Conservatism of Existing Prestress Loss Estimation Methods

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Abstract

The prestress loss estimates in the AASHTO LRFD Bridge Design Specification had been recalibrated in 2005 to be more accurate for "high-strength [conventional] concrete." Greater accuracy implies less conservatism, the result of which may be flexural cracking of beams under service loads. Concerns regarding the level of conservatism and the degree of complexity of the recalibrated prestress loss estimates prompted an investigation at the University of Texas at Austin. The primary objectives of the investigation were to assess the conservatism and accuracy of the current loss provision and to identify the strengths and weaknesses of its use. A prestress loss database containing over 230 specimens was assembled for the purposes of evaluating the recalibrated prestress loss estimation methods.

Keywords: Prestress losses, AASHTO, database compiling, database evaluation.

1. INTRODUCTION

In the 1990s, the use of high-performance concrete became widespread among state Departments of Transportation (DOTs). Among some individuals, concern arose that while the equations developed in the 1970s had been proven effective for estimating prestress losses in bridge girders fabricated with normal-strength concrete, they might do so too conservatively for girders of higher strength concrete. As a result, National Cooperative Highway Research Program (NCHRP) Project 18-07 was funded in 2000, and the University of Nebraska – Lincoln (UNL) was tasked to “provide reliable estimates for high-strength concrete bridge girders.” The end product of this research project was NCHRP Report 496 [1], which provided new approximate and refined methods to estimate prestress losses. The NCHRP 496 methods were then incorporated into the 2005 Interim Revisions of the AASHTO LRFD Bridge Design Specification [2] with minimal modification. The methods have persisted within Article 5.9.5 of the Specifications, “Loss of Prestress,” and will be referenced in this paper via the most current edition (i.e. prestress loss provisions of AASHTO LRFD 2012 [3]).

The AASHTO LRFD 2012 prestress loss provisions account for a large number of factors that are thought to influence prestress losses, with the objective of achieving accurate estimations. The resulting complexity of the method far exceeds that of the preceding provisions of the 2004 AASHTO LRFD Bridge Design Specifications [4]. Many have commented that the current method is difficult to implement because it requires the calculation and interpretation of a large number of variables and equations. [5] Moreover, the relevance of some of the factors may be questioned when considering that their effect is surpassed by the variability of other, more relevant parameters.

The prestress loss estimates of AASHTO LRFD 2012 are also considerably less than those of AASHTO LRFD 2004 in some cases; prompting DOTs and researchers to question the conservatism of the method. Research was undertaken at the University of Texas at Austin to provide additional experimental/analytical verification of the recalibrated provisions. [6]

2. RESEARCH APPROACH

The primary objectives of this investigation were: (1) to assess the conservatism and accuracy of the current prestress loss provisions versus the previously used provision and (2) to identify the benefits and weaknesses of using the prestress loss provisions contained within the 2004 and 2012 Editions of the AASHTO LRFD Bridge Design Specifications.

The project objectives were accomplished through a combination of experimental and analytical efforts. The conservatism and accuracy of the AASHTO LRFD Bridge Design Specifications were evaluated through the use of a prestress loss database that included 30 field-representative girders – fabricated and tested within the context of the current study. Implementation and implications of the prestress loss provisions were examined within an extensive literature review and parametric study.

The focus of this paper will be on the effort of compiling and analyzing a comprehensive database of available experimental investigations pertaining to prestress loss. The database assembled in this project is the largest, most comprehensive database of prestress loss measurements collected to date.

3. EVALUATION DATABASE

The research team identified a total of 29 prestress loss studies in literature published between 1970 and present. Prestress loss data for 237 specimens were extracted from the collection of studies. This data included a total of 30 full-scale prestressed beam tests conducted during the course of this project and discussed briefly below, which will be discussed in detail in another paper within the 2013 PCI/NBC proceedings[7]. The prestress loss was primarily measured through the use of either cracking load or internal strain measurements. The specimens and the corresponding prestress losses represented a broad range of materials (including high strength concrete) and girder geometries. All of the specimens contained in this database are pretensioned girders only.

