Camber Variability in Prestressed Concrete Bridge Beams

by Dr. Maher Tadros, eConstruct

Beams cast with extra camber in storage yard at Concrete Technology Corporation; camber shown is exceptionally large for illustration purposes. Photo: Concrete Technology Corporation.

Precast, prestressed concrete girders experience camber (upward deflection) when the prestressing strands are detensioned and the prestressing force is transferred from the casting bed to the concrete member. When the girder is stored in the yard of the precast manufacturer, its camber continues to change with time, influenced by the ambient air conditions, and even the orientation of the girder as it is exposed to the sun. When the girder is erected on its seats at the bridge site and just before the deck is placed, its camber at that time affects the haunch (build up) concrete required to ensure that the top of deck surface meets the roadway profile requirements.

Initial camber after detensioning is used to indirectly check the quality of the product, for example, the level of prestress and other production issues. Camber at the time of girder shipping is sometimes required to be checked for contractual purposes. Camber just before deck placement and the elastic deflection due to deck weight are used to determine the elevation of the formwork supports at the edges of the top flange. Accurate measurements and calculations at this stage result in minimizing grinding of the deck to bring it to the required profile.

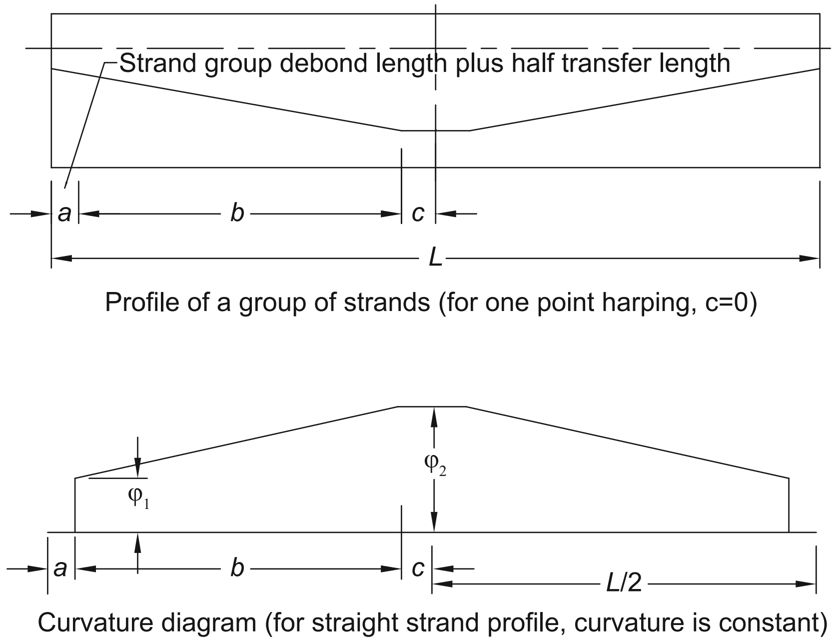

Figure 1. Beam elevation showing general profile for a group of pretensioned strands. Figures: eConstruct.

A negative camber (downward deflection or sag) while the bridge is in service may cause concern for inspectors and the public and, if excessive, may have structural and functional impacts as well. A number of state highway authorities (SHA) have specified that the final long-term camber due to all loads, except live load, must be positive, that is, upward.

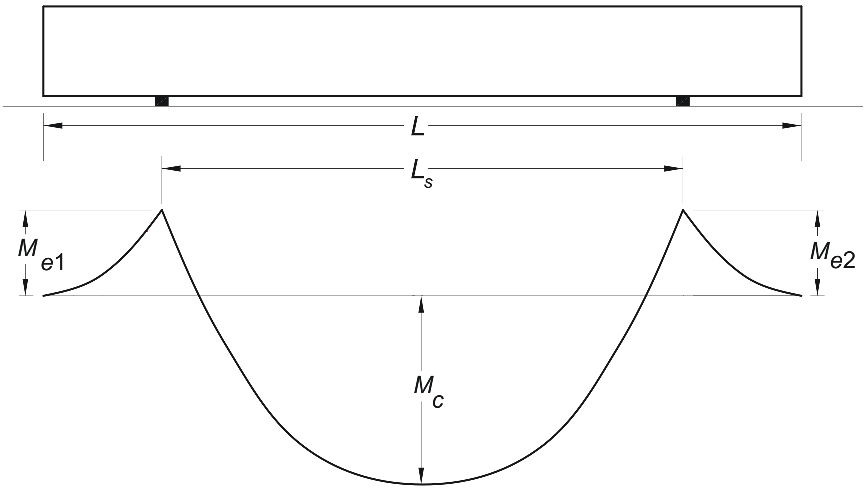

Figure 2. Bending moment diagram for beam in storage, note the considerable overhang. Figure: eConstruct.

