# A CASE STUDY FOR IMPROVING CAMBER PREDICTION AND TOLERANCES IN DESIGN-BUILD PROJECTS

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## ABSTRACT

*Predicting prestressed girder camber is a frequent problem for Engineers, since camber is largely controlled by project specific variables either unknown or out of the control of the Engineer in traditional Design-Bid-Build delivery projects, including supplied concrete strength, precast stressing operations, climate variables and erection schedules. Even with good data available for these variables, there is inherent variability in camber that should be accounted for through construction tolerances incorporated into the design.*

*A major structure on the North Metro Rail Line currently under construction as part of Denver's Regional Transportation District (RTD) FasTracks program is the Skyway Bridge; a 9,533' long, 64-span bridge comprised of 192 prestressed concrete BT-84 girders varying in length from 120' to 170'.*

*This project was delivered as a Design-Build which, unlike traditional Design-Bid-Build, allows the Engineer to work with both the Contractor and Precaster during the design phase.*

*This paper will use a case study of girders on the Skyway Bridge to discuss recommendations for improving camber predication accuracy while providing project specific tolerances for camber variability, gained through collaboration between the Engineer, the Contractor, and the Precaster on this Design-Build project. Project-specific modifications to national design codes will also be explored.*

**Keywords:** Camber, Case Study, Design-Build, Precast, Prestressed

## INTRODUCTION

As America's transportation infrastructure continues to age, the demands for new modern transportation corridors and mass transit systems are growing. State DOT's and other transportation and transit agencies are often pressured to implement these corridors and systems in minimal time and with limited funding. Such owners are increasingly turning to alternate project delivery methods such as Design-Build. Design-Build allows the Owner to negotiate a set scope for a set price and delivery schedule. Design-Build also provides the opportunity for innovation and collaboration between the Engineer and Contractor throughout the design and construction process, which can lead to reduced project costs and schedules while improving constructability and overall construction quality.

An example of a constructability advantage obtained through collaboration in Design-Build projects are improvements to prestressed girder camber prediction and construction tolerances. Camber is largely controlled by project specific variables either unknown or out of the control of the Engineer in traditional Design-Bid-Build delivery projects, including supplied concrete strength, precast stressing operations, climate variables and erection schedules. In contrast, Design-Build delivery allows the Engineer to work with both the Contractor and the Precaster during the design phase in order to better define some of these variables to improve camber predictions. Due to the large number of interacting variables affecting camber, there will still be some inherent variability in actual vs predicted cambers that should be accounted for and incorporated into the design. Incorporating the expected camber variability into the design can improve constructability by allowing for a more accurate range of camber construction tolerances without compromising the strength or serviceability of the structure.

This paper will evaluate a case study of a large Design-Build bridge project in Denver, Colorado that utilized prestressed bulb-tee girders. Recommendations will be made for improved camber prediction and construction tolerances for Design-Build projects based on the lessons learned from the case study. The recommendations will be based on a simplified rational approach developed through collaboration between the Engineer, Contractor, and Precaster. These recommendations will be tailored specifically to Design-Build projects, where fast paced schedules may preclude the use of more refined analytical methods. Project-specific modifications to national design codes will also be explored.

# A CASE STUDY: THE NORTH METRO SKYWAY BRIDGE

## PROJECT BACKGROUND

A major structure on the North Metro Rail Line currently under construction as part of Denver's Regional Transportation District (RTD) FasTracks program is the Skyway Bridge; a 9,533' long, 64-span bridge comprised of 192 prestressed concrete BT-84 girders varying in length from 120' to 170'. The bridge is designed to carry commuter rail loading and utilizes a "direct fixation" deck. This rail line will provide rapid transit service for travelers along the congested highway corridor from Denver's Union Station through Commerce City, Thornton and Northglenn to Highway 7 in North Adams County. The bridge crosses BNSF tracks, Brighton Boulevard, UP spur tracks, FRICO Ditch, Metro Waste Water and Suncor sites, Sand Creek and Interstate 270.

