5-2017

Predicted vs Measured Initial Camber in Precast Prestressed Concrete Girders

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Recommended Citation

Freedle, Luke T., "Predicted vs Measured Initial Camber in Precast Prestressed Concrete Girders" (2017). *Civil Engineering Undergraduate Honors Theses*. 40.
http://scholarworks.uark.edu/cveguht/40

Predicted versus Measured Initial Camber in Precast Prestressed Concrete Girders

An Undergraduate Honors College Thesis

in the

Department of Civil Engineering

College of Engineering

University of Arkansas

Fayetteville, AR

By

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May, 2017

1. Introduction

Prestressing of concrete is the introduction of permanent internal stresses in a structure or system in order to improve its performance [1]. Concrete is strong in compression but weak in tension. The tensile strength of concrete is approximately 10% of the concrete's compressive strength [2]. Prestressing strands helps counteract this by introducing compressive stress in the area that will experience tensile stress because of the service load. In precast prestressed concrete girders, strands are placed in the bottom flange of the girder. These strands are tensioned to approximately 75% of their ultimate tensile capacity. After placing the concrete and after the required compressive strength has been achieved, the strands are cut and the tension forces transfer from the strands to the concrete. This creates a large compressive stress in the bottom flange. The eccentricity of the pretensioned strands in the prestressed concrete girders creates a bending moment that causes the girder to deflect upward, and this is called camber. This camber is reduced by the downward deflection of the girder due to the girder self-weight [2].

Camber in prestressed concrete girders is effected by several factors, such as the girder's cross sectional properties, concrete material properties, strand stress, ambient temperature, and relative humidity [2], [3]. Some methods of predicting camber use the initial camber that occurs immediately after cutting the strands to predict the camber at the time of girder erection. There are many sources of errors in predicting camber in a concrete girder including the differences in the actual and the design value of concrete properties and of strand stress [3].

In this study, the difference between the measured and the predicted initial camber will be investigated on six AASHTO Type VI girders. All girders were 108 feet long and the cross-section details are illustrated in Fig. 1. The initial camber was predicted using the simple elastic analysis. The measured initial camber was then compared with the design camber. The difference between using the gross section properties and the transformed section properties to predict camber was quantified. Actual concrete properties including compressive strength, elastic modulus and unit weight were used to assess the current design method. Camber obtained from the actual, measured concrete properties will be called the predicted camber in this study. The effect of using the actual and the design elastic shortening losses on the estimation of the initial camber was also quantified.

