prestressing strands earlier and move

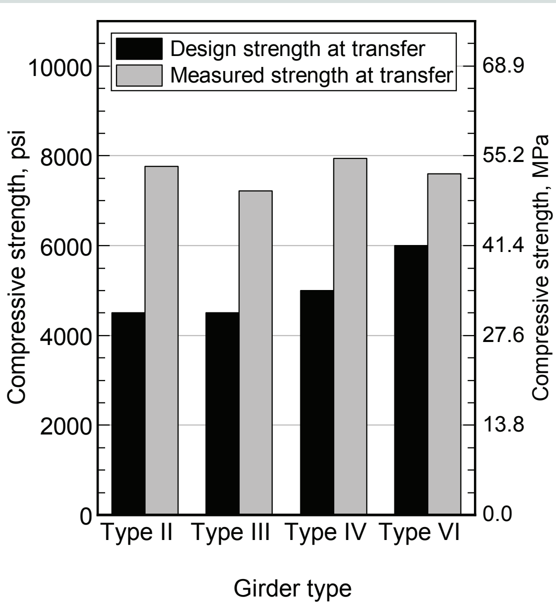

Figure 5. Comparison of the measured and design compressive strength at transfer.

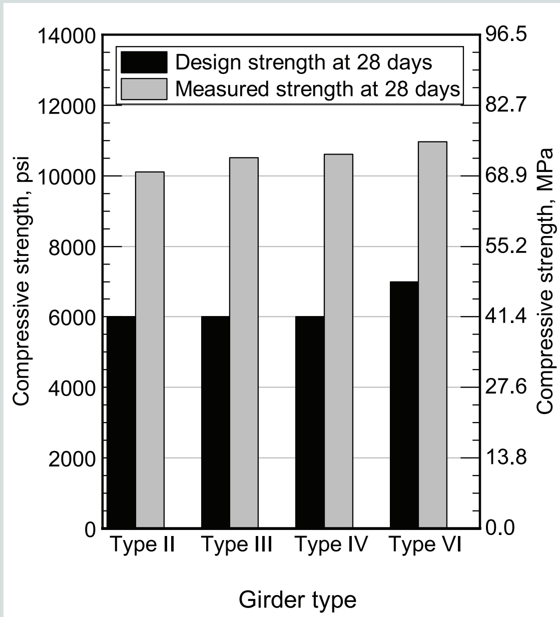

Figure 6. Comparison of the measured and design compressive strength at 28 days.

the girders from the prestressing bed so that the production cycle can be shortened without compromising the quality of the precast concrete girders. A typical production cycle is not more than 24 hours. Failure to obtain the design transfer strength in time will affect the daily work schedule because strands cannot be detensioned until the concrete achieves the specified compressive strength at transfer.

Elastic modulus of concrete

Figure 7 compares the measured modulus of elasticity at transfer with the design values calculated using two common equations. The first equation is AASHTO LRFD Eq. (5.4.2.4-1)[10] and the second is the ACI-363 Eq. (5-1).[25]

$$E_c = 33{,}000 K_1 w_c^{1.5}\sqrt{f'_c} \text{ for } w_c \text{ in kip/ft}^3 \text{ and } E_c,\ f'_c \text{ in ksi}$$

(AASHTO LRFD 5.4.2.4-1)

$$E_c = 0.043 w_c^{1.5}\sqrt{f'_c} \text{ for } w_c \text{ in kg/m}^3 \text{ and } E_c,\ f'_c \text{ in MPa}$$

$$E_c = \left[1000 + 1265\sqrt{f'_c}\right]\left(\frac{w_c}{0.145}\right)^{1.5} \text{ for } w_c \text{ in kip/ft}^3 \text{ and } E_c,\ f'_c \text{ in ksi}$$

(ACI 363 Eq. 5-1)

$$E_c = \left[6900 + 3320\sqrt{f'_c}\right]\left(\frac{w_c}{86}\right)^{1.5} \text{ for } w_c \text{ in kg/m}^3 \text{ and } E_c,\ f'_c \text{ in MPa}$$

where

E_c = modulus of elasticity of concrete

w_c = unit weight (density) of concrete

K_1 = correction factor for source of aggregates

f'_c = specified concrete strength at final service conditions

The design values for the modulus of elasticity in Fig. 7 were calculated using the specified design compressive strength from the construction plans for each girder type along with an assumed concrete unit weight of 0.150 kip/ft^3 (2403 kg/m^3) and correction factor for the source of aggregates K_1 of 1.0. More details about the prediction of modulus of elasticity, mixture proportions, aggregate types, and correction factor for the source of aggregates K_1 values are available at Almohammedi et al.[18]

