Prestress loss calculations: Another perspective

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- Thirty full-scale bridge girders with a variety of design parameters were instrumented, constructed, monitored, and tested; a comprehensive experimental database containing data from 140 full-scale bridge girders was assembled; and an extensive analytical program was conducted to investigate the sensitivity of current estimation methods and implications of loss estimation on final designs.
- Through the work of this project, a prestress loss estimation procedure was developed that is simple to use and precise.
- This procedure can be used for both time-dependent and final prestress loss estimation.

To properly design prestressed concrete girders, designers must estimate the prestressing force that the strands apply on the concrete section, allowing the stress in the concrete to be estimated. The designer will typically accomplish this objective by specifying the initial force or stress to which the strand should be tensioned, which is known as f_{pi} or the jacking stress f_{pj}, and then estimating the amount of stress the strand will lose due to the time-dependent deformations (prestress loss Δf_p). The total prestress loss is composed of loss due to shrinkage of the concrete Δf_{pSR}, loss due to concrete creep deformations Δf_{pCR}, and loss due to strand relaxation Δf_{pR}. For design, the prestress loss is used to estimate the stress in the concrete at different sections (primarily to prevent cracking in the concrete) and to estimate deformations of the beam (to ensure constructibility and serviceability of the bridge).

The accuracy, precision, and conservatism of prestress loss estimation must be carefully balanced to ensure a safe, serviceable, durable, and economically viable girder. When prestress loss is underestimated, the designer assumes a greater stress in the strands than is actually present. This underestimation can lead to service-load cracking and long-term durability concerns due to corrosion. Overestimation of prestress loss may lead to uneconomical designs and large cambers, which are both a result of an excessive number of strands being required.

Prestress loss estimation shares a history with prestressed concrete design that began with simplicity and conservatism and led to complexity and accuracy. Attempting to improve the accuracy of prestress loss estimation and applicability to modern materials and structural shapes, the National Cooperative Highway Research Program (NCHRP) project 18-07 was funded in 2000.[1] The end product of this research was NCHRP Report 496,[1] which provided new approximate and refined methods to estimate prestress losses. The NCHRP Report 496 methods were then incorporated into the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications, 3rd Edition—2005 Interim Revisions*[2] with minimal modifications. The approach offered in this revised procedure is a reversal in both complexity and conservatism from its predecessor: the new procedure is significantly more complex and leads to substantially smaller prestress loss estimates.

This paper focuses on the development of a conservative and precise method for estimating prestress loss that is based on a large research effort.[3] The loss estimation procedure developed during this research project expanded on the work in NCHRP Report 496.

For the purpose of this paper, the most recent AASHTO LRFD specifications,[4] the 2012 edition, will be referenced for the prestress loss procedure developed in NCHRP Report 496[1] and implemented in the 2005 interim revisions. The predecessor to this procedure will be referred to by the last year it was in the AASHTO LRFD specifications, which was 2004.[5] The prestress loss procedure found in the *PCI Bridge Design Manual*[6] will also be used as a point of comparison in this paper to show differing design philosophies.

Experimental procedure

The research conducted for this project was accomplished through full-scale experimental testing,[7] the assembly of a comprehensive experimental database,[8] and an analytical study investigating the sensitivity of the refined AASHTO LRFD specifications[4] procedure and the design implications of its use. Each of the three major research efforts will be discussed. A more in-depth discussion of the research efforts and findings can be found in other sources.[3,7–10]

Experimental program

In total, 30 full-scale pretensioned, precast concrete beams were fabricated to provide a relevant experimental basis for investigating the parameters influencing prestress loss and in order to assess the existing prestress loss provisions. This experimental program is discussed in more depth in Garber et al.[7] These specimens were representative of a broad range of the most influential factors that may affect prestress losses in structures fabricated within the United States (**Fig. 1**).

Sixteen of the 30 beams were Type C beams (40 in. [1000 mm] deep I-girder section); the remaining 14 beams were Tx46 beams (46 in. [1200 mm] deep bulb-tee section).[11] The I-girder and bulb-tee sections represent the two most commonly used section types in standard bridge design. The concrete and coarse aggregate types were intentionally varied from series to series to investigate their effect on prestress loss. Series I and III were fabricated in San Antonio, Tex., with conventional concrete and limestone coarse aggregate; series II was fabricated in Elm Mott, Tex., using conventional concrete and river gravel coarse aggregate; and series IV was fabricated near Eagle Lake, Tex., using both conventional and self-consolidating concrete with river gravel coarse aggregate. The specimens were conditioned for periods ranging from 93 days (one girder from series IV) to 980 days (final girder tested in series III) with an average beam age of 700 days. The specimens were conditioned at a total of five different storage locations across the state of Texas in order to investigate the effect of different relative humidities: San Antonio (average relative humidity *RH* of 63%), Austin (62%), Lubbock (51%), Elm Mott (63%), and Eagle Lake (75%).

The long-term loss of prestress within the specimens was assessed through the use of internal strain monitoring and flexural testing. The twofold assessment allowed for the validation of the accuracy and consistency of both methods. The development of prestress loss within 18 of the 30 specimens was monitored through the use of internal strain instrumentation. Concrete strains and temperatures were measured at several points through the depth of each instrumented cross section using vibrating wire gauges and were then used to calculate the change of strain at the centroid of the prestressing strands. Due to compatibility between the prestressing strands and the surrounding concrete, it was possible to further calculate the loss in prestressing force on the basis of the prestressing strand modulus and area. By monitoring the strain and temperature periodically throughout the conditioning of each specimen, the prestress loss could be calculated over time.

The flexural demands (for example, moment due to load) under which a pretensioned girder will crack are uniquely dependent on the beam geometry, concrete tensile strength, and effective prestressing force. Measurement of the cracking moment and concrete tensile strength combined with knowledge of the beam geometry enables the calculation of the effective prestressing force, and by association, the prestress loss at the time of testing. By measuring the prestress loss through both internal strain monitoring and external service load testing, two of the most commonly used methods for loss measurement were verified (ensuring the accuracy of both the experimental result of this research program and those included in the experimental database discussed in the following).