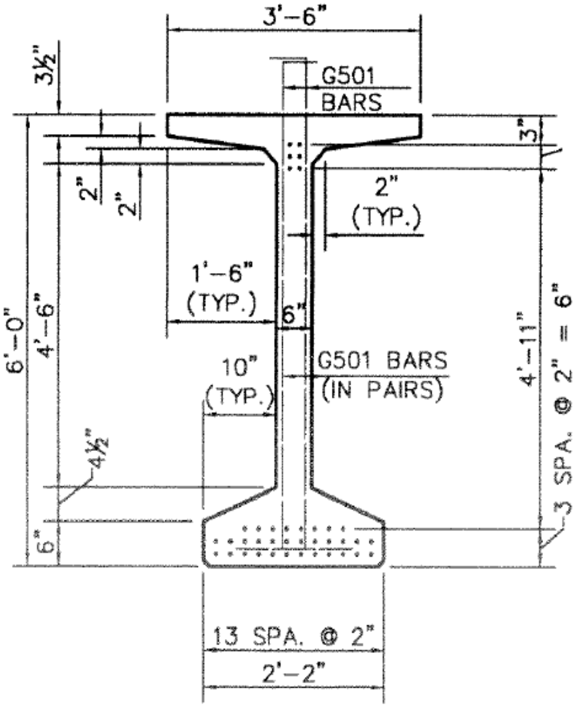

Figure 1. AASHTO Type VI Girder Cross Section

2. Previous Camber Research

In 2007, Rosa et al. conducted research aimed to increase the accuracy of camber prediction. The authors evaluated the camber prediction method used by the Washington Department of Transportation. Based on field measurements, material testing, and prediction models, the research group developed a program that reduces the difference between the design and the actual camber. Concrete material testing performed included compressive strength, elastic modulus, shrinkage, and creep properties. Rosa et al. found that the compressive strength at release is 10% higher, on average, than the design strength and that the elastic modulus predicted by the AASHTO LRFD method is an average of 15% less than the measured values. The research team measured the camber for several girders belonging to two different bridges and collected camber and compressive strength values from the girder manufacturer. By incorporating these findings with the creep, shrinkage, prestress losses, and field data, the research modified the previous methods used by the Washington Department of Transportation, and improved the accuracy of camber prediction. Using the optimized method developed in the study, the average error seen in predicting the camber at release was reduced from 0.47 inches to 0.24 inches [1].

Tadros et al. (2011), developed new equations for predicting camber and self-weight deflection of precast prestressed concrete girders. Commonly used methods were modified to consider the draped and the deboned or shielded strands. Prestressing strands are commonly draped, debonded, or shielded to reduce excess prestress force near the ends of the beam. Usually, after the girders have been cast but before they are erected, these girders are supported by wood blocks at a specified distance from the ends of the girder. This means that the span length is actually less than the full length of the member, and a negative moment occurs at the ends of the girder that reduces the deflection due to member self-weight. The study takes this into consideration, and also acknowledges some factors that contribute to the variability of initial camber, including random variability of concrete elastic modulus, actual concrete strength versus specified concrete strength, differential temperature at prestress release, and friction at girder ends due to prestress release. The author states that local material properties, girder storage conditions, and construction practices should be considered in camber design. Tadros recommended allowance for camber variability by as much as of 50% [3].

Honarvar et al. (2015), from Iowa State University, conducted a study to modify the previous methods used for camber prediction. This study begins by evaluating the methods used to predict camber of prestressed precast concrete girders used by Iowa Department of Transportation. The authors found that the camber of long bulb-tee girders is usually overpredicted by the state's method, while the camber of shorter beams is usually under predicted. Inaccurate camber predictions can cause challenges in construction. They found that a major obstacle in predicting long-term camber was the variability of time dependent concrete properties, specifically creep and shrinkage. After examining typical models used to estimate these values, two equations were developed to calculate the average creep coefficient and shrinkage strain. Effects of support locations and thermal effects were also investigated. The research focused on the factors affecting the instantaneous camber such as, prestressing bed deflections, inconsistent beam depth, and friction between the girder ends and the bed. Properties such as elastic modulus, prestress force, prestress losses, transfer length, sacrificial strands, and section properties were examined analytically in order to quantify the influence of each of these properties. Finally, multipliers were recommended, including a temperature multiplier, to be used to calculate the at-erection camber based on the predicted instantaneous camber. The proposed multipliers improved the accuracy of camber prediction compared to the methods previously used by Iowa Department of Transportation [4].

2.1 Initial Camber

The initial camber of a concrete girder, as it pertains to this report, can be defined as the upward net deflection soon after the transfer of prestress forces. In manufacturing of the prestressed concrete girders, the strands are cut after the concrete has gained a specified strength. The tension forces then transfer from the strands to the surrounding concrete creating a compression stress at the bottom flange. As a result, bending moment is developed in the middle of the girder, causing camber. The friction between the girder's ends and the precasting bed restricts the ends from moving and reduces the initial camber value. Ward et al. 2007, states that the friction between the bed and the girder's ends reduces both the elastic shortening losses and the initial camber [5]. It is very important that the initial camber be predicted and measured accurately because it is often used to predict long-term camber [6]. Inaccurate prediction of camber can cause difficulties in construction, including increased haunch depths, the jutting of bridge girders into the bottom of the deck, and increased construction time. These issues often lead to increased construction costs, and while inaccurate camber prediction doesn't affect the capacity of a girder, it can cause serviceability issues [7]. The initial camber can be estimated using the following equation [8].

$$\Delta\uparrow = \frac{PeL^2}{8EI} \tag{1}$$

Where,

E: Modulus of elasticity of concrete (ksi)
I: Moment of inertia of the girder (in^4)
P: Force in the prestressed strands after the elastic shortening losses (kip)
L: Span length (in)