The measured modulus of elasticity at transfer was 15% to 44% higher than the design values calculated by AASHTO LRFD Eq. (5.4.2.4-1). When using the ACI Committee 363 equation, the measured values were 25% to 53% higher than the design values. The underestimation of the elastic modulus was not only because the measured compressive strength was higher than the design value but also because the AASHTO LRFD equation and ACI Committee 363 equation underestimate the elastic modulus by as much as 25% and 29%, respectively. This was found when comparing the measured

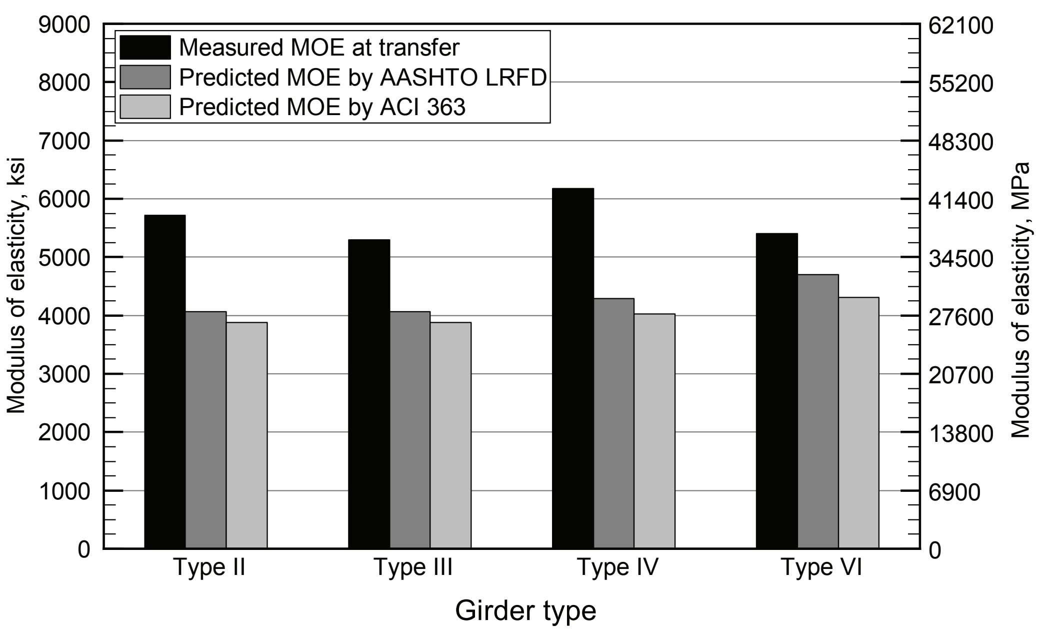

Figure 7. Comparison of the measured and predicted modulus of elasticity at transfer. Note: AASHTO LRFD = Eq. (5.4.2.4-1) from the American Association of State Highway and Transportation Officials *AASHTO LRFD Bridge Design Specifications*; ACI 363 = modulus of elasticity equation from ACI's *State-of-the-Art Report on High Strength Concrete*; MOE = modulus of elasticity.

elastic modulus with the design values calculated using the actual compressive strength. As compressive strength increases, the elastic modulus also increases, which in turn increases girder stiffness. Higher girder stiffness at transfer reduces the initial camber and the growth in camber with time, which ultimately decreases the erection camber.

Design values compared with measured values of initial camber

The initial camber was measured right after placing the girders in the storage yard. Due to the timing of the measurements, the concrete creep or shrinkage or the uncontrolled ambient temperature and humidity had yet to affect the camber. Therefore, the initial camber could be calculated relatively accurately; however, the measured initial cambers were 53% and 39% less than the design values for AASHTO Types II and III girders, respectively. This is attributable mainly to the actual concrete strength being higher than the design concrete strength at transfer, which led to a higher elastic modulus. The measured concrete strength was on average 66% higher than the design strength, which increased the girder stiffness and consequently reduced the initial camber. Using the measured concrete properties in the calculations makes the calculated initial camber closer to the measured initial camber for AASHTO Types II, III, and VI girders (**Fig. 8**). However, this was not the case for Type IV girders, which may be attributed to the type of coarse aggregate used in the concrete. Type IV girders were cast in plant 2 using river gravel, while the other girder types were cast in plant 1, where they used crushed limestone. Figure 7 also clearly shows that the measured modulus of elasticity for Type IV girders was the highest. Note that the measured concrete properties are unknown during the design stage without prior field testing.

