Improving the Accuracy of Camber Predictions for Precast Pretensioned Concrete Beams

tech transfer summary

Implementing the recommendations of this study is expected to significantly improve the accuracy of camber measurements and predictions and to ultimately help reduce construction delays, improve bridge serviceability, and decrease costs.

July 2015

RESEARCH PROJECT TITLE
Improving Accuracy of the Deflection and Camber Predictions for Prestressed Concrete Bridge Girders

SPONSORS
Iowa Highway Research Board (IHRB Project TR-625)
Iowa Department of Transportation (InTrans Project 11-390)

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The Bridge Engineering Center (BEC) is part of the Institute for Transportation (InTrans) at Iowa State University. The mission of the BEC is to conduct research on bridge technologies to help bridge designers/owners design, build, and maintain long-lasting bridges.

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Problem Statement

Construction schedule delays and additional costs are common problems when the actual camber of precast pretensioned concrete beams (PPCBs) are different from those expected during bridge design.

Background and Research Overview

The camber of a PPCB is relatively complex because it is sensitive to variations in several parameters, including the mix design, tolerances on prestressing forces and moisture control, bed configuration, curing process and handling, storage environment, and support location during storage. In addition, the aggregate types, cement, and admixtures used in the concrete mix play a significant role in the mix's creep and shrinkage behavior, which in turn significantly affect the long-term camber.

The method that the Iowa Department of Transportation (DOT) was using to formulate the camber for PPCBs frequently overpredicted the long-term camber of some of the most often used long PPCBs in Iowa bridges, while it underestimated the long-term camber of shorter PPCBs.

Therefore, a systematic study was undertaken to identify the key parameters affecting camber, needed improvements to construction practices, and potential refinements to the predictive analytical models. The discrepancy between the predicted and actual camber is reduced by addressing the concerns associated with each of these areas.

Objectives

- Quantify the engineering and time-dependent properties of concrete to reduce the uncertainties associated with the variability of material properties in the camber prediction of PPCBs
- Propose suitable refinements to the measurement approach to accurately capture the instantaneous camber and recommend appropriate modifications to the PPCB fabrication process to decrease variations in the camber of identical PPCBs
- Improve the method for predicting the instantaneous camber and verify the accuracy of the method using data collected from PPCBs produced at three local precast plants
- Address the long-term camber variability resulting from thermal effects and the locations of temporary supports
- In conjunction with the measured field data and the accurate analyses of PPCBs, develop a new set of multipliers to predict the camber accurately when the PPCBs are erected in the field

Material Characterization

Three normal concrete (NC) and four high-performance concrete (HPC) mix designs, which were representative mixes from three precast plants, were investigated for their engineering and time-dependent properties.

A total of 14 cylindrical specimens for each mix design were brought to the laboratory. Three specimens were used for one-day compressive strength tests, three were used for 28-day compressive strength tests, four were subjected to creep tests, and the remaining four were used to monitor shrinkage strains.

For the creep and shrinkage tests, half of the specimens were sealed using a coating material (Sikagard 62), and the rest were unsealed.

- Based on the results of creep and shrinkage measurements, equations were produced to calculate the average creep coefficient and shrinkage strain for the HPC.
- The American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) creep and shrinkage models were found to give the best estimates when compared to the measurements taken from the four HPC and three NC mixes over one year.
- Shrinkage strains taken from sealed specimens corresponded well with the strains obtained from a segment of full-scale PPCB, suggesting that strains taken from sealed rather than unsealed specimens would produce more realistic creep and shrinkage strains for PPCBs.

Instantaneous Camber Measurements

Using data collected for 105 PPCBs from three precast plants, the causes of error associated with the instantaneous camber measurement were investigated. The following conclusions were drawn:

- Values obtained from field measurements showed that the camber on average is affected by 0.030 in. ± 0.062 in. due to bed deflection, 0.392 in. ± 0.294 in. due to friction between the beam and steel bed, 0.099 in. ± 0.142 in. due to the inconsistent top flange surfaces along the beam length, and 0.113 in. ± 0.119 in. due to inconsistencies in the top flange surfaces resulting from local effects.
- Data obtained from the PPCBs at the transfer of the prestress by tape measure, rotary laser level, and string potentiometers showed good agreement when adjusting for possible camber measurement errors. Despite good agreement between the tape measure and rotary level, tape measure data are easily affected by human error and are not recommended.

Loaded specimens for creep tests in environmentally controlled chamber (top) and shrinkage test specimens in environmentally controlled chamber (bottom)

- The reverse friction is small in magnitude and can be ignored. The contribution of vertical displacement due to the friction can be obtained by lifting/setting the PPCBs on the precast bed and then taking the camber measurement.

Instantaneous Camber Predictions

Challenges faced in predicting the instantaneous camber during design are related to the designer's ability to accurately estimate the material properties and model the applied forces exerted on the PPCB after accounting for the effect of the prestress losses. Therefore, using the moment area method, different parameters affecting the instantaneous camber prediction, including the modulus of elasticity, prestress force, prestress losses, transfer length, influence of sacrificial strands, and section properties, were investigated.

The instantaneous camber was consequently predicted using the AASHTO modulus of elasticity based on the measured compressive strength with due consideration given to the applied prestress force, prestress losses, the AASHTO transfer length, sacrificial prestressing strands, and transformed moment of inertia.

Comparing these results with the measured camber of 50 PPCBs, for which measurement errors were eliminated, produced an agreement of 98.2±14.9%, which is a significant improvement in the predictive accuracy of the instantaneous camber.