EXPERIMENTAL PROGRAM

A total of 30 full-scale prestressed concrete beams were fabricated to provide a relevant empirical basis for assessment of the existing prestress loss provision (and for the development of new provisions). These specimens were representative of a broad range of the most influential factors that may affect prestress losses in structures including: (1) type of concrete (CC and SCC), (2) coarse aggregate (Limestone and River Gravel), (3) sectional geometry (Type C and Tx46), and (4) climate (humidity from 51% to 63%). The amount of prestressing steel in each specimen varied from about 1.13 percent to 1.37 percent of the gross cross-sectional area. This large amount of prestressing steel was used in order to generate high initial compressive stresses, on the order of $0.65f'_{ci}$, to maximize the potential for prestress losses.

Internal instrumentation was used to monitor prestress losses in 18 of the 30 specimens. As part of the experimental program, tests for compression, tension and modulus of elasticity were conducted on a large number of cylinders at multiple concrete ages. These concrete properties were used to assess the effect of the different concrete mixes. Flexural testing was conducted at the end of the conditioning period, and the load at the time of first cracking (together with measured concrete tensile strength) was used to back-calculate the total prestress loss.

DATA COLLECTION AND FILTERING

Additional relevant and potentially relevant research conducted on pretensioned girders was collected from the literature and assembled into a database. The database was assembled to enable evaluation of the past and present prestress loss provisions of the AASHTO LRFD Bridge Design Specification.

Prestress loss was determined either by internal strain measurement or by back-calculating strand stress from service load testing results. Some of the studies explicitly reported the prestress losses that occurred within their specimens. These results were verified, if possible, through the use of other data reported within the study. If the prestress loss was not explicitly reported, the loss was calculated using either service load testing results or reported internal strain measurements. When a loss was reported and could be determined from both internal strain measurements and cracking load test results, only the loss from the most accurate measurement method (internal strain measurement)[6] was used in database analysis.

Once the results were fully vetted, a two-stage filtering process, shown in Table 1, was conducted to ensure that code performance would only be evaluated on the basis of relevant data. The filtering process provided assurance that: (1) the prestress loss measured in each specimen was an accurate representation of behavior encountered in the field, and (2) the specimens were of representative scale and detailing.

Table 1: Filtering of the prestress loss database

Collection Database		***237 tests***
Stage 1 Filtering	*Critical information not reported* - Concrete tensile strength - Concrete release strength - Prestress loss - Total prestressing area	- 57 tests
	Inaccurate prestress loss estimate	- 3 tests
Filtered Database		***177 tests***
Stage 2 Filtering	*Height*: $h > 15\ inches$	- 36 tests
	Concrete stress at release: $\frac{f_{c,bottom}}{f_{ci}} < 0.7$	- 1 tests
Evaluation Database		***140 tests***

The first filtering process was performed on the database to eliminate specimens for which critical details could not be ascertained; information deemed critical is shown in Table 1 and discussed here. The concrete tensile strength, compressive release strength, and prestressing strand area were essential to assessment of the load test results and estimation of the prestress losses. A failure to report measurements (as opposed to design values) of these properties resulted in dismissal of the specimen from the database. Moreover, if the prestress loss was not reported and ancillary data could not be used to back-calculate the prestress loss, the specimen was similarly dismissed from the database. After the first stage of filtering, each of the specimens within the Filtered Database was accompanied by sufficient detail to accurately estimate the prestress loss and compare it to the reported/calculated value.