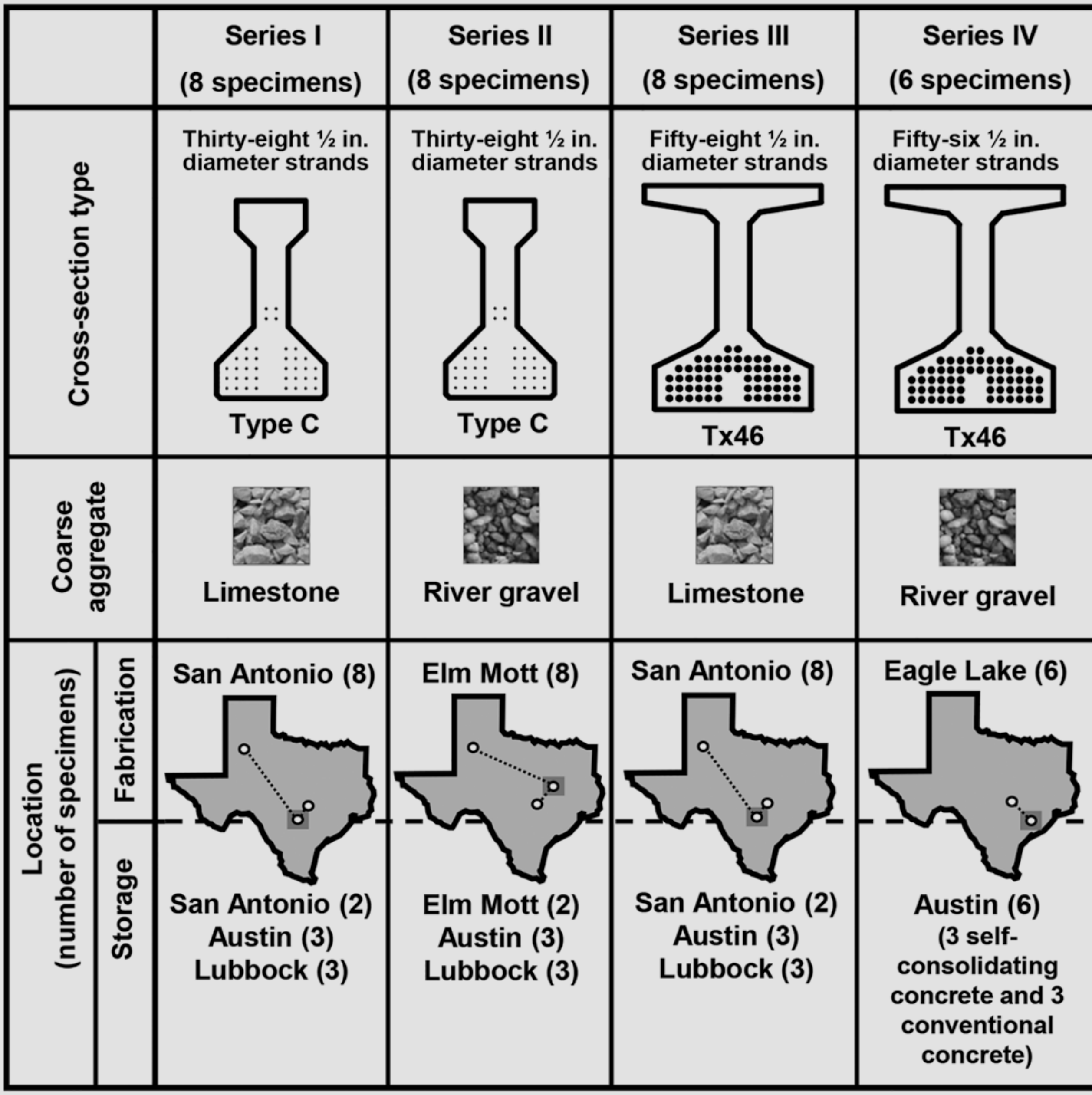

Figure 1. Summary of experimental program. Note: 1 in. = 25.4 mm.

Figure 2 shows a summary of the experimental results from the testing program. The beam test results are grouped by similar experimental variables (for example, the results for the three beams from series I that were conditioned in Lubbock are all grouped together with their average, maximum, and minimum measured prestress loss plotted). The relative humidity of the conditioning sites and the modulus of elasticity of concrete at time of release E_{ci} for each of the different concrete mixtures is also included in the figure. The stiffness of the concrete had the most effect on the development of prestress loss. The beams made with concrete with a greater modulus of elasticity (series II and IV) developed significantly smaller prestress losses than those made with concrete with a lesser modulus of elasticity (series I and III). The relative humidity had only a slight effect on the prestress loss development, with a higher relative humidity generally resulting in slightly smaller prestress losses. The experimental results are further analyzed in Garber et al.[7]

The results from this experimental testing program were added to the experimental database developed in this research program and discussed in the following section.

Experimental database

A comprehensive database[8] of available experimental investigations pertaining to prestress loss was compiled as a

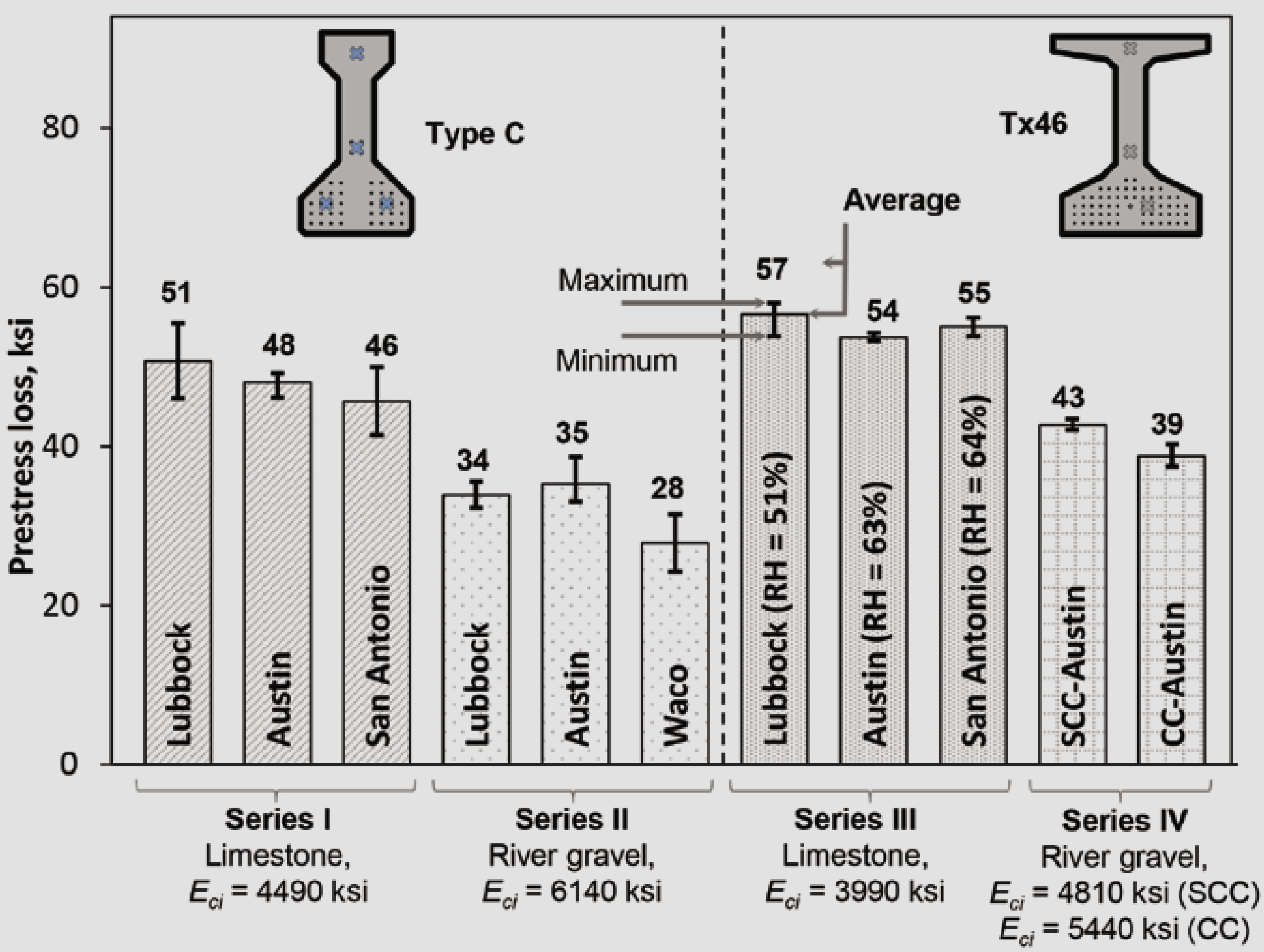

Figure 2. Summary of experimental results. Note: CC = conventional concrete; SCC = self-consolidating concrete. 1 ksi = 6.985 MPa.

major part of the research. This database contains information on 237 specimens, including 140 specimens for which prestress loss was reported, or enough accurate information was provided to calculate prestress loss that occurred at the time of testing.