Long-Term Camber Measurements

Camber measurements were taken for 66 standard PPCBs, including different types of PPCBs of various lengths and depths fabricated for five different bridges in Iowa, using a rotary laser from the top flange at release, during storage, and when erected on-site.

To distinguish between the PPCBs with high and low camber values, the PPCBs were divided into two groups: small-camber PPCBs with the estimated instantaneous camber less than 1.5 in. and large-camber PPCBs with the estimated instantaneous camber greater than 1.5 in.

Overhang distances of the PPCB ends vary during storage on temporary supports at the precast plants

During storage at the precast plants, the PPCBs were placed on temporary supports with varying distances from the ends to maintain stability. The resulting overhang length was found to vary from less than 20 in. (0.015 L, where L is the overall length of the beam) to as high as 87 in. (0.05 L), with a mean overhang length of L/30. As a consequence, the researchers found that long-term camber is affected by the overhang length.

Variations from expected trends in the long-term camber data, including unusually high camber at early ages and a reduction or no significant increase in camber, were frequently observed. Because the camber measurements were performed at different times during the day, the thermal effects created by the vertical temperature gradients down the beam depth were suspected to be contributing to the scatter in the data.

An investigation of the thermal effects of 22 PPCBs confirmed the effects of the temperature gradients on the long-term camber. The researchers found that temporary camber growth of as much as 0.75 in. is possible on a warm summer day, which explains the unusual trends in long-term camber.

Long-Term Camber Predictions

For the measured PPCBs, a combination of simplified analysis and finite element analysis (FEA) was utilized to study the change in camber from time of release to when erected and beyond. The FEA was performed with and without beam overhang to determine the extent to which the elastic and long-term deflection of overhangs contributes to camber and subsequently to eliminate these contributions from the measured data.

For design practice, a multiplier as a function of time, a set of average multipliers, and a single multiplier with and without the influence of overhang were developed to calculate the long-term camber. In addition to these multipliers, a temperature multiplier (λ_T), was introduced to improve the expected camber by addressing the short-term deflection due to the thermal effects.

Using midas Civil software, finite element models (FEMs) of PPCBs were also developed to study camber variation versus time, with due consideration to the measured creep and shrinkage behavior, the changes in prestressing force, the locations of the temporary supports, and the thermal effects.

Based on the long-term predictions, the following conclusions were drawn:

- For predicting the long-term camber using a simplified analysis, Naaman's method provided the best agreement with the measured long-term camber values.

- The FEA results showed that the long-term camber can be predicted with a mean error of 8.6% ± 14.5% and 24.1% ± 29.5% for the large-and small-camber PPCBs, respectively, when the thermal effects are ignored.
- Based on a sensitivity analysis, the scatter in the long-term camber data was adequately captured by using a linear temperature gradient down the beam depth with a temperature difference of 15°F between the top and bottom flanges.
- By incorporating the 15°F temperature difference in the long-term camber predictions, the corresponding errors were reduced to -1.2% ± 10.7% and -14.7% ± 22.5% for the large- and small-camber PPCBs, respectively.

Key Findings

- When AASHTO LRFD is used to estimate the modulus of elasticity, the release strength should be taken 40% and 10% higher than the specified concrete strength for PPCBs when the design value is in the 4500–5500 psi and 6000–8500 psi range, respectively.
- The sources of errors caused by the current instantaneous camber measurement techniques were identified and subsequently eliminated by the proposed measurement technique.
- By isolating the measurement errors from the errors caused by the prediction methods, the accuracy of the instantaneous camber prediction was improved using a combination of appropriate material properties and design procedures.
- The accuracy of the long-term camber prediction was improved when the multipliers were used and the errors in the instantaneous camber prediction were reduced.
- Using the FEM of the PPCBs developed with consideration given to measured creep and shrinkage, thermal effects, and changes in the prestress and support locations significantly improved the accuracy of the long-term camber predictions.
- The multipliers, which include adjustments for the overhang and thermal effects, improved the long-term camber predictions compared to those from the method used by the Iowa DOT.

Implementation Readiness

Based on the findings of this work, recommendations, which are included in the final report for the project, were presented for the concrete time-dependent properties, camber measurements, and instantaneous and long-term camber predictions.

Recommendations for Precasters and Contractors

To eliminate the differences in the camber due to the measurement technique, a simplified procedure was formulated that can be used by both precasters and contractors to accurately measure the camber. The recommended technique and other recommendations are included in the final project report.

Observations and independent camber measurements at three separate precast plants led to the following recommendations for minimizing the difference between the expected and measured camber of PPCBs:

- The camber is highly sensitive to the prestress force; therefore, monitor and apply the designed prestress force as accurately as possible.
- Aim for reaching and not exceeding the design strength of concrete at the transfer of prestress.
- Ensure consistency of the concrete mixes and base materials (e.g., aggregates) regardless of the time and day of casting.
- Ensure consistent curing conditions and ensure that PPCB curing conditions match those of the sample cylinders used for obtaining the release strength.
- When there is change in material or the curing process, time-dependent properties including creep and shrinkage behavior of concrete should be appropriately revised.
- Minimize the error in the instantaneous camber of identical PPCBs cast on different beds or at different times or days.
- Use the proposed camber measurement procedure to measure instantaneous camber.
- When PPCBs are stored in precast plants, use an overhang length of zero or L/30 (where L is the PPCB length).

Implementation Benefits

Implementing the study recommendations is expected to significantly improve the accuracy of the camber measurements and predictions.

As a result, the difficulties during bridge construction by the inaccurate camber values when the PPCBs are erected on-site will be alleviated, thereby reducing construction schedule delays, improving bridge serviceability, and decreasing costs.