The second stage of the filtering process was conducted to ensure that the specimens within the Evaluation Database possessed field-representative scale and detailing. Two parameters (refer to Table 1) were examined to make this determination: (1) specimen height (h) and (2) initial bottom fiber stress ($f_{c,bottom}$). The smallest section used in common practice in the United States is limited to a height of 15 inches. Moreover, a cursory database analysis revealed that the flexural cracking resistance of smaller specimens was generally exaggerated in relation to reported concrete tensile strength; resulting in lower than realistic prestress loss assessments. All specimens under 15 inches in depth were therefore eliminated from Evaluation Database. In the current bridge specification the limit for the maximum compressive stress at prestress transfer is $0.6f_{ci}$. Research has been conducted to investigate the potential of increasing this limit, which would allow for longer span lengths, a reduction in harped or debonded strands, and a faster turnaround time for beams in prestressing beds. An upper limit of $0.65f_{ci}$, recommended by TxDOT Project 0-5197 [8], has been adopted by some owners and state agencies. To be inclusive of members subjected to high initial compressive stresses, an upper limit of $0.7f_{ci}$ was adopted for inclusion within the Evaluation Database.

The final Evaluation Database contains the specimens from the Filtered Database that met the height and initial stress qualifications outlined above. The origin of the reference, geometry of the specimens, concrete materials used, and amount of prestressing in the specimens included in the Evaluation Database will be briefly discussed in the following sections.

EVALUATION DATABASE CHARACTERISTICS

The prestress loss database was used heavily in evaluation of both the past and present prestress loss provisions. Due to the central role played by the database, it is important to demonstrate that the database provides a comprehensive representation of pretensioned girder design and fabrication across the United States.

The methods used to measure the prestress loss in the specimens contained in the Evaluation Database are shown in Figure 1. The two primary methods of assessing prestress loss (vibrating wire gages and flexural cracking tests) make up the majority of the Evaluation Database. Vibrating wire gages (VWGs), used in about half of the specimens, were found to be the most consistent means of prestress loss assessment; with flexural cracking being the second-most utilized, and consistent, means of assessment.

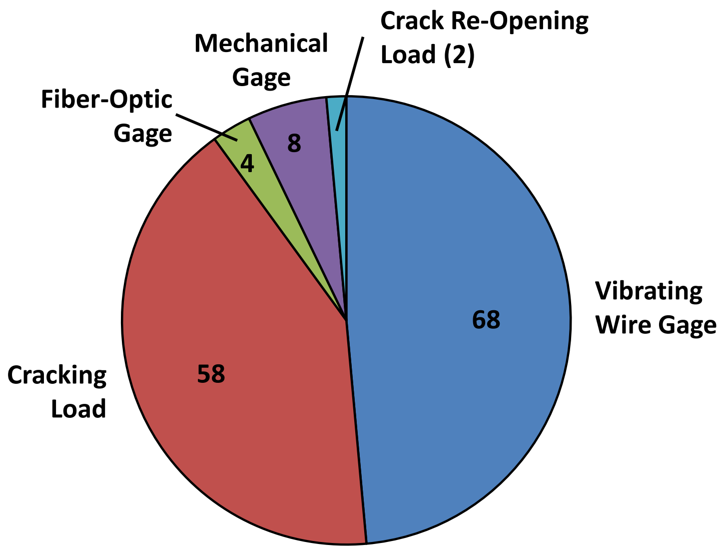

Figure 1: Method used for measuring prestress loss

The fabrication and conditioning locations of the specimens are presented in Figure 2. Although the majority of the specimens are from Texas, many other states are also represented, ensuring that various climates are captured by the database. The average relative humidity reported for the conditioning locations fell between 40 and 80 percent, with the majority between 60 and 75 percent. It should be noted that the majority of the entire country has an average ambient relative humidity between 60 and 75 percent [3].