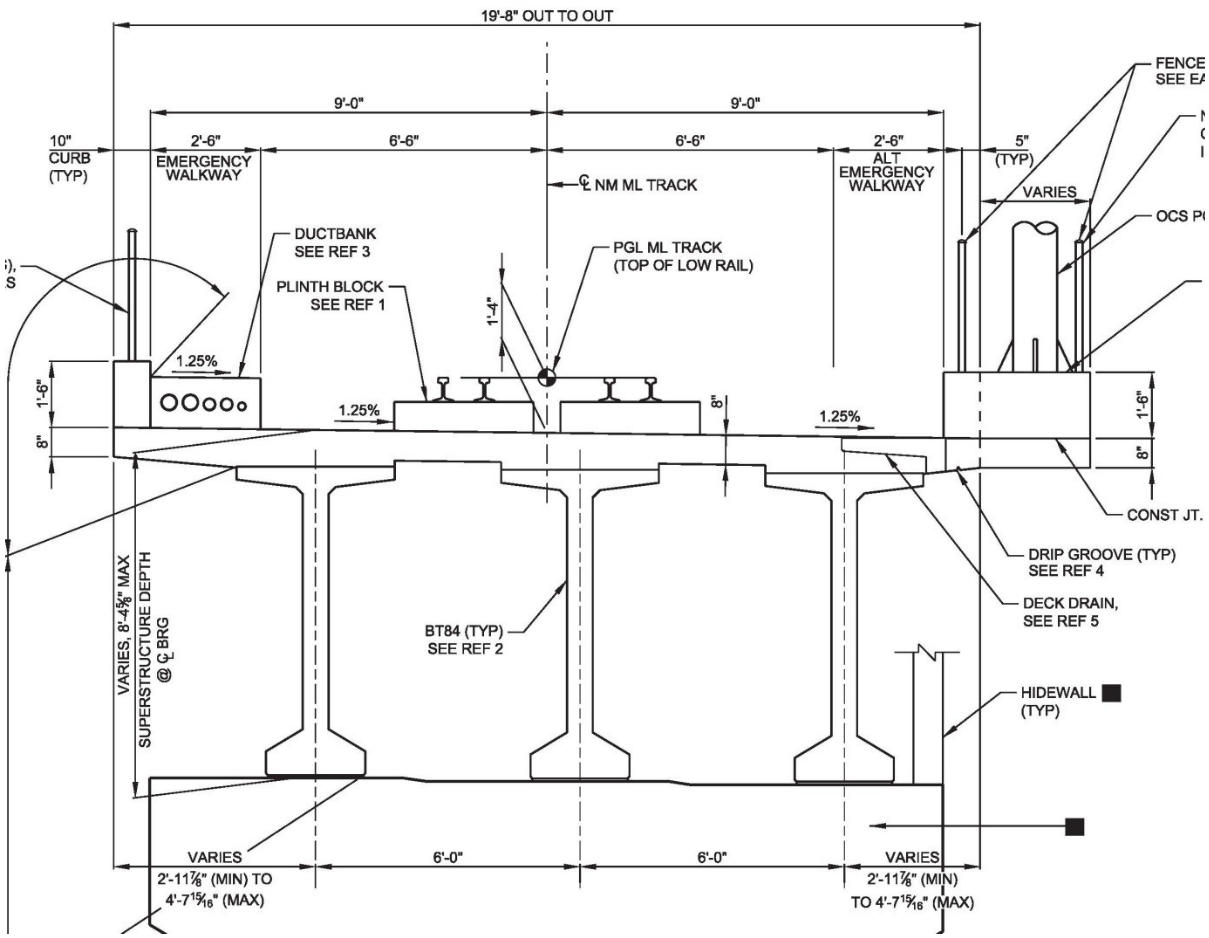


Fig. 1 Skyway Bridge Typical Section

Fig. 2 North Approach of the Skyway Bridge during Construction

Fig. 3 Skyway Bridge Spans Under Construction

Site constraints necessitated many unique girder designs on this long structure including numerous variations in span lengths, horizontal curve geometry, and several long and unbalanced continuous span units. This bridge was on the critical path schedule for the project, meaning that the design needed to be completed quickly, yet be simple, efficient, and constructible enough to minimize the fabrication and construction time required and to minimize costs.

Predicted camber is used to determine the haunch thickness, which varies from a set value at the girder ends to an estimated value at midspan. Typically, the designer provides a depth of haunch at midspan that provides construction tolerance to account for variances in under or over camber field conditions without a detrimental impact to the strength or serviceability of the girder.