2.2 Modulus of Elasticity

Concrete is a non-homogenous material composed of aggregate, cement, water, and some additional chemicals. This makes predicting the behavior of concrete difficult, especially over time [6]. The modulus of elasticity of concrete is an important factor to consider when predicting the camber of a prestressed concrete beam [2]. Concrete strength, water content, material properties of aggregates, aggregate content, and concrete unit weight are some of the factors that affect the elastic modulus. The accurate prediction of the modulus of elasticity can help lead to a better prediction of initial camber and initial prestress losses. Currently, there are many methods used to predict the modulus of elasticity of concrete [9]. ACI committee 363 recommends using Eq. 2 for estimating modulus of elasticity of concrete. Al-Omaishi et al. (2009) suggested using Eq. 3 for estimating modulus of elasticity of normal weight concrete and this equation will be used in this study [10], [11].

$$E_c = (w_c/0.145)^{1.5}(1000 + 1265)\sqrt{f'_c} \tag{2}$$

$$E_c = 33000K(w_c)^{1.5}\sqrt{f'_c} \tag{3}$$

w_c = (0.140 + f'_c /1000)
0.145 kip/ft^3 < w_c < 0.155 kip/ft^3
w_c: Unit weight of concrete
f'_c: Concrete compressive strength

2.3 Elastic Shortening

Prestress losses are a time dependent property of prestressed concrete, and they are effected by factors including modulus of elasticity, creep, shrinkage, and relaxation characteristics of the prestressing strands. These losses in turn affect the camber of prestressed precast concrete girders [12]. One significant contributor to prestress losses is elastic shortening.

Elastic shortening is caused by the shortening of the prestressing strands over time. As the compressive force is exerted on the beam by the strands, the beam shortens. Due to the bond between the concrete and the strands, the prestressing strands shorten with the girder. This reduces the strain in the strands and thus the force placed on the beam by prestressing. As this force is reduced, the camber of the girder will decrease. This is counteracted by the strain placed on the strands by the self-weight of the beam. Together, these components cause elastic shortening [6].

3. Experimental Work

3.1. Concrete Material Testing

The compressive strength and modulus of elasticity were measured for six girders at release and at multiple subsequent stages. Through two visits to the plant, concrete was sampled during the casting of each girder. The girders were cast in groups of three. Therefore, concrete properties will be considered the same for each group of three girders that were placed together. Concrete cylinders which were 4 by 8 in. were made from each cast. As shown in Figure 2 below, all the cylinders were stored beside the girders under the tarps to simulate the same curing conditions of the girders. Six cylinders were then tested for compressive strength and modulus of elasticity at release.

Figure 2. Concrete cylinders placed beside the girders forms

3.2 Initial Camber Measurements

The initial camber was measured immediately after cutting the strands and moving the girders to the storage yard. A self-leveling rotary laser level was used to take elevations on the top of the bottom flange. The laser receiver was attached to a wooden rod with a scale fixed on both of its sides. By setting the level near one of the girder ends, elevations of the ends and the mid-length of the girders were recorded. Camber was then calculated by subtracting the average of the end readings from the mid-span reading. Figure 3 shows the laser level with the receiver attached to the wooden rod.

Figure 3. Rotary Laser Level with Receiver Used in Camber Measurements

4. Results and Discussion

Figure 4 shows the differences between the measured camber and the design camber calculated using design values for strength and modulus of elasticity. The gross and the transformed section properties were used to calculate the design camber to quantify the difference in both cases. As shown in the Fig. 4, using the design values for strength and elastic modulus in combination with gross section properties leads to a consistent over-prediction of camber for these six girders. On average, the predicted camber using gross section properties was 26% higher than the measured values. The errors seen in camber prediction using this combination of parameters can partly be attributed to the fact that the actual values for strength and modulus of elasticity are usually more than the design values. The measured compressive strength was an average of 26% higher than the design strength of 6 ksi. The measured elastic modulus was on average 20% higher than the design value. These values are shown in Table 1.