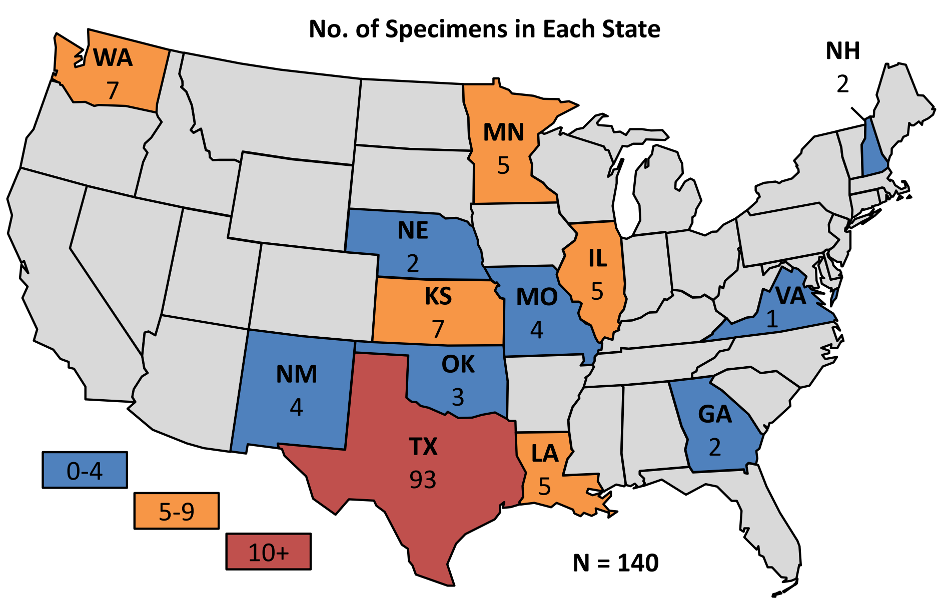

Figure 2: Location where specimens were fabricated/conditioned

A variety of different specimen geometries are captured by the specimens included in the Evaluation Database. The majority of the specimens are 25 to 75 feet in length and 20 to 60 inches in height, although longer spans and deeper cross-sections are also present. The gross cross-sectional area of the specimens varied from 250 to 1250 square inches. The majority of the specimens have a volume-to-surface area ratio of between three and four; nearly all typical cross-sections have a volume-to-surface ratio within this range.

A variety of concrete mixtures with different types of aggregates are captured within the Evaluation Database, as shown in Figure 3. The majority of the specimens were fabricated using conventional concrete, although some specimens were fabricated using self-consolidating concrete. The two main types of course aggregate used in common practice, river gravel and limestone; make up the majority of the specimens in the database.

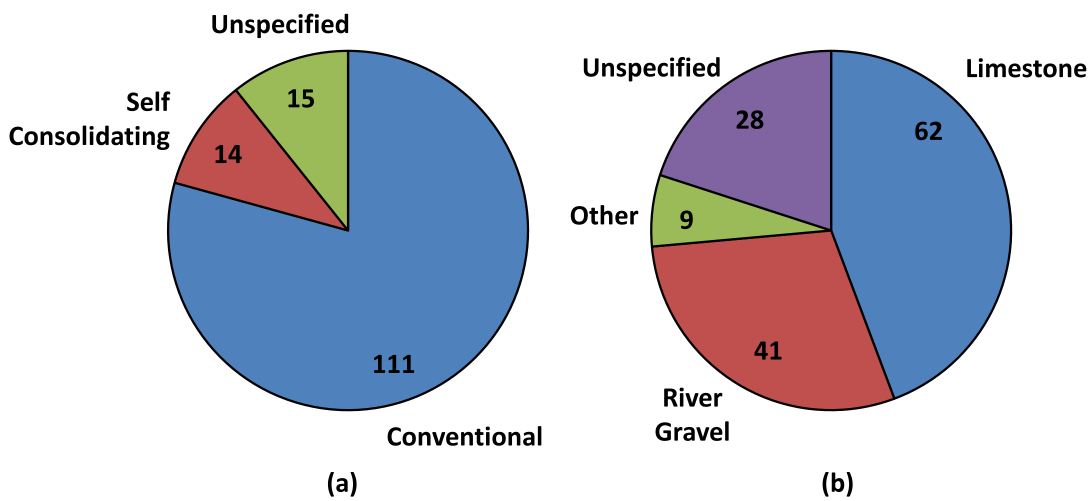

Figure 3: (a) Type of concrete mixture and (b) type of aggregate used to construct specimens

While previous material property and prestress loss equations were developed and verified using either only lower strength concrete (< 6 ksi) or only higher strength concrete (> 6 ksi), the Evaluation Database contains a wide variety of concrete strengths, as shown in Figure 4. The concrete design is typically chosen so that the concrete will reach the desired release strength less than a day after casting. This release strength will typically range between 4 and 7 ksi and results in a concrete mix with an ultimate strength of between 8 and 12 ksi. These typical values make up the largest portion of the specimens contained in the database. It should also be noted that 89 out of the 140 specimens included in the Evaluation Database attained an ultimate strength of over 10 ksi.