The friction between the girder ends and the prestressing bed prevented full cambering, which can lead to inaccurate readings for the initial camber depending on when the measurements are taken. The effect of the friction on the initial camber measurements was confirmed by other researchers.[15,21] The friction effect is neither consistent nor predictable. For example, for three Type VI girders, the camber measured on the prestressing bed was 50%, 35%, and 8% less than the cambers for the same girders measured in the storage yard. Therefore, the initial camber should be measured as soon as the girders are moved to the storage yard. Precasters can improve the predictability of cambers by maintaining consistent curing times before prestress transfer. Longer curing time will increase the stiffness of the concrete and lead to much less camber than expected.

Design values compared with measured values of erection camber

Field measurements revealed differences between the design and measured camber for all girders. **Figures 9** through **12**

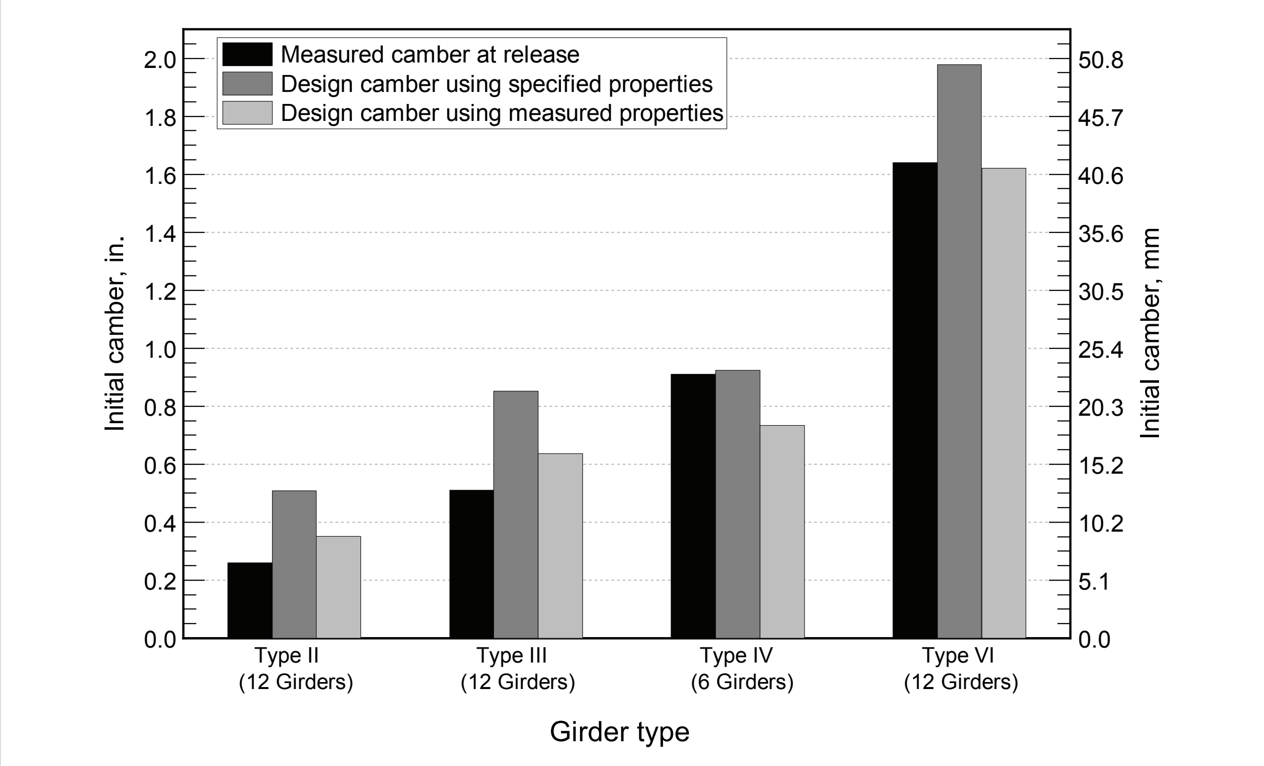

Figure 8. Comparison of the average measured initial camber with the design values.

compare the measured cambers with the design cambers calculated using the PCI multiplier method and Tadros et al.[12] method, both of which are described earlier in this paper. Figures 9 through 12 show the design cambers that were calculated using the specified design properties and the design cambers that were calculated using the measured concrete properties, though the measured properties are not available during the design stage. This indicates how accurate the prediction of camber can be if the designer has a better estimation of the concrete properties. The erection camber taken from the bridge construction plans was calculated using commercial software by the Arkansas Department of Transportation (ARDOT), which uses multipliers to predict the erection camber.