Tolerance for over camber is necessary to prevent the girder top flange from protruding into the deck and interfering with the placement of the deck reinforcement. Tolerance for undercamber is necessary to prevent sag in the girders, which is both visually disturbing to the public and could cause ponding on the deck or vertical clearance issues. Undercamber also adds additional dead load to the structure due to the increase in haunch thickness near midspan, and this added weight may need to be considered in the structural design if there is potential for it to be significant.

Accurate predication of camber, haunch concrete quantities and suitable tolerances for camber variability were important and more pronounced than on typical projects due to:

- <u>Schedule –</u> Girder casting schedules needed to be optimized to allow the erection contractor to move sequentially without delays from out of tolerance camber. The critical path schedule for this bridge made any unexpected delays resulting from such problems extremely costly and undesirable. Additionally, the substructure design package was released for construction ahead of the superstructure design package, and as a result, many piers were constructed prior to the girder fabrications. Large adjustments to pier cap seat elevations to correct for actual measured cambers were not feasible in most cases.

- <u>Direct Fixation Rail –</u> Direct fixation rail bridges have tight tolerances on bridge deck and plinth elevations, meaning that it is very difficult to adjust the bridge and rail profile in the field if there is too much overcamber.

- <u>Quantities / Cost –</u> Conversely, a small amount of undercamber would add significant concrete volume to the structure. As an example, with the 9,533ft bridge length, 3 girder lines, and 43in top flanges, an average 1" difference between predicted and actual cambers would add approximately 317 cubic yards of concrete, or $254,000 (at $800/CY), to the project. Some of the longer girders were up to 2.5" under predicted camber. In some cases, thicker haunches due to undercamber required reinforcement, adding more labor and material costs. In cases of very large undercamber, additional analysis was required to verify the strength and serviceability of the final structure, adding engineering costs and delaying girder erection schedules.

- <u>Capacity Limitations –</u> Undercamber added a significant dead weight to the structure due to the added haunch, especially in the longest girder spans of 160ft to 170 feet. In terms of weight, an average 1" difference between predicted and actual cambers would add approximately 135 plf per bridge width, or 1300kips total (at 150pcf), to the structure. Some of the longer girders were up to 2.5" under predicted camber.

Fig. 4 Skyway Bridge Girder Being Delivered to the Site

Fig. 5 Skyway Bridge Girders Being Erected at the Site

## PROJECT ESTIMATION OF CAMBER VARIABILITY

The following section discusses the original design philosophy and calculations performed to determine the expected level of camber variability and incorporate a suitable camber tolerance into the design. The computations considered historical data provided by the Precaster and estimation methods provided in technical literature. Due to the fast paced project schedule and to allow flexibility in the erection schedules, a conservative, simplified rational approach was used to estimate camber variability for this project.

There are numerous methods for estimating the potential camber variation from predicted values available in technical literature. PCI MNL-116[1] recommends a general tolerance of +/- 1” maximum variation for girder lengths over 80ft. Alternatively, Tadros, 2015[2] proposed a general tolerance of +/-50% of the predicted camber for predicted camber values greater than 1in. The girders used on this project where significantly longer than 80ft, and a number of the longer girders had predicted camber values of up to 7”. As a result, it was determined that the PCI MNL-116[1] method likely didn’t provide enough tolerance, and the method proposed by Tadros, 2015[2] allowed more tolerance than could economically be achieved. As a compromise, an equation proposed in the Colorado Department of Transportation’s (CDOT) Bridge Manual[3] was used to predict the expected variability of camber on this project. CDOT bridge manual Subsection 9.1.C36 states…

> *The variability of camber (the range of cambers that might occur without any efforts to control variability) should be roughly proportional to*

*0.0002*K1*K2*(span^2)*sqrt(required f'ci or f'c)/depth of girder. K1 reflects the stiffness of the structure geometry, 0.2 for continuous fixed both ends, 1.0 for simple span, 4.0 for a cantilever fixed on one end. K2 reflects the influence of time with K2 = 1.0 at time zero (release), and increasing to perhaps 3.5 at very long times, with 2.5 being representative of a typical time of erection.*

Girder spans less than 160' in length were designed for a compressive strength at release and 28-day of 6500psi and 8500psi respectively. Girder spans equal to or greater than 160' in length were designed for a compressive strength at release and 28-day of 7000psi and 9500psi respectively. These values were specified to comply with the upper bound limits on concrete strengths allowed by project specific criteria. Using the above concrete strengths, a K1 value of 1.0, a K2 value of 2.5, and a girder depth of 7ft, the estimated camber variability for different span lengths on the project is summarized in Table 1 below.