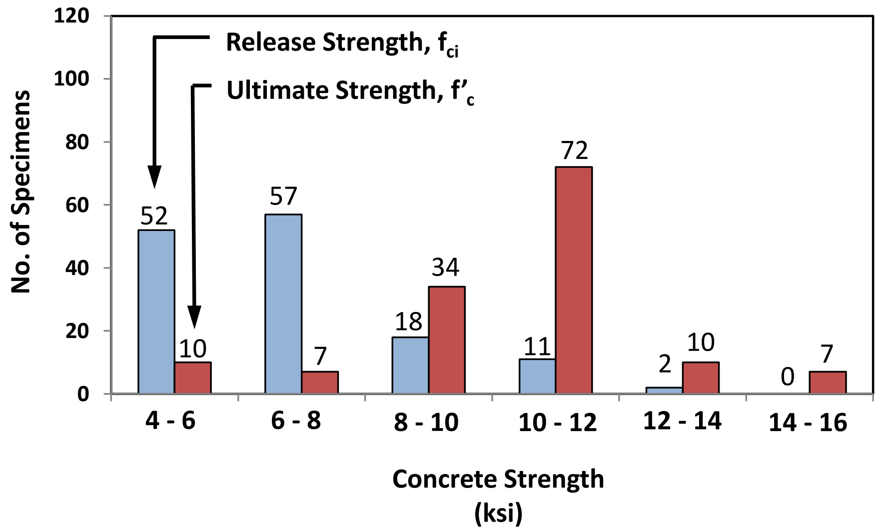

Figure 4: Release strength and ultimate strength of concrete used to construct specimens

The majority of the prestressed reinforcement ratios for the specimens contained in the Evaluation Database are below 1.5 percent. In practice, it is not practical to have a prestress ratio higher than 1.5 percent, as these higher ratios lead to compressive stress concerns.

4. DATABASE EVALUATION OF CURRENT AND HISTORIC PRESTRESS LOSS PROVISIONS

The performance of the 2004 and 2012 (introduced in 2005) AASHTO LRFD Bridge Design Specifications will now be presented and discussed. The performance of each procedure is evaluated by comparing the estimated prestress loss to the measured prestress loss of each Evaluation Database specimen; calculation of the ratio of the estimated-to-measured prestress losses (*E/M*) is helpful in that regard. Key statistics from the *E/M* ratios calculated for the prestress loss expressions in AASHTO LRFD 2004 and 2012 are presented in Table 2. Please note that an accurate means of prestress loss estimation will be characterized by an average *E/M* ratio close to 1.00 (i.e. estimated and measured prestress losses are equal). More conservative means of prestress loss estimation will be characterized by an *E/M* ratio greater than 1.00 (i.e. estimated prestress losses exceed the measured prestress losses). Prestress loss estimates provided by AASHTO LRFD 2004 are more conservative than those provided by AASHTO LRFD 2012, as shown in Table 2.

Table 2: Comparison of AASHTO LRFD 2004 and 2012 performance using estimated-to-actual ratio (E/M) from Evaluation Database

	Total Loss	
	AASHTO 2004	**AASHTO 2012**
Minimum	0.86	0.59
Average	1.74	1.25
Maximum	3.69	2.20
Co. of Variation	0.26	0.24
St. Deviation	0.45	0.30

The relationship between the estimated prestress losses and the measured prestress losses is further examined in Figure 5 ((a) AASHTO LRFD 2004 and (b) AASHTO LRFD 2012). All results contained within the Evaluation Database are plotted against the total prestress loss estimate on the vertical axis and the measured total prestress loss on the horizontal axis. If a procedure exhibits perfect precision, all of the specimens will fall on a straight line that originates from the origin. A procedure with no excess conservatism and perfect precision will place all of the specimens on the line of equality, which is the solid black line extending from the origin in Figure 5. It should also be noted that all of the specimens that fall below the line of equality are estimated unconservatively by the particular prestress loss provisions.