At best, camber prediction can have ±25% variability, but more realistically it can have ±50% variability. The prediction is impacted by things that are known within a narrow band of variability such as the cross-section dimensions, amount of prestress, and span length, which are considered here to be deterministic variables. It is also impacted by random variables, outside of the control of the designer at time of design, such as source of aggregates, relative humidity and temperature of the ambient air, method of curing, method of detensioning, conditions of storage, and time elapsed between girder production and deck placement.

Calculation of Initial Camber

Reference 1 gives a survey of the history of camber prediction and proposes a method that can be programmed in a spreadsheet. Only two equations are required.

Equation 1 is used to calculate initial camber due to prestress using a general profile of a group of pretensioned strands (Fig. 1). The equation is valid for straight and draped strands and for cases where debonding at the ends is utilized. The equation may be applied to the different "types" of strand groups, and then superposition used to combine the individual results to determine the full effect.

$$\Delta_{ip} = \frac{\varphi_1}{2}(b+c)(2a+b+c) + \frac{\varphi_2}{6}(3ab+2b^2+6ac+6bc+3c^2) \qquad \text{Eq. 1}$$

The distances *a*, *b*, and *c* are defined in Fig. 1. The curvatures φ_1 and φ_2 are equal to *P/EI* for Sections 1 and 2 at the location at which prestress is effective at the end of the girder (dimension *a*) and at midspan, respectively. The values of *P*, *e*, *E*, and *I* are the prestress force, its eccentricity, the concrete modulus of elasticity, and the cross section moment of inertia, respectively, at the section considered for the curvature calculation. The starting section location (at dimension *a* from the end of the girder) is affected by length of debonding plus an allowance for transfer length.

Equation 2 is used to determine deflection due to beam weight (Fig. 2). In recent years, long beams have required lifting, storage, and shipping with overhangs as long as 20 ft. The equation accounts for overhang length.

$$\Delta_{gi} = \frac{5L_s^2}{48EI}(0.1M_{e1} + M_c + 0.1M_{e2}) \qquad \text{Eq. 2}$$

For this equation, the length L_s is length between supports during beam storage. Figure 2 defines the moments in Eq. 2 and their locations.

The example in Reference 1 is used here for discussion purposes. Not all data are given here. The I-beam is 72 in. deep, 137 ft 1 in. long, and prestressed with forty-four 0.6-in.-diameter straight strands, 12 of which are debonded in three equal groups for 6, 8, and 14 ft from the beam ends. Specified concrete strength at transfer is 6 ksi and at service is 8.5 ksi.

Equation 1, applied four times for the four groups of strands, yields a predicted prestress-only camber Δ_{ip} of 5.33 in. The groups are 32 strands that are 137.1-1.5-1.5 = 134.1 ft long, and three groups of four strands that are 122.1, 118.1, and 106.1 ft long. The 1.5 ft quantity used to compute the length for the 32 strand group is an allowance for averaging the effect of the 3 ft transfer length for the 0.6-in.-diameter strands.

Equation 2 is applied assuming a storage span of 135.5 ft. The corresponding deflection is 2.32 in. The net predicted self-weight camber is therefore 5.33 – 2.32 = 3.01 in.