A total of 29 prestress loss studies published between 1970 and the present were identified. Prestress loss data for 237 specimens were extracted from the collection of studies and assembled to create the collection database. The results contained in the collection database underwent a two-stage filtering process to ensure that code performance would only be evaluated on the basis of relevant data. The filtering process (described in more detail in Garber et al.[3,8]) provided assurance that the prestress loss measured in each specimen was an accurate representation of behavior encountered in the field and that the specimens were of representative scale and detailing.

The first filtering stage was performed on the collection database to eliminate specimens for which critical details (such as concrete tensile strength, compressive release strength, prestressing strand area, or the final prestress loss) could not be ascertained. The concrete tensile strength, compressive release strength, and prestressing strand area were essential to assessing the load test results and estimating the prestress losses. A failure to report measurement (as opposed to design values) of these properties resulted in omission of the specimen from the filtered database. Moreover, if the prestress loss was not reported and ancillary data could not be used to calculate the prestress loss, the specimen was similarly dismissed from the filtered database. Each of the specimens within the filtered database is accompanied by sufficient detail to accurately estimate the prestress loss and compare it with a reported or calculated value.

The second stage of filtering was conducted to ensure that the specimens within the evaluation database possessed field-representative scale and detailing. Two parameters were examined to make this determination: specimen height h and initial bottom fiber stress $f_{c,bottom}$. The smallest section commonly used in practice is limited to a height of about 15 in. (380 mm), corresponding to the height filter placed on the evaluation database. In the current AASHTO LRFD specifications,[4] the maximum allowable compres-

Table 1. Sample analysis design for two-variable system using one factor at a time design

Analysis number	Variable 1	Variable 2
1	Average	Average
2	Minimum	Average
3	Maximum	Average
4	Average	Minimum
5	Average	Maximum

Table 2. Sample analysis design for two-variable system using full-factorial design

Analysis number	Variable 1	Variable 2
1	Minimum	Average
2	Minimum	Minimum
3	Minimum	Maximum
4	Average	Average
5	Average	Minimum
6	Average	Maximum
7	Maximum	Average
8	Maximum	Minimum
9	Maximum	Maximum

sive stress at prestress transfer is 0.6 f'_{ci}. Research[12] has suggested that this limit may be increased to a higher value of 0.65f'_{ci} or 0.7f'_{ci}, which corresponds to the filter placed on the evaluation database (compressive stress at release less than or equal to 0.7 f'_{ci}). The final evaluation database, which consists of 140 specimens, contains only specimens from the filtered database that met the height and initial stress qualifications outlined previously.

The evaluation database contained a wide assortment of specimens from across the United States, with the majority of the specimens being constructed or conditioned in Texas. Although the majority of the specimens are from Texas, many other states are also represented to ensure that various climates and fabrication techniques are captured by the database, thus no bias occurred in the results or equations. The average relative humidity of the conditioning locations varied from 45% to 80%, with the majority of the specimens being conditioned in climates with an average relative humidity between 60% and 70%.

The evaluation database primarily contained specimens in which prestress loss was determined using either vibrating wire gauges or flexural cracking tests. These two methods correspond to the measurement methods chosen for the experimental program within this study and were validated against each other through testing and direct comparisons.

A variety of different specimen geometries are captured by the specimens in the evaluation database. The majority of the specimens are 25 to 75 ft (7.5 to 23 m) long and 20 to 60 in. (500 to 1500 mm) high, though longer spans and deeper cross sections are also present.

In addition, a variety of concrete mixtures with different types of aggregates are captured within the evaluation database. The majority of the specimens were fabricated using conventional concrete, though some specimens were fabricated using self-consolidating concrete. The two main types of coarse aggregate used in common practice (river gravel and limestone) make up the majority of the specimens in the database. Concrete release strengths within the database range from 4.0 to 13 ksi (28 to 90 MPa) and concrete 28-day strengths range from 5 to 15 ksi (34 to 103 MPa), with 89 of the 140 specimens attaining a 28-day compressive strength of more than 10 ksi (69 MPa).

The specimens contained in the evaluation database were used in order to evaluate the existing prestress loss estimation procedures and develop the simplified approach presented within this paper. A more in-depth discussion and analysis of the experimental database can be found in Garber et al.[3,8]

Analytical investigation

A parametric study was undertaken to investigate the influence of various inputs on output loss estimation parameters (sensitivity analysis) and assess the impact of prestress loss estimation on beam design (impact analysis). Both of these analyses will be covered in brief in this section. A more thorough treatment of them can be found in Garber et al.[3]

Sensitivity analysis A sensitivity analysis was conducted on the 2012 AASHTO LRFD specifications' loss procedure using an extreme value analysis. In an extreme value analysis, the effect of the maximum and minimum possible values for the input variables on the output parameters is investigated. For this study, the extreme value analysis was used to investigate the effect that various input parameters have on the calculation of the different components of prestress loss.

Two different factorial designs were used in the experimental design for the extreme value analysis, one factor at a time (**Table 1**) and full factorial (**Table 2**). The one factor at a time design was used to investigate the effect of each individual input variable on the output variables. For this analysis, only one variable is set to a design extreme while the other input variables are kept at an average value (Table 1).

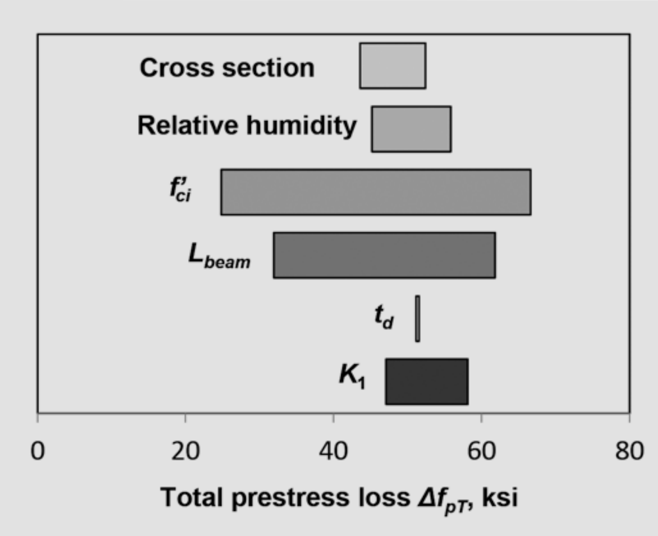

Figure 3. Sample results from sensitivity analysis, range of total estimated prestress loss for variation of different input parameters. Note: f'_{ci} = concrete strength at release of prestress; K_1 = correction factor for source aggregate; L_{beam} = total girder length; t_d = age of concrete at time of deck placement. 1 ksi = 6.895 MPa.