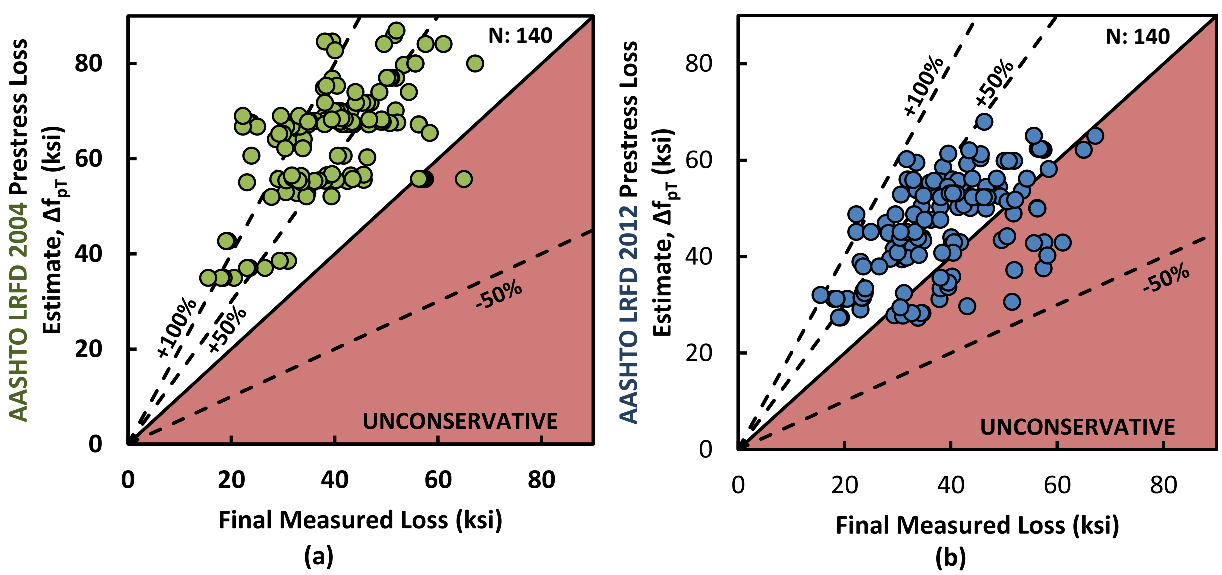

Figure 5: (a) AASHTO LRFD 2004 and (b)AASHTO LRFD 2012 prestressed loss estimate vs. final measured loss

Calibration of the AASHTO LRFD 2012 prestress loss provisions for accurate estimations is apparent in Figure 5 (b); nearly a quarter of the specimens fall below the line of equality. Moreover, the lack of conservatism is achieved through a substantial increase in complexity and only a minor improvement in the precision of the estimates (refer to the coefficient of variation in Table 2).

The performance of each specification can be further investigated by breaking the final prestress loss into elastic shortening and long-term loss components. This division was only possible in specimens where VWGs were used and/or elastic shortening was reported separately, which was only the case for 38 specimens in the Evaluation Database. Key statistics from the *E/M* ratios calculated for elastic shortening and long-term losses for both provisions are presented in Table 3.