Table 1 Project Estimated Camber Variability

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **K1** | 1.0 | | | | | | |
| **K2** | 2.5 | | | | | | |
| **Girder Depth (ft)** | 7.0 | | | | | | |
| **Specified F'ci (ksi) at Release** | 6.5 | 6.5 | 6.5 | 6.5 | 6.5 | 7.0 | 7.0 |
| **Specified F'c (ksi) at 28-day** | 8.5 | 8.5 | 8.5 | 8.5 | 8.5 | 9.5 | 9.5 |
| **Span Length (ft)** | 120 | 135 | 145 | 150 | 155 | 160 | 170 |
| **Camber Variance (in) (+/-)** | 1.50 | 1.90 | 2.19 | 2.34 | 2.50 | 2.82 | 3.18 |
| **Min. CL Girder Haunch Required at Midspan (in)** | 2.00 | | 2.50 | | | 3.00 | |

Through collaborative discussions with the Contractor, it was determined that the cost of a potential schedule delay from out-of-tolerance girder cambers outweighed the cost of additional haunch concrete that would be necessary to build a comfortable camber tolerance into the design, particularly since the bridge was on the critical path schedule. Therefore, the design team determined that a camber tolerance of up to 30% over the predicted camber and 30% under the predicted camber could be allowed without significant changes to the preliminary girder designs.

The 30% tolerance for overcamber was built into the design by setting the minimum centerline of girder haunch thickness at midspan in accordance with Table 1 above. The 30% tolerance for undercamber was built into the design by considering the extra dead load of haunch concrete in the structural design. The composite section properties of the haunch thickness were considered in the analysis for the undercamber condition only, since this condition ensures that the haunch thickness will be present. Additionally, adjusted concrete strengths were considered in the undercamber analysis based on historical data provided by the Precaster. The historical data included release and 28-day break data for 262 specimens cast in 2014 indicating an average compressive strength at release and 28-day of 9782psi and 13875psi respectively. These average strengths were approximately 40-50% higher than the release strength assumed in the girder design, and approximately 45-65% higher than the 28-day strength assumed in the girder design.

The undercamber analysis determined that the girders had sufficient strength to resist the additional dead load of haunch concrete, and still had net positive upward camber under long term total dead loads. Although the added weight of haunch concrete from undercamber was significant, the additional haunch depth, due to undercamber, and girder stiffness, due to higher concrete strengths, provided greater moment capacity, greater allowable stresses, and greater resistance to deflections.

It should be noted that actual measured cambers in the construction phase indicated numerous girders exceeded the allowed 30% undercamber limit. A supplemental analysis was performed by the design team in the construction phase using a philosophy similar to that performed in the design phase, but with adjustments made to the concrete strengths based on concrete acceptance cylinders for the girders on the project. The results indicated that the allowable undercamber limit could be increased to -50% on the project, since actual concrete strengths based on concrete acceptance cylinders were higher than estimated in the original design. This improved tolerance brought all girders back into specifications.

## PROJECT CAMBER PREDICTION METHODOLOGY

The following section discusses the original design philosophy and calculations performed to predict the girder camber in the design phase, based on historical data provided by the Precaster and estimation methods provided in technical literature. The predicted cambers assumed in the design phase are then compared to adjusted predicted cambers computed from post-design research and as-built girder data made available during the project's construction phase.