The results indicated that the design erection cambers that were shown on the construction plans were greater than the average measured cambers by 67%, 128%, 61%, and 25% for AASHTO Types II, III, IV, and VI girders, respectively. These results confirmed the need for a calibrated camber prediction method based on common practices in prestressed concrete plants. In general, the differences between the design and the measured camber are higher in shorter girders (Types II and III) than in longer girders (Types IV and VI). This indicates that short girders with smaller depths tend to camber less than long girders with larger depths, which are typically subjected to higher amounts of prestressing force. The main reason the erection camber was less than the design value for all girders was that the measured modulus of elasticity was higher than the design values. This conclusion was also determined by other researchers.[2,13] A higher elastic modulus increases girder stiffness, which reduces the camber at the time of transfer and erection.

ARDOT and other state agencies and structural design firms use commercial software to calculate the erection camber.[12,14] Most design software still uses multipliers similar to those in Martin's method due to their simplicity and because they are still adopted by the *PCI Design Handbook: Precast and Prestressed Concrete and PCI Bridge Design Manual*.[3,4,12] The results shown in Fig. 9 through 12 indicate that the commercial software used by ARDOT overestimates camber at erection for all girders included in the study. The construction plans provide the erection camber at 90 days from transfer. This camber is calculated using the specified concrete compressive strength and the estimated strand stress; however, even when using the specified concrete strengths that were supposedly used in the design software, the PCI multiplier method provides a better estimate for camber.

When the measured concrete strength and modulus of elasticity were used in the calculations, the calculated cambers were only 0.7% greater than the measured cambers. Figures 9 through 12 evaluate the accuracy of the PCI multiplier method and Tadros et al.[12] method. The PCI multiplier method with transformed section properties provided a prediction close to that of the Tadros et al. method.

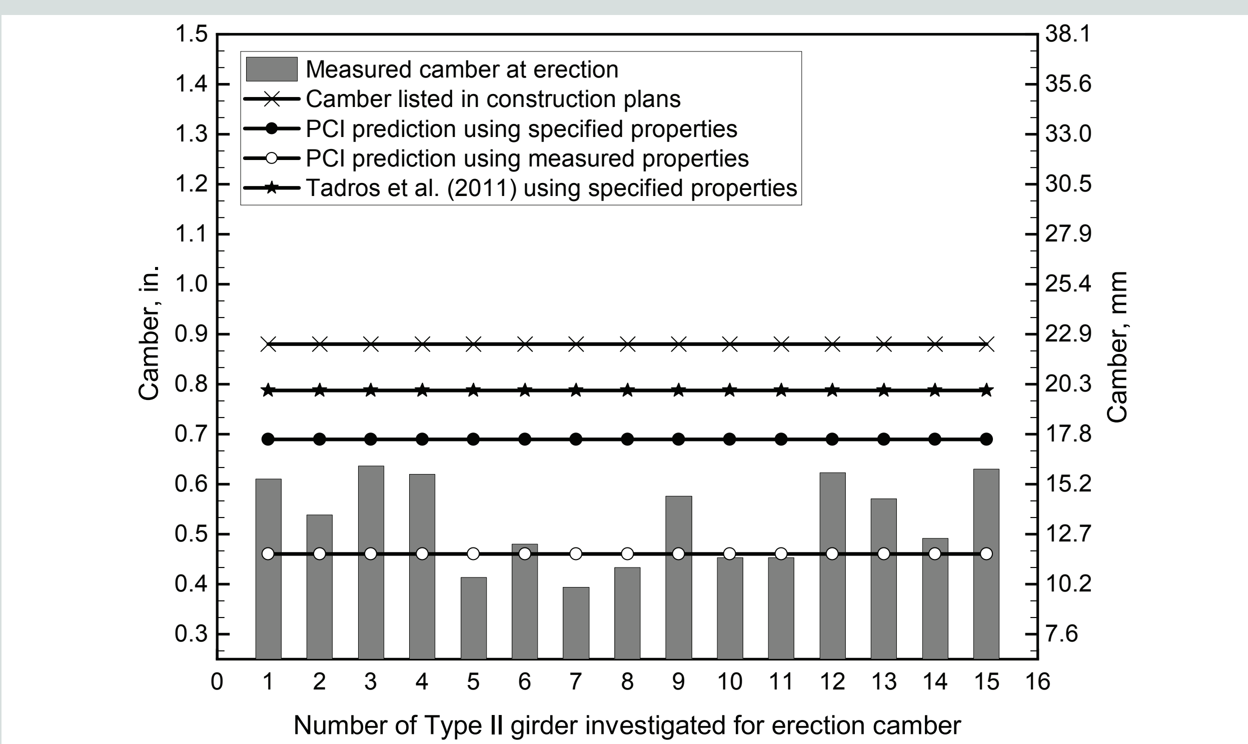

Figure 9. Comparison of the measured erection camber for 15 AASHTO Type II girders with the design value calculated using different methods.