Causes of Initial Camber Variability

Many factors influence the value of camber at transfer of prestress, some of which are random variables beyond the control of the designer. Several of the more important factors are listed here:

- The modulus of elasticity of concrete. The computed modulus of elasticity of concrete has been shown to vary from the measured value by 22% for confidence between 10 and 90 percentiles, according to the NCHRP study[2] that proposed the aggregate correction factor, K_1, which now appears in Equation 5.4.2.4-1 of the *AASHTO LRFD Bridge Design Specifications*. The stiffness of aggregates plays an important role in the modulus variability. Thus, the results are dependent on the aggregate source. Also, a designer who specifies 6 ksi concrete transfer strength is unlikely to get it matched during production of all the beams in a project.
- Curing versus ambient temperature. This factor can be very significant in the first 48 hours of concrete age. The concrete temperature may be as much as 120°F above the ambient temperature because of curing and cement hydration. This could decrease the tension in the strands by as much as 20 ksi. This temporary difference may cause significant changes in camber and prestress loss.[3] However, within about 72 hours, this temporary effect seems to dissipate.
- Location of lifting inserts and storage supports. The effect of

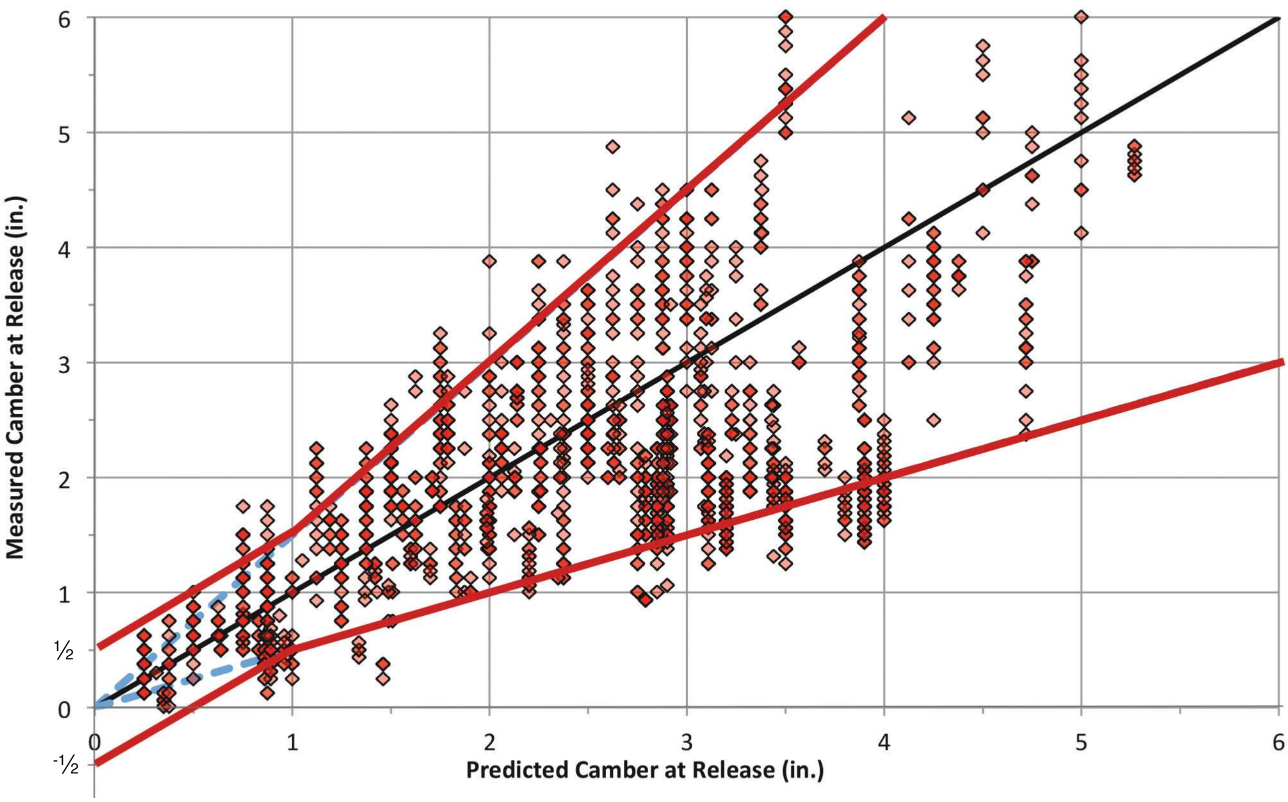

Figure 3. Initial-camber data collected by the PCI Fast Team from nine sites in eight states. The red lines show proposed ±50% ≥ ½ in. tolerance. Figure: PCI Fast Team with modification by eConstruct.

variation in support locations is illustrated using the example girder. If it is lifted and stored on supports that are 10 ft from the ends, the camber in the example used in the previous section changes by about 9%.