Table 1. Design vs measured values of concrete strength and elastic modulus

Girder Number	E predicted (psi)	E measured (psi)	f'c predicted (psi)	f'c measured (psi)
1	4509400.916	5144500	6000	7635
2	4509400.916	5144500	6000	7635
3	4509400.916	5144500	6000	7635
4	4509400.916	5661000	6000	7523
5	4509400.916	5661000	6000	7523
6	4509400.916	5661000	6000	7523

Rosa et al found that the measured elastic modulus was 15% higher than the design values in his study [1]. In addition, gross section properties mean that the area of the strands is equal to the area of concrete regardless of the difference in the stiffness between both materials. This results in weaker section and higher design camber. In the case of the transformed section properties, the area of the strands is converted to its equivalent area of concrete by multiplying by the modular ratio. This leads to stiffer cross section and lower design camber. However, the design camber calculated using the transformed section properties was still higher than the measured camber by an average of 7%. Using transformed section properties resulted in a more accurate prediction of the initial camber [2].   High compressive strengths at release were also found by other researchers [1]. Honarvar et al suggested taking the compressive strength at release equal to 10% higher than the design strength if the design strength is between 6000 and 8500 psi [4].

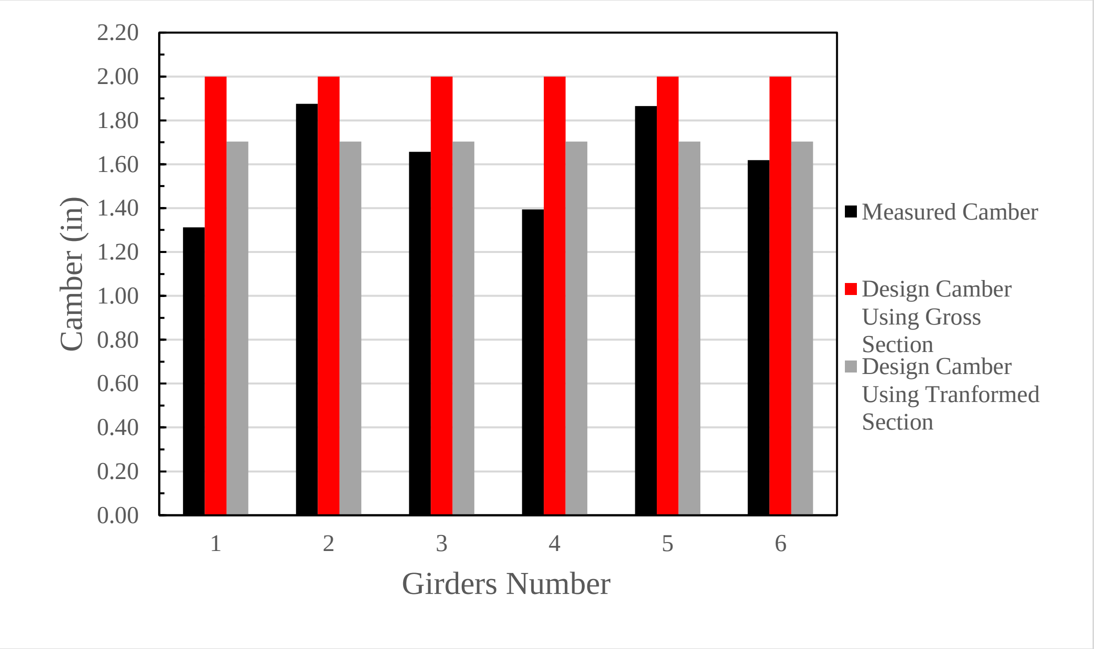

Figure 3. Measured camber vs design camber

In another way of comparing and assessing the accuracy of the current design method, the actual, measured values of concrete properties, including compressive strength and the elastic modulus, were used with the measured elastic shortening to calculate the predicted camber. Figure 4 shows the measured camber compared to the predicted camber using actual values for strength, modulus of elasticity, and elastic shortening with transformed section properties and then again with gross properties. As shown, this prediction method under-estimated the camber for five of the six girders, and the measured camber of the girders was 10% higher on average than the predicted camber using this combination of parameters. Under-prediction of the initial camber was also observed in other studies [1], [4], [7]. Tadros et al recommended allowing for an error of 50% in camber prediction because of the variability in camber [3]. The measured camber was also compared with the predicted camber calculated using the gross section properties. As shown in Fig. 4, this method was the most accurate in predicting the camber, and the measured value was only an average of 5% lower than the values calculated using this method.