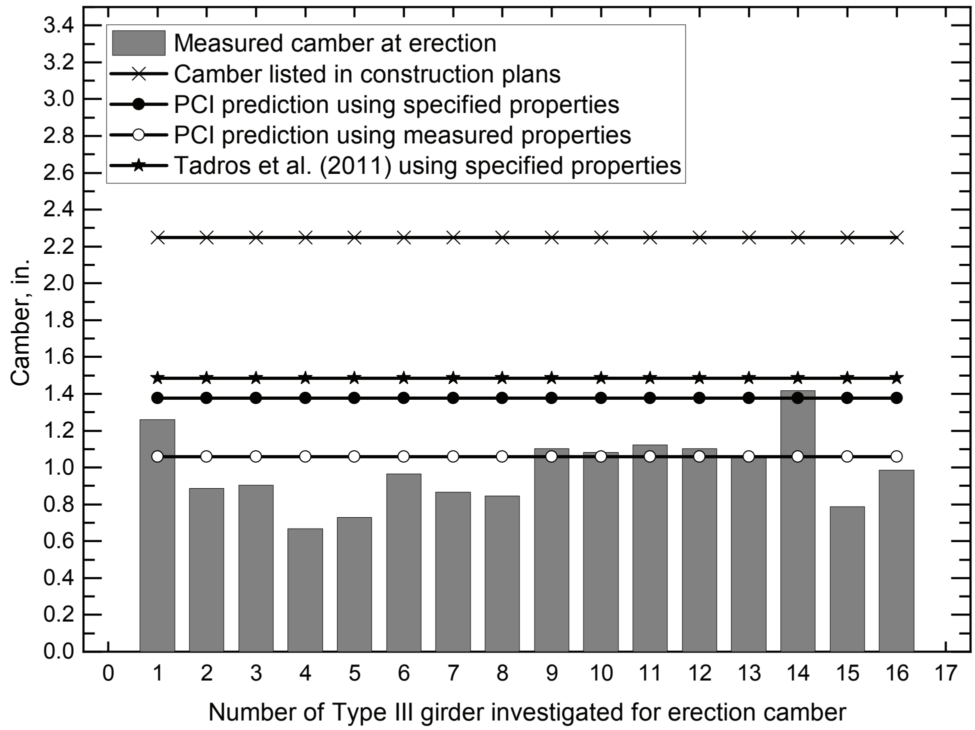

Figure 10. Comparison of the measured erection camber for 16 AASHTO Type III girders with the design values calculated using different methods.

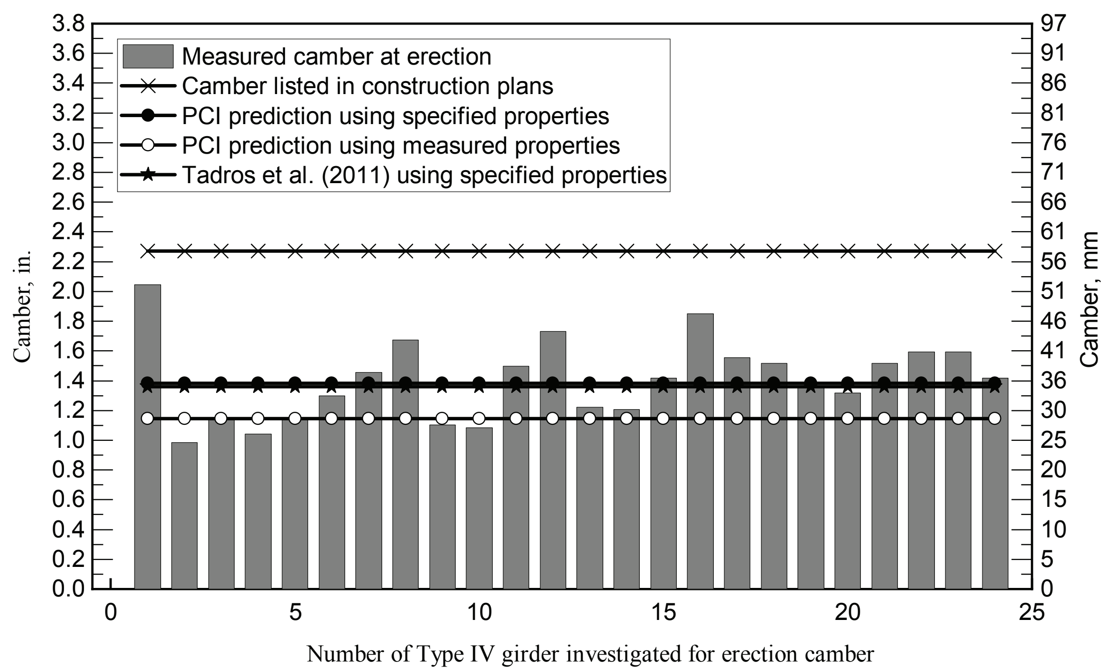

Figure 11. Comparison of the measured erection camber for 24 AASHTO Type IV girders with the design values calculated using different methods.