- If prestress is higher than the theoretical value by 5% and self-weight is lower by 5%, both of which are quite plausible, the net camber in the example in the previous section would increase by 13%.

Initial Camber Tolerance Limits

Because of the random variability of the influencing parameters, it is difficult to accurately predict initial camber immediately after strand detensioning. If the girder concrete is allowed to cool for 72 hours, prediction accuracy may be most optimistically within ±25%. Accurate formulas, such as Eq. 1 and 2, and values of the modulus of elasticity reflecting aggregate type and concrete strength would be assumed to be used. However, the designer is not likely to know producer-specific materials, environmental conditions, and production practices in advance.

The PCI Tolerance Committee has been debating in recent years how to update the tolerance limits for camber in bridge beams that are given in PCI MNL-116[4], in order to accommodate recent changes in technology. Concrete strengths in the 8 to 12 ksi range, 0.6-in.-diameter strands, and more efficient I-girder shapes have been in common use, resulting in pretensioned products as long as 200 ft.

A Fast Team was formed by the PCI Committee on Bridges and the Bridge Producers Committee to recommend adjustments to the current MNL-116 tolerances to account for the recent changes in practice. Their recommendation is shown in Fig. 3. It essentially sets the tolerance limits on camber variance from the predicted value at 0.1% of the product length with an upper limit of 1½ in. and no lower limit. Even with this proposed removal of the current upper limit of 1 in., the Fast Team report indicated that the percentage of out-of-tolerance girders longer than 80 ft was still 12%, compared to the current 37% level (using the 1 in. upper limit). Accordingly, the Fast Team stated, "out of tolerance camber should not be a sole source for rejection." While this sentence is well intentioned and justified, it seems to be in conflict with the concept of tolerance enforcement that is expected in a tolerance manual.

Proposed Initial Camber Tolerance

Because camber is an important quantity that can be easily measured, camber tolerance limits are expected to continue to be required by most owners. Based on the author's experience with this topic for nearly 40 years, and on recent discussions by PCI committees, producer groups, and state highway agencies, including Colorado, Washington, Iowa, and Pennsylvania, the following recommendations are proposed for initial camber of prestressed beams, which differ from the recommendations of the PCI Fast Team:

- Initial camber should be measured 72 to 96 hours after beam concrete placement and after the beam has been set on storage supports. This would allow for the internal concrete temperature to reach equilibrium with the ambient air and for the storage span to be set. Measurements should be made early in the morning when the girders should have a neutral thermal gradient.

- For predicted camber ≤ 1 in., tolerance is ± ½ in.
- For predicted camber > 1 in., tolerance is ±50% of the predicted camber.
- Out-of-tolerance products should be further investigated by qualified personnel to identify the presence of possible deficiencies. Camber alone should not be the sole cause of rejection.

Camber Variability at Deck Placement

Camber prediction at time of deck placement is needed to establish elevations for beam seats and for formwork for the deck. This is necessary so that the top of road elevation and the overhead clearance below the bridge are consistent with design requirements.

Concrete creep and shrinkage cause prestress to be lost. In addition, creep causes the beam to continue to camber with time. Creep and shrinkage are functions of the concrete ingredients, section dimensions, and environmental conditions. Furthermore, it is not known in advance how much time will elapse between girder production and deck placement. Camber does not always grow between initial storage conditions and deck placement.

This observation has recently been reported for relatively long beams. The creep multiplier for prestress effects (camber) is not as large as the creep multiplier for beam self-weight because prestress continues to decrease with time. For example, a 10 in. initial camber due to prestress multiplied by a 1.7 creep factor is 17 in. An 8 in. deflection due to beam self-weight multiplied by a 2.0 creep factor is 16 in. The net predicted camber at deck placement is 1 in. This is compared to an initial camber of 10 – 8 = 2 in.

Methods of accurate prediction of camber at time of deck placement are summarized in the article by Tadros et al.[1] Several states, in collaboration with designers and precast producers, have developed their own "creep multipliers" to account for camber growth between prestress release and deck placement. It would seem reasonable to show upper and lower bound camber multipliers, based on local prevailing construction and environmental conditions.