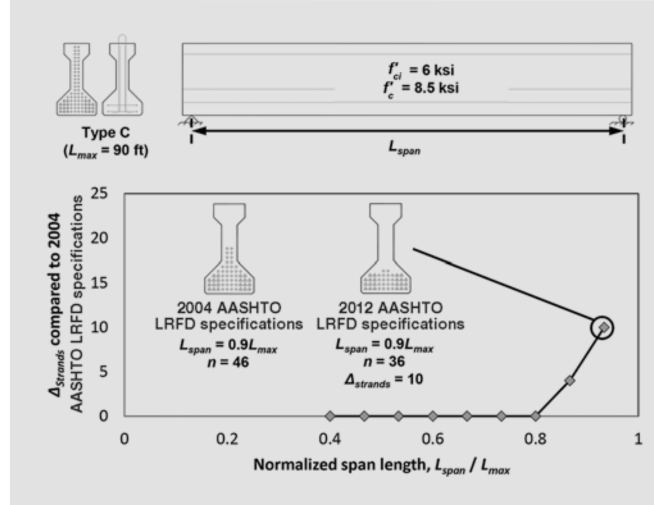

Figure 4. Sample results from impact analysis, difference in total strands required by 2004 AASHTO LRFD specifications versus 2012. Note: f'_c = specified compressive strength of concrete; f'_{ci} = concrete strength at release of prestress; L_{max} = maximum length achievable using a specific section type and strand layout; L_{span} = total distance from center to center of supports; n = number of strands; $\Delta_{strands}$ = difference in strands between design using 2004 AASHTO and 2012 AASHTO LRFD specifications prestress loss procedures.

The general trends observed in the one factor at a time analysis can be observed in the input parameters' effect on the total prestress loss (**Fig. 3**). A larger spread in the plot signifies that the input variable (for example, cross-section type) has a significant effect on the output (for example, the total prestress loss). The concrete release strength and the beam length were found to have the largest impact on the total prestress loss estimate. The cross-section size, relative humidity, and coarse aggregate correction factor were each found to have a relatively similar impact on the loss estimate. The time of deck placement does not significantly affect the loss estimate.

The second factorial design used was a full factorial design (Table 2). In this technique, the input variables are systematically varied from their maximum and minimum design extremes in order to attempt to find the most severe combination of extreme input variables on each output parameter. Every possible combination of design minimums, maximums, and average values of each variable are investigated within a full factorial design. Through the full factorial analysis, the loss due to relaxation Δf_{pR} and the differential shrinkage of the deck concrete Δf_{pSS} were found to have only a minor contribution to the total prestress loss and had the least amount of variation.

Impact analysis In addition to the sensitivity analysis, an impact analysis was conducted to investigate the tangible design impact inferred from different loss expressions. The impact analysis was accomplished by completing a full girder design for more than 1800 different design scenarios. Through the analysis, different cross-section types (I-girders, bulb tees, box beams, and U beams), bridge layouts (with various girder spacing and span lengths), and different concrete types and strengths were investigated.

Figure 4 shows a sample of the trends observed in the impact analysis. The difference in the number of prestressing strands required for a design using 2012 AASHTO LRFD specifications compared with a design using the 2004 AASHTO LRFD specifications is shown for eight different span lengths. Because the design of shorter span lengths is typically controlled by flexural strength requirements (as opposed to compressive or tensile stress limits), there is no difference in strands required between the two specifications. This is a result of the ultimate strength capacity not being affected by prestress loss (because it only depends on the strands' ultimate strength). For the cross-section types investigated, the transition point between service-level flexural stresses and ultimate flexural strength controlling design occurred between 75% and 85% of the maximum allowable span length. When one or both of the designs were governed by stress limit checks, a difference in the strands required by the two specifications was generally observed. The controlling stress limit was typically the bottom-fiber tensile stress check at midspan under service loading. The design highlighted in Fig. 4 was a Type C girder at a span of approximately 90% of the maximum span length L_{max}. A design using the 2012 AASHTO LRFD specifications would require 10 fewer strands than a design using the 2004 AASHTO LRFD specifications, about a 25% reduction in the number of required strands.

The results and observations from the analytical investigation were used in the assessment of the current prediction methods and the development of the simplified procedure.

Table 3. Comparison of procedure performance for elastic shortening loss estimations using estimated-to-measured ratio *E/M* from the evaluation database (36 specimens)

	Transformed section approach	Gross section approximation	Iterative gross section approach	Proposed
Minimum *E/M*	0.70	0.68	0.69	0.71
Average *E/M*	0.89	0.87	0.87	0.92
Maximum *E/M*	1.18	1.15	1.15	1.31
COV of *E/M*	0.14	0.14	0.14	0.15
Standard deviation of *E/M*	0.12	0.12	0.12	0.14
$0.8 \leq E/M < 1.0$	21	19	20	25
$0.6 \leq E/M < 0.8$	8	12	10	3
$E/M < 0.6$	0	0	0	0

Note: *COV* = coefficient of variation.

A complete description of the analytical investigation is beyond the scope of this paper and can be found elsewhere.[3,9]

Optimizing existing methods

As mentioned, the main objective of these research efforts was to develop a simple and precise method for estimating prestress loss. During the early stages of development, many different loss estimation procedures and concrete material behavioral models were considered. The concrete material models[13–15] typically have been developed and calibrated based on comprehensive creep and shrinkage databases primarily composed of standard concrete cylinder size samples (4 in. [100 mm] diameter and 8 in. [200 mm] length). The researchers found that these models did not adequately represent the observed behavior in full-scale prestressed beam specimens (when directly implemented). Further work was done by Gallardo[10] (and is ongoing) to investigate ways to use these detailed material-based models for the estimation of prestress loss in full-scale bridge girders.

The subsequent investigations were focused on methods currently (and previously) used for estimating the prestress loss in bridge design. Many of the previous loss estimation procedures[5,6,16] offer simple methods for estimating loss with large levels of conservatism. These methods were all considered and investigated during the development of the loss procedure proposed in this paper.

The work of Tadros et al. in NCHRP Report 496[1] was aimed at bridging the gap between the material-based models and the simple models developed solely for girder design. This effort resulted in a complex procedure that provides a relatively accurate estimate of prestress loss. This procedure was seen as a satisfactory starting point for optimizing the estimation procedure for prestress loss in prestressed members.

The focus of this section is the optimization of the procedure developed by Tadros et al.[1] and found in the 2012 AASHTO LRFD specifications. The experimental results gathered from the aforementioned efforts were used in the development of this approach for estimating prestress loss. The experimental program, involving the construction, monitoring, and testing of 30 full-scale girders, was used to investigate the influence of several variables thought to influence prestress loss development. The analytical program was used to evaluate the value of each individual parameter currently used in loss estimation with the objective of eliminating unnecessary complexity. The comprehensive experimental database was used to evaluate all of the prestress loss estimation procedures to assess their accuracy, conservatism, and precision.

The scope of this paper does not include an explanation of each of the different methods explored in this investigation, though a better knowledge of how each method should be used would aid in the understanding of the provisions developed in this paper). The authors recommend several other resources for this purpose.[3,6,8,17,18]

Performance of current prestress loss estimation procedures

Elastic shortening loss The performance of a variety of different prestress loss estimation procedures was investigated using the evaluation database (introduced previously). Because loss estimation is typically broken down into elastic shortening (or short-term loss) and long-term loss, the performance of elastic shortening loss estimation procedures was separated. **Table 3** shows the estimated versus measured elastic shortening loss for 36 specimens in the experimental database in which elastic shortening loss was reported. Table 3 shows the proposed method and the three currently used procedures for estimating elastic short-