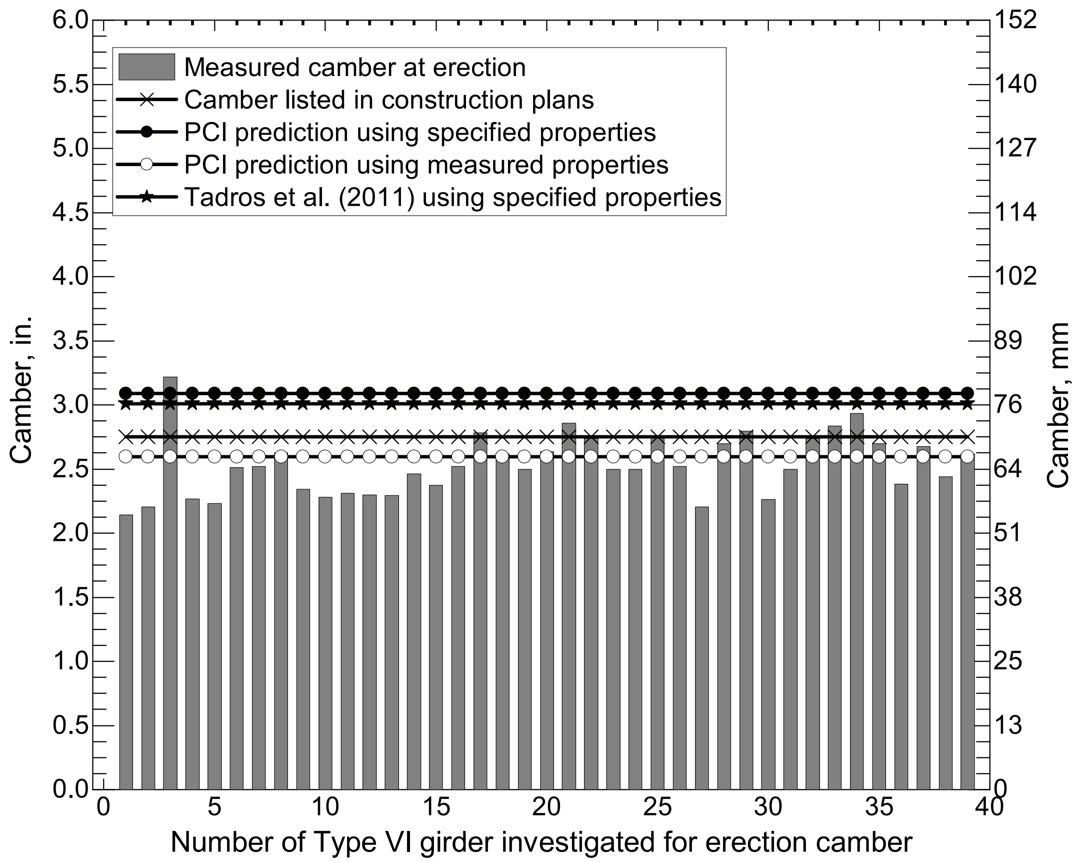

Figure 12. Comparison of the measured erection camber for 39 AASHTO Type VI girders with the design values calculated using different methods.

Proposed camber prediction

Based on the observations from the material tests and the field measurements, the researchers proposed a revised PCI multiplier method to enhance the prediction of erection camber. As mentioned, the PCI multiplier method uses two multipliers: 1.85 for the initial elastic deflection from the member weight and 1.80 for the initial elastic camber from the prestressing force at transfer as shown in Eq. (1). The proposed method uses a single multiplier of 1.40 for AASHTO Types II, III, IV, and VI girders to estimate the erection camber. The erection camber can be determined by applying the new multiplier to the initial camber calculated using transformed section properties as shown in Eq. (5).

$$\Delta_{erection\ camber} = 1.40 \times (\Delta_{initial\ camber}) \tag{5}$$

where

$\Delta_{erection\ camber}$ = camber at time of girder erection

$\Delta_{initial\ cambe}$ = initial camber of prestressed concrete girder at time of prestress transfer

Figure 13 shows the efficiency of the proposed multiplier by comparing the results with the actual cambers that were measured at the bridge sites. The proposed method results in an improved camber prediction. The estimated error ranges from -8% to 18%, which can result in an absolute difference between the measured and predicted camber of less than 0.5 in. (13 mm) (Fig. 13). The 1.40 multiplier is applicable for a time lapse of 60 to 180 days between the time of prestress transfer and the time of girder erection. In rare occasions, the erection age of the girders may be much longer than 180 days. In this case, the contractor should expect the erection camber to be higher than the design and should verify the deck longitudinal profile accordingly. The 1.40 multiplier can be used to estimate the erection camber for prestressed concrete girders other than the types that were investigated in this study if erection camber values are available from previous projects to verify the accuracy of the prediction.