For example, Washington State guidelines show a lower bound of 50% of the camber at 40 days, and an upper bound of 100% of the camber at 120 days. The author recommends a multiplier to be determined by each precaster for the region served by their company. For example, Supplier X serving Western State Y would provide the owner with a lower bound and upper bound multipliers of 0.9 and 2.6 applied to initial camber to predict camber at time of deck placement.

The data presented in Fig. 4, which has been supplied by Troy Jenkins of Northeast Prestressed Products, illustrates camber variability at 120 days for girders produced by his company in several states in the Northeast. The figure shows that only a few points fall outside the proposed camber tolerances indicated by the red lines.

It is suggested that the PCI Committee on Bridges and Bridge Producers Committee should consider setting up uniform national guidelines for achieving this important task.

Accommodating Differences

There are two options for accommodating differences between predicted and measured camber at deck placement.

Measured camber larger than predicted camber

Assume for this discussion that

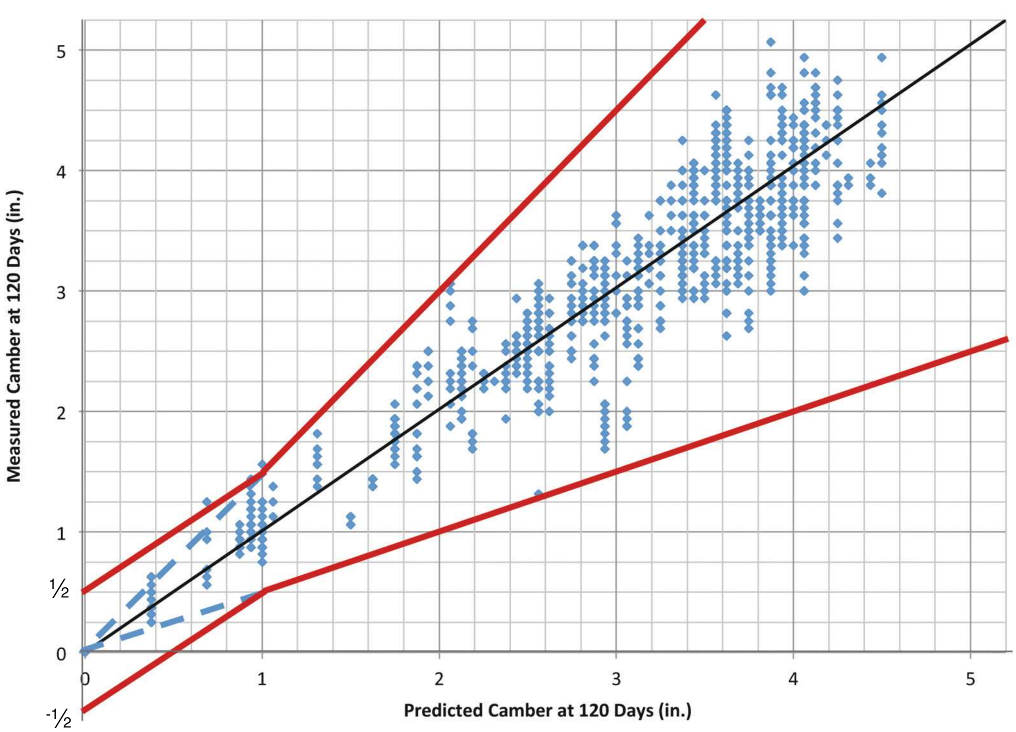

Figure 4. Measured camber at 120 days. Red lines show proposed ±50% ≥ ½ in. tolerance. Data: Northeast Prestressed Products.

predicted camber for a 150-ft-span beam is 3 in. while the measured camber is 6 in. The designer had allowed for a cast-in-place concrete haunch of 1 in. above the top flange of the beam at midspan. The simplest solution is for the owner to allow raising the roadway by 2 to 3 in. Alternatively, the girder seats could be set 2 to 3 in. lower than previously specified. This option would require appropriate preplanning.

Measured camber smaller than predicted camber

Assume for this discussion that predicted camber is 3 in. while the measured camber is 1.5 in. The seats may be raised to avoid infringing on overhead clearance below the bridge, if this is a factor, and to avoid excessive haunch concrete. Also, adequate drainage needs to be checked to avoid water ponding on the bridge.

References

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