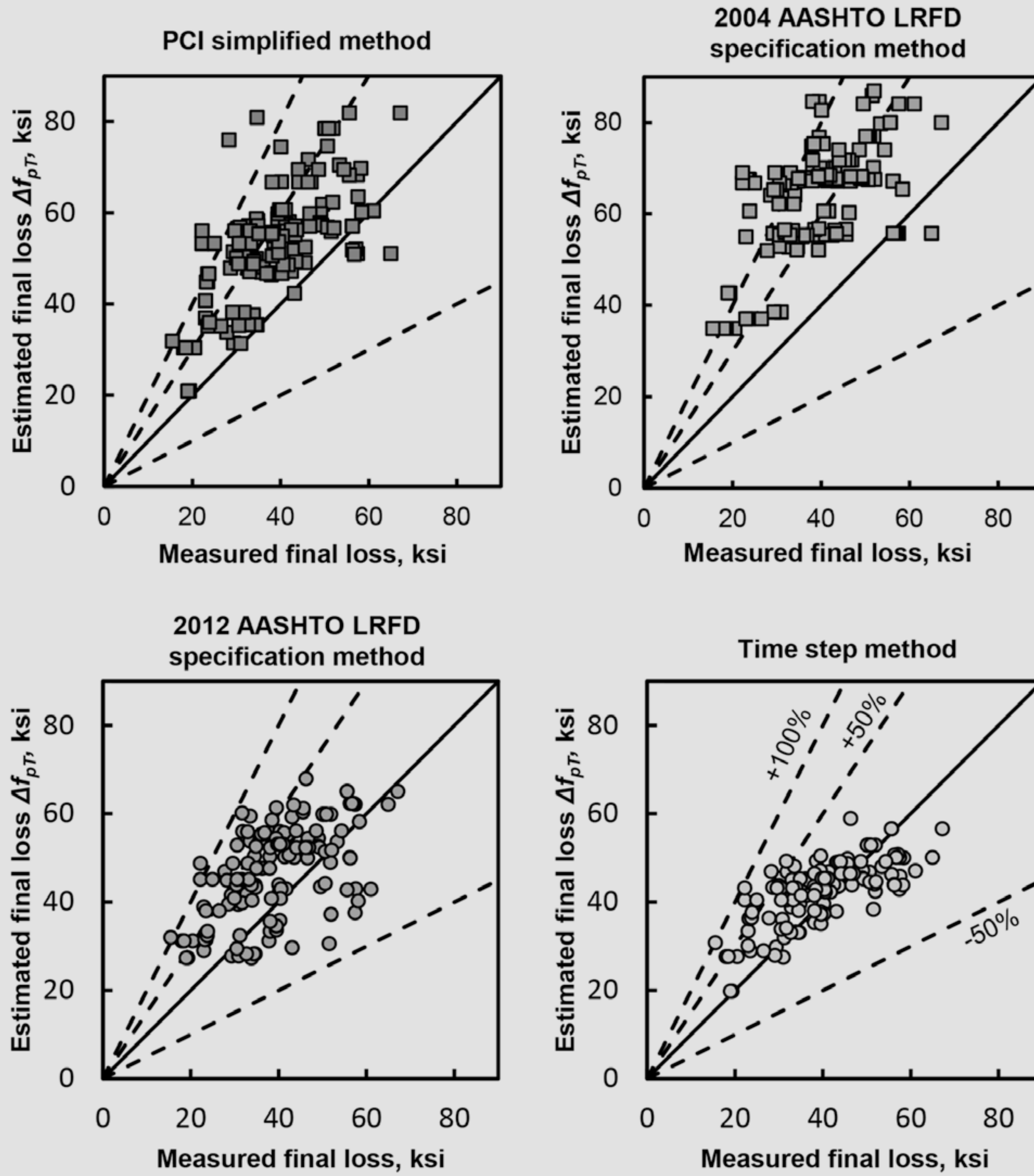

Figure 5. Estimated versus measured final prestress loss. Note: 1 ksi = 6.895 MPa.

ening loss: the transformed section approach, gross section approximation, and the iterative gross section approach. Although the three different methods vary significantly in complexity, all three of the methods performed similarly, with average estimated-to-measured ratios *E/M* of about 0.88 and coefficients of variation *COV* of 0.14. In a significant number of specimens (12 out of 36 specimens for the gross section approximation), the elastic shortening loss was underestimated by more than 20%. These observations were all factored in when the recommended elastic shortening loss estimation procedure was developed.

Final loss The performance of numerous prestress loss estimation procedures was also investigated using the final measured prestress loss gathered for the specimens in the evaluation database. **Figure 5** and **Table 4** show the *E/M* for two simplified procedures (PCI simplified[6] and 2004 AASHTO LRFD specifications) and two detailed procedures

Table 4. Comparison of procedure performance for final loss estimation using estimated-to-measured ratio *E/M* from the evaluation database (140 specimens)

	Simplified methods			Detailed methods		Proposed
	PCI simplified	2004 AASHTO LRFD specifications	Simplified 2012 AASHTO LRFD specifications	Refined 2012 AASHTO LRFD specifications	Time step	
Minimum *E/M*	0.79	0.89	0.73	0.59	0.74	0.84
Average *E/M*	1.42	1.74	1.15	1.25	1.13	1.32
Maximum *E/M*	2.69	3.69	2.12	2.20	1.99	2.31
COV of *E/M*	0.23	0.26	0.22	0.24	0.22	0.20
Standard deviation of *E/M*	0.32	0.45	0.25	0.30	0.24	0.27
$0.8 \le E/M < 1.0$	6	1	34	22	34	21
$0.6 \le E/M < 0.8$	1	0	8	7	8	0
$E/M < 0.6$	0	0	0	1	0	0

Note: *COV* = coefficient of variation

(refined AASHTO LRFD specifications[4] and a time step approach[18]). The PCI simplified and 2004 AASHTO LRFD specifications approaches offered the most conservative estimation of the final prestress loss. The other three approaches all performed similarly, with similar average *E/M*, *COV*, and number of unconservatively estimated loss values.

The simplicity of the various proposals was investigated by comparing the total variables and total number of mathematical operations required to estimate the final prestress loss for each of the procedures.

- The *PCI Design Manual* has approximately 40 operations and 14 variables.
- The 2004 AASHTO LRFD specifications has approximately 40 operations and 12 variables.
- The 2012 AASHTO LRFD specifications has approximately 600 operations and 70 variables.
- The proposed method has approximately 60 operations and 24 variables.

The 2004 AASHTO LRFD specifications procedure was designed to be both simple and conservative. The 2012 AASHTO LRFD specifications procedure was created with theoretical accuracy in mind, which is reflected in the greater magnitude of complexity.

Optimization process

The proposed prestress loss procedure was developed through the following optimization steps:

1. Dissociation of deck placement and long-term estimates
2. Consideration of typical construction details
3. Further simplifications (related to concrete release strength and elastic shortening)

Each of these optimization steps will be briefly discussed in this section.

Dissociation of deck placement and long-term estimates The first series of simplifications was made to simplify the loss estimation with relation to time. In the 2012 AASHTO LRFD specifications, there are three different components that introduce time dependency:

- the use of the stress loss caused by other prestress loss to determine the additional creep component
- a time development factor k_{td}
- including stress gain resulting from differential shrinkage between the deck and the girder

The creep after deck placement is calculated using two different stresses:

- stress developed from prestress losses before deck placement
- stress developed from sustained dead loads

This creep stress is then used to calculate the additional prestress loss due to creep that the girder will undergo from

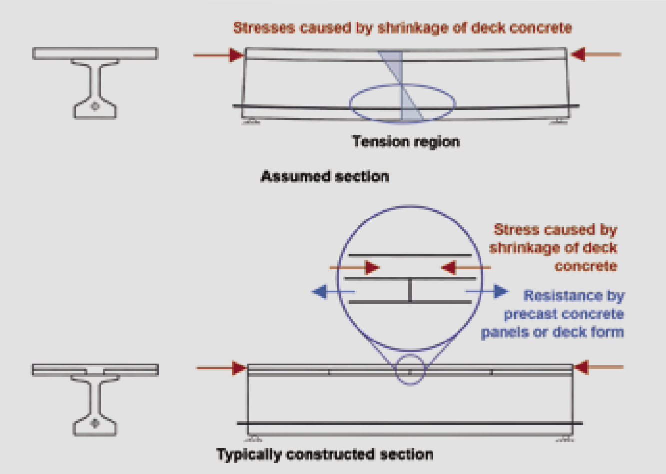

Figure 6. Stress introduced to system by differential shrinkage of deck concrete.