It was determined that the refined time dependent analysis for camber predictions recommended in AASHTO LRFD specifications[4] was not practical for this project due to the number of unique girder designs and the fast tracked project schedule. Instead, the approximate method, or PCI multiplier method[5], was utilized to predict long-term cambers and deflections using standard PCI multipliers. The design variables affecting the computation of the initial elastic cambers and deflections were adjusted based on information obtained through collaboration with the Contractor and Precaster, and using recommendations in the study by Storm, Rizkalla, and Zia, 2013[6]. Although less accurate than the refined time-dependent method, the approximate method significantly reduced the computation time required and allowed the use of commercially available computer software to compute the predicted cambers.

Based on the historical data provided by the Precaster and methodologies recommended in Storm, Rizkalla, and Zia, 2013[6], the following adjustment factors were included in the original design camber predication analysis. Initial concrete strength at release was increased by a factor of 1.25, 28-day concretre strength was increased by a factor of 1.45, girder density was assumed to be 150pcf, and an aggregate adjustment factor, K, of 0.85 was used. Transformed section properties of mild steel reinforcement were also considered in the deflection computations, based on shop drawings provided by the Precaster. Precasters often include additional mild reinforcement above that specified for design based on their own experience and production practices, and this additional steel can have a significant impact on long-term camber and deflection computations.

In the construction phase, actual fabricated cambers at release were generally up to ¼" higher than predicted values for spans 120' to 135' in length, but were generally up to ¾" lower than predicted values for spans 145' to 160'. Actual fabricated cambers near 90 days measured by the Precaster just prior to shipping were generally within +/- ½" of predicted values for spans 120' to 135' in length, but were generally 1" to up to 2.5" (20%-50%) lower than predicted values for spans 145' to 160'. This is illustrated in Tables 2 and 3 below. Each data point represents a single girder.

Table 2 - Comparison of Predicted Camber @ Release vs Actual Measured Camber

Table 3 - Comparison of Predicted Camber @ 90 days vs Actual Measured Camber

A significant lesson learned from the methodology used to compute the predicted camber in the original design was the determination of the aggregate adjustment factor, K, used to compute the concrete modulus of elasticity in AASHTO LRFD specifications[4]. A K factor of 0.85 was estimated for the project based on recommendations provided in the study by Storm, Rizkalla, and Zia, 2013[6]. That study had used data collected from a number of east coast states to develop an average aggregate adjustment factor of 0.85. The K values of individual data points in that study, however, varied widely, ranging from 0.62 to 1.15. Additionally, the Skyway bridge project is located in Colorado, and the aggregates of this state may have significantly different properties from those used in the east coast study. The K factor varies based on different aggregate types, sources, and pits, and sometimes aggregates are not even consistent within the same source. Even in design build projects, the designer may not know the aggregate source at the design stage. All of these factors make accurate estimation of the K factor for a particular region or project a difficult process requiring significant historical data and frequent calibration.

Measured cambers were generally significantly lower than predicted cambers from the original design, suggesting that a higher K factor may have been warranted on this project. Fabricated concrete strengths based on test cylinders also indicated average concrete strengths at both release and final on the order of 45% to 60% higher than specified. Additionally, data provided for the fabricated girders showed an average girder density of close to 160pcf, compared the 150pcf assumed in the predicted camber analysis. For the sake of comparison, predicted girder cambers were recomputed using the adjusted values for the as-fabricated concrete strengths, a girder density of 160pcf, and a K factor of 1.00. Adjusted predicted cambers at release were typically lower, but within similar degree of accuracy as the original predicted values. These adjustments produced significantly more accurate predicted cambers at 90 days for spans longer than 135’, within +/- ½” of fabricated cambers in most cases. For spans 120’ to 135’, the adjusted camber computations produced slightly less accurate predicted cambers at 90 days.

A comparison of original design cambers to adjusted cambers determined from post-design research is illustrated in Tables 4 and 5 below. To simplify the computations, the average cambers of the 3 girders in a given span were lumped into one data point, so each data point in the table below represents a span average.

Table 4 - Comparison of Adjusted Predicted Camber @ Release vs Actual Measured Camber

Table 5 - Comparison of Adjusted Predicted Camber @ 90 days vs Actual Measured Camber

There was insufficient data available for this project to determine with confidence why the shorter 120’ to 135’ spans came out less accurate after the adjustments. There are a number of unknown factors that could have contributed to this, such as variability between computed and actual prestress force, elastic modulus, support conditions during storage, and thermal differences in the concrete and casting bed at time of pour. Such variability is discussed in more detail in research by Tadros, Fawzy, and Hanna, 2011[7].