Evaluation of deflection at deck placement

In an attempt to quantify the long-term creep deflection, camber measurements were taken for some existing bridge girders that were in service. The results revealed deflections that

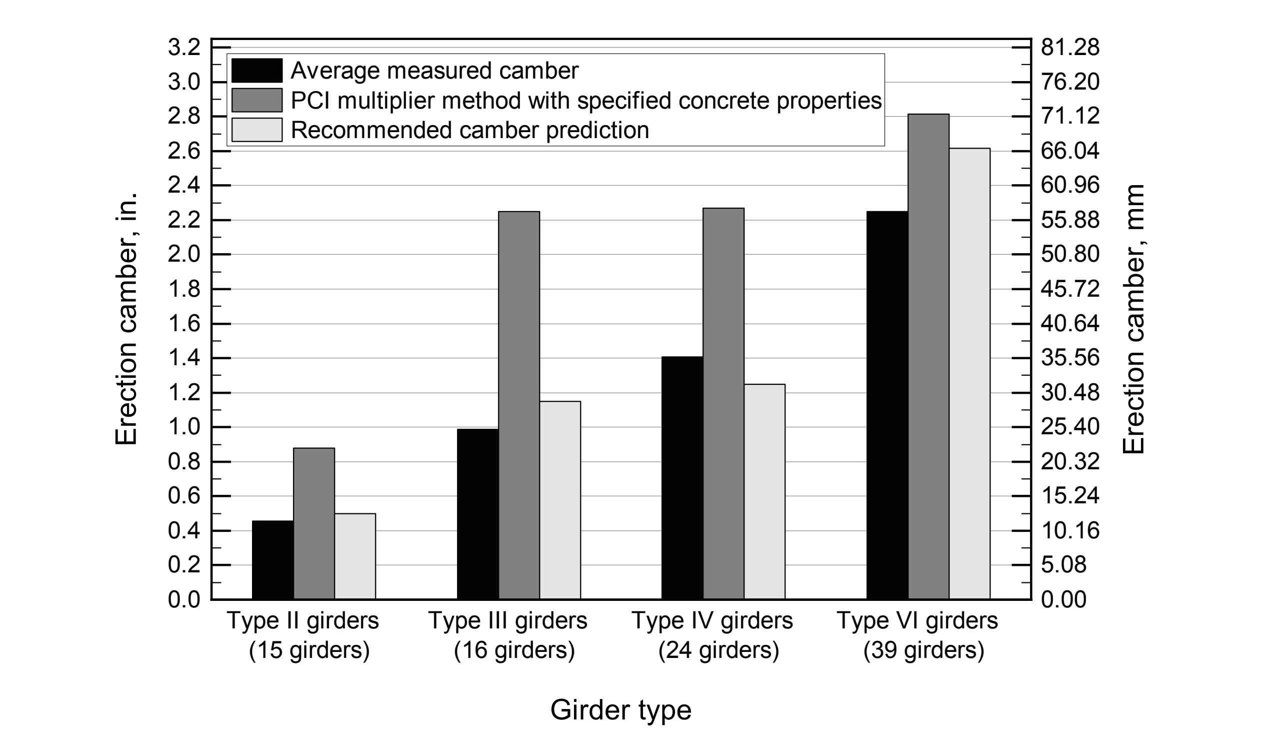

Figure 13. Comparison of the predicted camber calculated by the recommended method with the measured and design cambers for AASHTO Types II, III, IV, and VI girders.

reached up to 0.7 in. (18 mm) in Type III girders, which may indicate that the camber for these girders was overestimated. This confirms the necessity of developing updated camber and deflection predictions.

For this paper, the midspan deflection was calculated using basic structural analysis. The concrete deck weight was assumed to be uniformly distributed over a simply supported beam. **Fig. 14** compares the measured deflections with the design values. The figure shows that all girders deflected much less than predicted in the design, which may be attributed to two main reasons. First, the actual concrete compressive strength was much greater than expected. This increased girder stiffness and in turn decreased the deflection. Second, the girders were laterally restrained at the ends and at midspan before deck placement. This restraint made the girders deflect as a group, which increased the rigidity of the system.[12] Figure 14 shows that the measured deflections of the AASHTO Types II and III girders were less than the predicted values determined from either design procedure. Using the actual concrete properties improved the accuracy of the estimate. Barr and Angomas found a 40% reduction in the measured deflection compared with the design values.[26] For AASHTO Type VI girders, using the measured concrete properties improves the estimation of the elastic deflection at deck placement. In general, having less deflection than expected is not considered a performance-related problem for bridge girders, especially when there is less camber at erection than