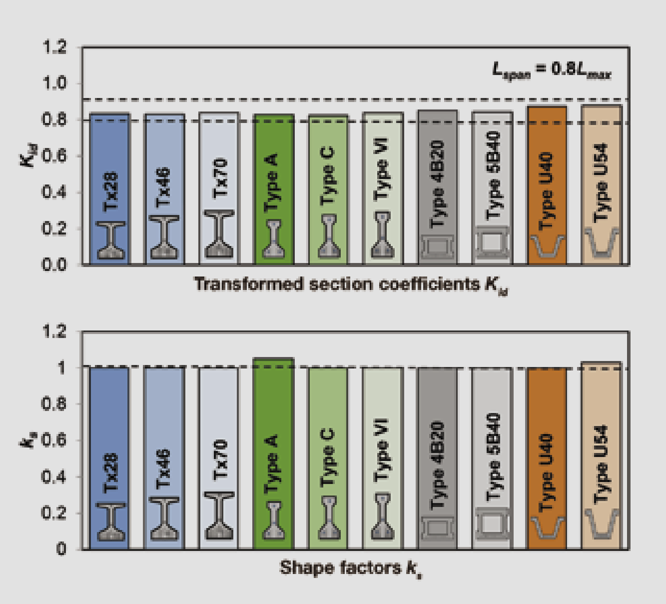

Figure 7. Typical values for transformed section coefficients K_{id} and shape factors k_s.

the time of deck placement until final time Δf_{pCD}. The stresses that develop as a result of the prestress loss before deck placement are minor compared with those developed from sustained dead load. This results in less than a 1 ksi (6.9 MPa) difference in the post-deck-placement creep-related prestress loss. Such a minor difference does not warrant the complexity that including the pre-deck-placement loss causes.

The 2012 AASHTO LRFD specifications account for the development of creep- and shrinkage-related prestress loss using a time development factor k_{td}. In typical design, the use of the time development factor simply divides the shrinkage- and creep-related prestress loss into before- and after-deck-placement components.

If the prestress loss at the time of deck placement is not needed, then using a time development factor of 1.0 is sufficient and will simplify the procedure. Using a time development factor of 1.0 would also be conservative for calculating the prestress loss at the time of deck placement. For more sensitive designs and situations in which the time development of prestress loss is required, this factor can be reintroduced. Time dependency is discussed further in a later section.

An additional stress gain is thought to develop as a result of differential shrinkage between the deck and the girder (**Fig. 6**). Extending the shear stirrups into the deck creates composite action between the deck and the girder. At the time of deck placement (typically up to 180 days after casting the girder), the girder usually has already undergone the majority of its shrinkage. The shrinkage of the deck concrete is then thought to cause the girder to go into positive bending, increasing the stress in the strand and the concrete around the strand (Fig. 6).

In most cases, partial-depth precast concrete deck panels or deck forms are used (Fig. 6). In these situations, the precast concrete panel will resist much of the deck shrinkage so there will be negligible effect on the girder. The differential shrinkage component was removed from the procedure because it does not accurately model the true behavior of the system and is only a minor contributor to the overall final estimated prestress loss.

By making these three simplifications, the creep-, shrinkage-, and relaxation-related prestress loss can be found in one step.

Consideration of typical construction details

The next three simplifications were made based on typical construction details found in bridge design. More than 1800 unique bridge designs were created using the 2012 AASHTO LRFD specifications (within the analytical investigation discussed previously) and by keeping track of all of the output variables. Two different variables introduced in the 2012 AASHTO LRFD specifications procedure were found to have minimal variation throughout the analytical investigation, the transformed section coefficient K_{id} and the shape factor k_s. **Figure 7** shows a small sample of these results. The transformed section coefficient was found to always fall between 0.8 and 0.9 for typical bridge configurations in which the prestress loss would affect design. The shape factor was found to nearly always be 1.0 (other than in a few situations where it was only up to 1.05). With these two observations in mind, the procedure was simplified by setting the transformed section coefficient to 0.9 (a conservative simplification) and setting the shape factor to 1.0.

The creep coefficient was further simplified by setting standard times for release (one day after initial casting) and deck placement (120 days after initial casting). These simplifications were both made with standard construction practices and conservatism in mind.