Table 3: Comparison of AASHTO LRFD 2004 and 2012 elastic shortening and long-term loss estimations using estimated-to-actual ratio (E/M) from Evaluation Database

	Elastic Shortening		**Long-Term Loss**	
	AASHTO 2004	***AASHTO 2012***	***AASHTO 2004***	***AASHTO 2012***
Minimum	0.71	0.69	1.15	0.63
Average	0.92	0.87	3.22	1.42
Maximum	1.31	1.15	8.07	2.23
Co. of Variation	0.15	0.14	0.50	0.29
St. Deviation	0.14	0.12	1.62	0.42

Both prestress loss provisions have been calibrated to yield both accurate and precise estimation for elastic shortening, as shown in Figure 6. This behavior is a result of elastic shortening being a well-understood phenomenon that is accounted for in both provisions via a theoretically based analysis. Despite providing accurate and precise estimation for elastic shortening, both provisions result in slightly unconservative estimates of elastic shortening in around two-thirds of the specimens. The unconservative nature of elastic shortening estimation is less of a concern since it can be so precisely estimated.

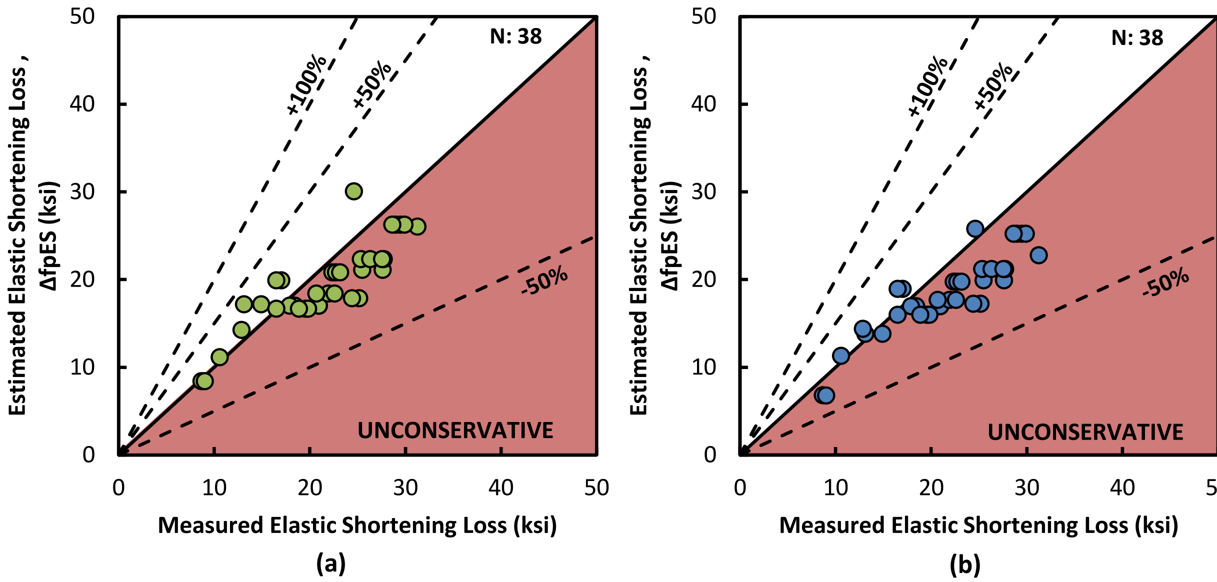

Figure 6: (a) AASHTO LRFD 2004 and (b) AASHTO LRFD 2012 estimated elastic shortening vs. measured elastic shortening

With respect to long-term losses, the AASHTO LRFD 2004 prestress loss provisions contain simple, empirically derived expressions for creep and shrinkage loss estimation. These expressions do not account for many of the variables that influence creep and shrinkage behavior. The result of this behavioral oversimplification can be seen in the large amount of variation and high level of conservatism (Table 3 and Figure 7). The recalibration of the loss provisions improved the accuracy and precision of estimating the long-term loss. There is still a notable amount of variation in the estimation of long-term losses.