It should be noted that predicted camber values in Tables 3 and 5 are based on a girder age of 90 days, but actual measured cambers prior to shipping were obtained anywhere from 22 days to 136 days after girder casting. An evaluation of girder camber variability vs girder age at time of camber measurement indicated that girder age did not seem to be a significant contributing factor on this particular project.

## CONCLUSIONS

The Design-Build method of project delivery allows a greater level of collaboration between the Engineer, the Contractor, and the Precaster during the design phase. With the goal of providing more accurate camber predications and reasonable tolerances for improved constructability, the author recommends the following points be considered on a project level basis:

- Historical Strength Data - Obtain the selected Precaster's historical concrete strength data from previous projects for the mix design that will be used on the current project, if available. If there is sufficient data available to indicate a good consistency of strengths among batches within an acceptable level of variance, the Engineer should consider adjusting the concrete strengths for the prediction of cambers and deflections. This is particularly important for release strengths, as this parameter has a significant influence on the initial cambers. However, adjustment of concrete strength should not be used for design strength and service stress checks unless explicitly allowed by code.

- Strength and Serviceability with Undercamber – Check the girder designs for strength and serviceability considering the worst case undercamber allowed by project construction tolerances. Consideration should be given to including the haunch thickness in the composite section properties when checking the girders for undercamber conditions. Typically, the haunch is neglected in composite section properties during the design phase since its actual thickness may be less due to overcamber; however, if girders are being analyzed for undercamber than the haunch thickness will be equal to the predicted haunch thickness plus the undercamber tolerance.

- Historical Camber Data - Obtain the selected Precaster's historical camber data from previous projects for girders of a similar type, size, and mix design as those being used on the project, if available. With sufficient data, this can be used to develop a more refined value for the aggregate adjustment factor, K, for computing the concrete modulus of elasticity in AASHTO LRFD specifications[4]. This data may also be used to determine a more accurate average girder density for the specific mix design in order to estimate concrete modulus and girder self-weight for deflections. For larger projects with many girders and longer construction schedules, it may be possible to use the camber and casting data obtained from early stage project girders to calibrate and adjust designs for subsequent girders on the project. Ideally, this calibration would occur prior to the affected pier cap construction so that seat elevations could be adjusted for the new predicted cambers.

- Other Project Specific Variables – This case study focuses on a specific project in a specific location with a single girder type. Projects with different precasters, different locations, and different girder types may produce different results. It is important for designers to consider any project specific variables that are within their ability to define and control. Project variables that cannot be defined or controlled should be accounted for through suitable camber tolerances.

- Calculate Project Specific Camber Tolerances - Regardless of the method used to predict camber, some inherent variability of camber will remain due to the complex interaction of numerous variables that cannot be entirely controlled. Some minimal level of camber tolerance should be incorporated into the design to account for this variability. If the level of variability estimated from rational methods results in an excessive girder design, constructability issues, or excessive haunch concrete, then the Engineer should discuss these concerns with the Contractor to determine if other adjustments, such as modifications to the construction schedule and sequencing could produce a more economical solution. For example, if the girders can be fabricated prior to the pier cap construction, then adjustments to the seat elevations based on actual fabricated cambers would be possible to minimize the required haunch thickness.

- Design Code Considerations - Many current design codes offer little guidance on how to evaluate and consider the effect of significantly under cambered girders in the structural design. In fast paced construction projects with large penalties for delays, more than typical PCI tolerances may be desirable. Additional code guidance on the following procedures would help promote consistent methodologies across projects for evaluation of undercamber in the design:
  - Provide a guide equation for computing expected camber variability with inputs for project specific conditions, such as the equation provided in the CDOT Bridge Design Manual[3], Subsection 9.1.C36.
  - Allow the use of higher concrete strengths for checking undercamber conditions if substantiated through historical data. Consider allowing the use of higher concrete strengths for the standard girder strength and serviceability checks contingent on buy-in from the selected Precaster.
  - Allow the use of the haunch depth and section properties in the computation of composite section properties when checking under camber conditions.
  - Allow the use of transformed mild reinforcement properties in the estimation of long term deflections.

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