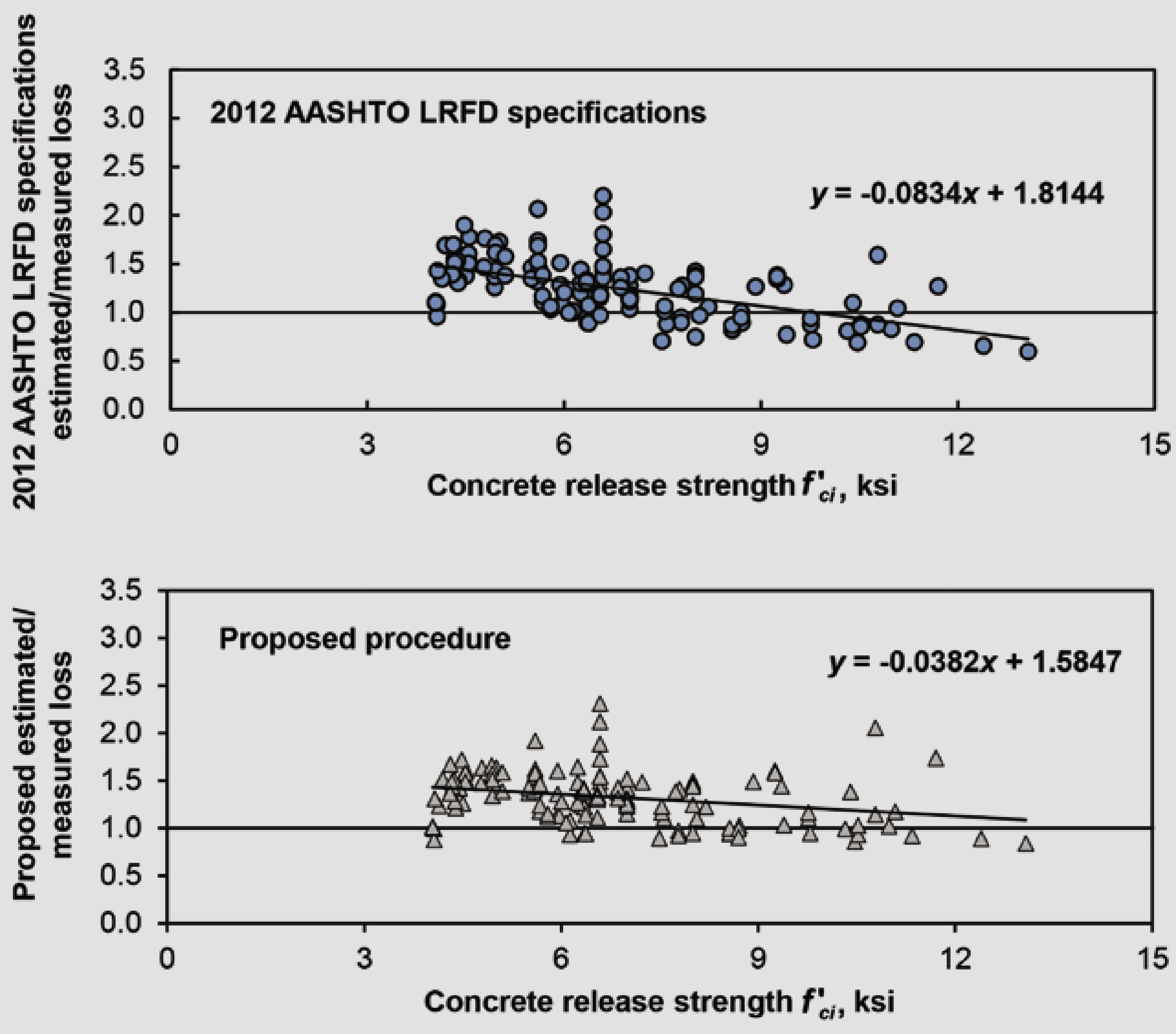

Figure 8. Concrete release strength versus estimated-to-measured prestress loss. Note: 1 ksi = 6.895 MPa.

Further simplifications The final two simplifications involved a recalibration of the procedure based on concrete release strengths and simplification of elastic shortening estimations.

The estimated-to-measured final prestress loss ratio using the refined AASHTO LRFD specifications procedure is plotted against the concrete release strength in **Fig. 8**. As the concrete release strength increases, the conservatism of the 2012 AASHTO LRFD specifications' prestress loss estimate decreases, as demonstrated by the line of best fit. Several other methods for accounting for concrete release strength effects on both creep and shrinkage were investigated. The concrete release strength coefficient that was previously located in the 2004 AASHTO LRFD specifications' article 5.4.2.3, Concrete Materials, was found to reasonably decrease the bias found in higher concrete release strengths (Fig. 8) in which the slope of the line of best fit is significantly closer to zero (a value representing no bias).

The final simplification of the loss estimation procedure involved modifying and clarifying the elastic shortening loss estimation. From the investigation of the elastic shortening procedures, there was little variation observed between the performances of each of the methods. For this reason, a gross-section approximation was chosen because it offered both conservatism and simplicity.

All of these optimization steps were undertaken to develop the proposed prestress loss estimation procedure described in the following section.

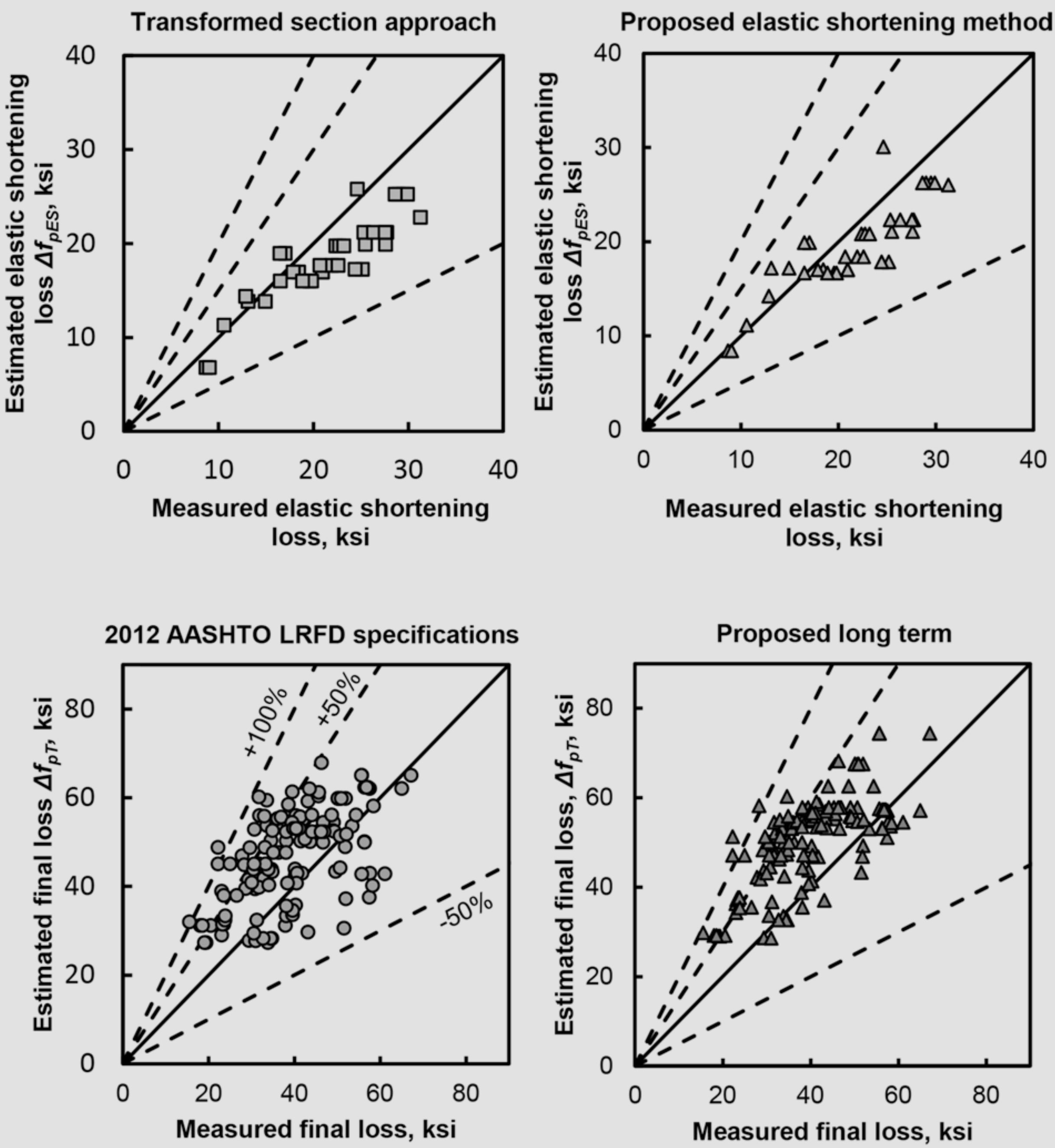

Figure 9. Estimated versus measured prestress loss using two different procedures for elastic shortening loss and two different procedures for long-term loss. Note: 1 ksi = 6.895 MPa.

Recommendations for the estimation of prestress loss

The proposed prestress loss procedure, which was developed on the basis of the experimental and analytical work and the simplification process discussed, is presented in the following sections. Recommendations are made for both the final and time-dependent prestress loss.

Final prestress loss

The final prestress loss can be found using Eq. (1) to (6). The procedure is self-contained (there is no need to jump between different sections of the specification), simple to use (variable inputs are unambiguous and minimal calculations are required), and both precise and appropriately conservative as will be discussed (**Fig. 9**) (Tables 3 and 4).

In the proposed procedure, the total prestress loss Δf_{pT} (Eq. [1]) is composed of four different components:

- elastic shortening Δf_{pES}, Eq. (2)
- loss due to concrete shrinkage Δf_{pSR}, Eq. (4)
- loss due to concrete creep Δf_{pCR}, Eq. (5)
- strand relaxation Δf_{pRE}, Eq. (6)

The elastic shortening loss requires the calculation of the stress in the concrete at the centroid of the prestressing strands f_{cgp} using the ultimate strength of the prestressing strands f_{pu}, the gross section properties of the section (area A_g, moment of inertia I_g, and eccentricity of the strands at midspan e_p), and the moment at midspan due to self-weight M_g.