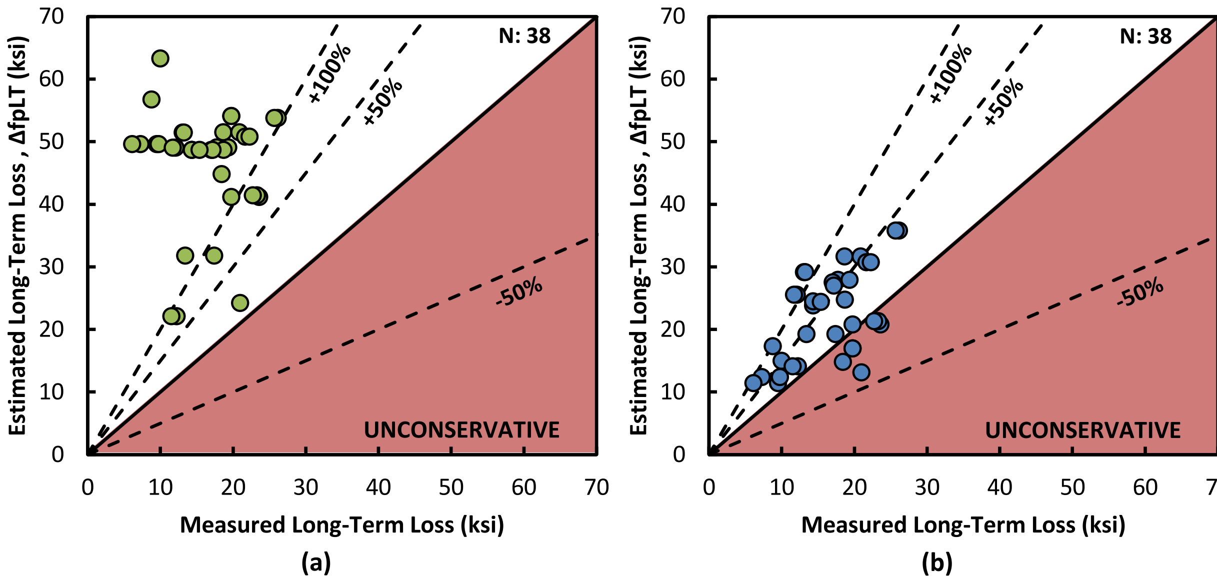

Figure 7: (a) AASHTO LRFD 2004 and (b) AASHTO LRFD 2012 estimated long-term loss vs. measured long-term loss

It should be noted that the accuracy and precision of elastic shortening estimation is heavily dependent on that of the modulus of elasticity; the other input parameters can be accurately estimated and the occurrence of elastic shortening is well understood. This is not the case for the long-term losses, as creep and shrinkage are complicated mechanisms involving many variable input parameters. For further discussion on the performance of the current modulus of elasticity expression please refer to the report of the parent investigation[6].

5. CONCLUSIONS

The prestress loss provisions within 2012 AASHTO LRFD Bridge Design Specifications were found to be unconservative in some cases and no more precise than the AASHTO LRFD 2004 provisions in total loss estimations. The following observations on the performance of AASHTO LRFD 2012 were made:

- *Elastic shortening estimates are unconservative*: As observed for AASHTO 2004, the AASHTO LRFD 2012 estimation of the prestress loss due to elastic shortening was consistently 10 to 15 percent less than the prestress loss measured within the 18 instrumented specimens of the experimental program.
- *Long-term loss estimates are more accurate and precise*: The AASHTO LRFD 2012 estimation of the long-term prestress loss accounted for more influential variables than AASHTO LRFD 2004, increasing precision, and was calibrated to produce more accurate long-term loss estimates.

- *Total prestress loss estimates are unconservative in some cases*: Nearly a quarter of the prestress loss measurements (32 of 140 specimens) included within the Evaluation Database were underestimated by AASHTO LRFD 2012. The unconservative nature of AASHTO LRFD 2012 is attributed to the approach taken by the authors of NCHRP Report 496 during derivation of the provisions; namely, the authors placed the highest priority on the accuracy (as opposed to conservatism) of the provisions.

An alternative prestress loss estimation procedure has been developed by researchers at The University of Texas at Austin[6] and will be presented in a future paper.

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