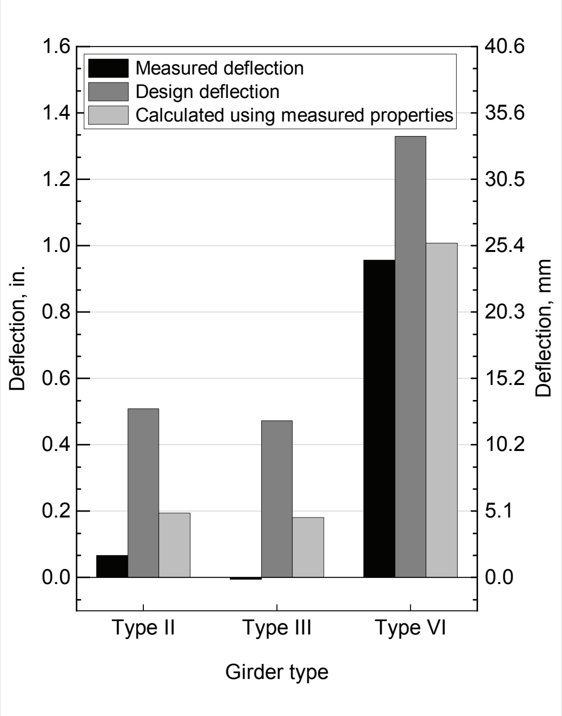

Figure 14. Comparison of the measured deflection with the design and the predicted values.

would be needed to offset predicted deflections, as in the case of Types II and III girders. In fact, having less deflection is useful because the remaining camber after deck placement is necessary to compensate for the long-term creep deflection.

Conclusion

After more than two years of taking measurements from the time of casting the girders to the completion of the bridge decks, this study provides several conclusions. The measured cambers at the time of transfer and at the time of erection are greater than the design cambers. After casting the concrete deck, all girders involved in the study deflected less than the design value. This is because when the actual compressive strength is higher than the expected strength, the girder will be stiffer and in turn more resistant to deflection. The overestimations of camber were attributed to the actual concrete compressive strength at transfer being greater than the specified minimum design strength. Girder producers overdesign the concrete to achieve the compressive strength at transfer in less than 24 hours. This has become a common practice to optimize productivity and maintain a consistent working schedule. As a result, the concrete strength and thus the modulus of elasticity are higher and the girders camber and deflect less than the designed values. If the camber is calculated using field-measured concrete properties, the design camber will be close to the actual camber; however, the measured concrete properties are not available at the time of the design. This study provides a simple and accurate method to predict long-term camber without the need for design software or field tests. The proposed procedure consists of a single multiplier of 1.40 applied to the initial camber that is calculated using transformed section properties.

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Notation

E_c = modulus of elasticity of concrete

f'_c = specified concrete strength at final service conditions

f_{pi} = prestressing steel stress immediately prior to transfer

K_1 = correction factor for source of aggregates

W_c = unit weight (density) of concrete

$\Delta_{elastic\ deflection}$ = elastic deflection due to long-term loss between initial time and deck placement

$\Delta_{erection\ camber}$ = camber at the time of girder erection

$\Delta_{initial\ camber}$ = initial camber of prestressed concrete girder at the time of prestress transfer

Δ_{ip} = initial camber due to prestressing force

Δ_{lt} = net long-term camber before deck placement

$\uparrow\Delta_{prestress}$ = upward component for initial camber due to prestressing force

$\downarrow\Delta_{self\text{-}weight}$ = downward component for initial camber due to self-weight of the member

ψ (120, 0.75) = creep coefficient between prestress transfer at 0.75 days and deck placements at 120 days

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Abstract

The current camber prediction procedure in the *PCI Design Handbook: Precast and Prestressed Concrete* results in variations between the design and the actual camber. These variations create difficulties in maintaining the design thickness of the bridge deck and the design longitudinal profile. This research aims at enhancing the PCI design method of estimating long-term camber and deflection of prestressed concrete girders. Field measurements included monitoring cambers for a total of 94 girders from fabrication through the erection at bridge sites. Compressive strength and modulus of elasticity were measured for several girders, and the results were compared with the design properties. The differences between the design and actual concrete properties were found to be the main reason for overestimation in camber and deflection. A modification to the PCI camber prediction method is proposed to improve the accuracy of predicting the erection camber based on field measurements and material tests on four types of bridge girders.

Keywords

Bridge, bridge girder, camber, deck, deflection, girder, prestress transfer, prestressing strand.

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