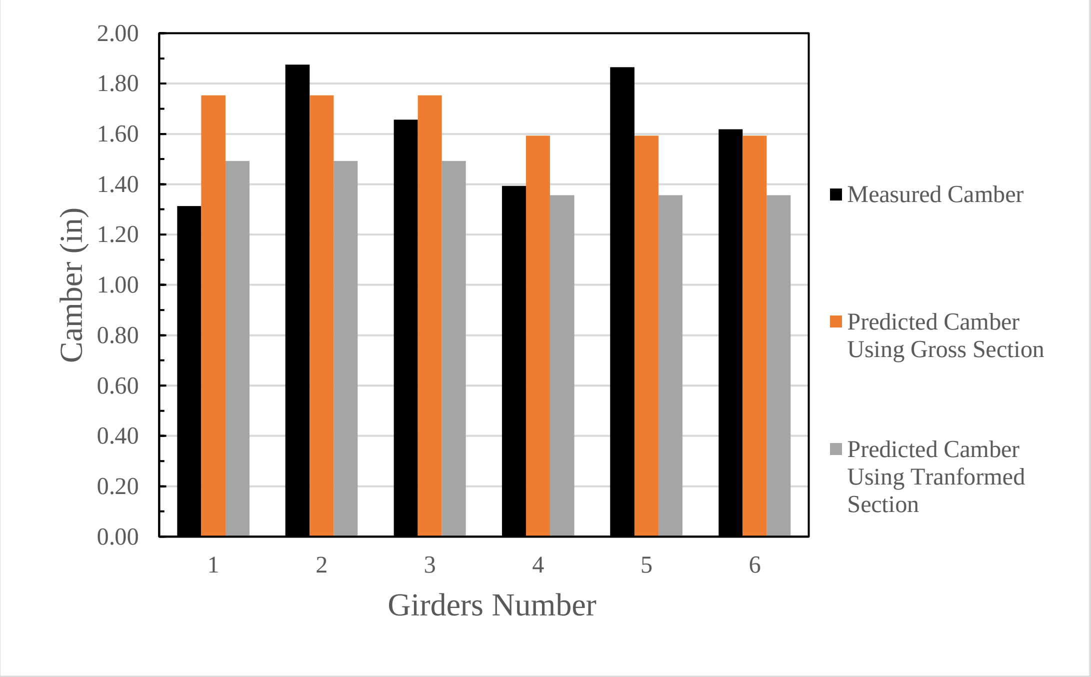

Figure 4. Measured camber vs. predicted camber

5. Conclusion

The goal of this research was to improve the prediction of the initial camber in precast prestressed concrete bridge girders. It was found that the measured concrete properties including the compressive strength and the modulus of elasticity were higher than the design values. The measured compressive strength was 26% higher than the design strength, and the measured modulus of elasticity was 20% higher than the design value. The initial camber in the six girders was over predicted by 6% to 52% when comparing the design camber calculated using the gross section properties to the measured camber. The over prediction in the initial camber can mainly be attributed to the higher compressive strength of concrete, which leads to a stiffer girder and lower initial camber. Predicted initial camber calculated using transformed section properties was closer to the measured initial camber with differences ranging from -9% to 30%. However, the most accurate combination of parameters was using gross section properties with the measured concrete properties, with an average error of 5%. Based on the results from this study, it is recommended that the gross section properties be used in combination with measured values of concrete properties to predict initial camber. If measured values of compressive strength and modulus of elasticity cannot be obtained, transformed section properties should be used with design values for concrete properties to predict the initial camber. More data is clearly required to better quantify the effect of concrete properties on the initial camber.

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