Total prestress loss

$$\Delta f_{pT} = \Delta f_{pES} + \Delta f_{pSR} + \Delta f_{pCR} + \Delta f_{pR} \qquad (1)$$

Elastic shortening

$$\Delta f_{pES} = \frac{E_p}{E_{ci}} f_{cgp} \qquad (2)$$

where

E_{ci} = modulus of elasticity of concrete at time of release

E_p = modulus of elasticity for prestressing strands

$$f_{cgp} = 0.7 f_{pu} A_{ps}\left(\frac{1}{A_g} + \frac{e_p^2}{I_g}\right) - \frac{M_g e_p}{I_g} \qquad (3)$$

A_{ps} = total area of prestressing strands

Shrinkage loss

$$\Delta f_{pSR} = E_p\left(\frac{140-H}{4.8+f_{ci}'}\right)4.4\times10^{-5} \qquad (4)$$

H = ambient relative humidity, %

Creep loss

$$\Delta f_{pCR} = 0.1\left(\frac{1495-H}{4.8+f_{ci}'}\right)\left(\frac{E_p}{E_{ci}}\right)\left(f_{cgp} + 0.6\Delta f_{cd}\right) \qquad (5)$$

where

Δf_{cd} = change in concrete stress at centroid of prestressing strands due to long-term losses between transfer and deck placement combined with deck weight and superimposed loads

$$\Delta f_{cd} = \frac{M_{sd} e_p}{I_g} \qquad (6)$$

where

M_{sd} = moment at midspan of girder due to deck weight and superimposed loads

Relaxation loss

$$\Delta f_{pR} = \left(\frac{2 f_{pt}}{K_L}\right)\left(\frac{f_{pt}}{f_{py}} - 0.55\right) \qquad (7)$$

where

f_{pt} = stress in prestressing strands immediately after transfer (proposed to be taken as 0.7_{fpu})

f_{py} = yield strength of prestressing strand

K_L = strand type factor = 30 for low-relaxation strands and 7 for other prestressing steel

Figure 9 and Table 4 show the performance of the proposed prestress loss estimation procedure. The proposed procedure offers improved precision with the lowest coefficient of variation (0.20 for the proposed compared with 0.24 for 2012 AASHTO LRFD specifications and 0.23 for PCI simplified procedures). The proposed procedure also has the fewest specimens in which the prestress loss is underestimated by greater than 20% (zero for the proposed compared with seven for 2012 AASHTO LRFD specifications and one for the PCI simplified procedures) while retaining a similar average estimated-to-measured prestress loss ratio (1.32 for the proposed, 1.25 for 2012 AASHTO LRFD specifications, and 1.42 for PCI simplified procedures). The other noticeable advantage of the proposed procedure is its dramatic improvement in terms of simplicity. It requires about one-tenth the computational effort of the 2012 AASHTO LRFD specifications procedure (Table 6). The additional complexity is further highlighted in an example problem developed in Garber et al.[3] in which the proposed loss expression is compared directly with the 2012 AASHTO LRFD specifications' procedure.

The *E/M* value is plotted against the concrete release strength for all of the specimens in the database in Fig. 8. The use of the 2012 AASHTO LRFD specifications resulted in specimens with higher release strengths having lower levels of conservatism (slope of the line of best fit in Fig. 8). The use of the proposed procedure decreased this bias (slope of the line of best fit approaching zero in Fig. 8). Therefore, the proposed method offers a more uniform level of conservatism over a broad range of concrete compressive strengths.

All of these advantages point to the fact that the proposed prestress loss procedure is well suited for everyday designs. The increase in conservatism will ensure that prestressed girders perform well, exhibiting good durability and serviceability. The increased simplicity will allow

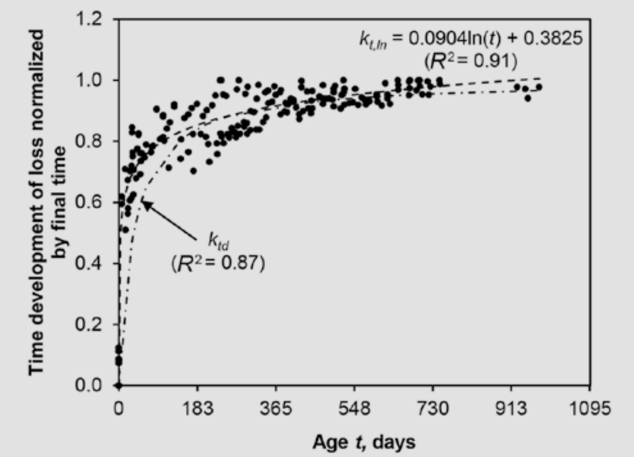

Figure 10. Time development of prestress loss measured during the experimental investigation. Note: k_{td} = time development factor (found in 2012 AASHTO LRFD specifications procedure); $k_{t,ln}$ = time factor based on logarithmic relationship; R^2 = correlation coefficient.

the design of prestressed girders to be more transparent. The improved calibration of the expressions with respect to the concrete release strength will ensure that increasing the release strength does not decrease the conservatism.

Time-dependent prestress loss

There is also value to being able to accurately estimate the development of prestress loss over time. A proposed approach for including the time development of prestress loss in the aforementioned final loss procedure will be introduced in this section.

The prestress loss was measured over time for the specimens of the experimental program previously discussed. All of these long-term prestress loss values (that is, total loss minus elastic shortening loss) were normalized by the final measured long-term prestress loss for each of the specimens (**Fig. 10**). The time development factor k_{td} (Eq. [7]), taken from the 2012 AASHTO LRFD specifications, is plotted with the measured prestress loss. Time effects in concrete (primarily creep) are typically thought to follow a natural logarithm behavior[13] (Eq. [8]), so a logarithmic regression was also plotted with the measured loss $k_{t,\ln}$.

Time development factor

$$k_{td} = \frac{t}{61 - 4f'_{ci} + t} \qquad (8)$$

t = age of concrete at time of interest

$$k_{t,\ln} = A \ln t + B \qquad (9)$$

where

A = constant

B = constant

Both expressions accounting for the time development of prestress loss k_{td} and $k_{t,\ln}$ reasonably estimate the development of prestress loss over time. The logarithmic model $k_{t,ln}$ would result in the prestress loss continuing to grow for its entire life. Alternatively, the time development factor k_{td} results in estimated losses leveling out after about two years. From the data points of this experimental program, the logarithmic regression appears to better represent earlier-age behavior (less than two years) and the time development factor appears to better model later ages (greater than two years). This observation would suggest that the continuous increase in prestress loss over the life of the girder represented by the logarithmic curve does not accurately reflect the actual development of prestress loss.

The time development factor k_{td} is recommended for general use because it is more generic and better estimates the long-term loss at times of interest for the designer (concrete ages greater than 180 days). This factor is used for prestress loss estimation by modifying the creep and shrinkage loss (Eq. [9] and Eq. [10]).

Time-dependent shrinkage

$$\Delta f_{pSR}(t) = k_{td}\left(\Delta f_{pSR}\right) \qquad (10)$$

where

$\Delta f_{pSR}(t)$ = prestress loss due to shrinkage of girder concrete between time of transfer and time of interest

Time-dependent creep

$$\Delta f_{pCR}(t) = k_{td}\left(\Delta f_{pCR}\right) \qquad (11)$$

where

$\Delta f_{pCR}(t)$ = prestress loss due to creep of girder concrete between time of transfer and time of interest

In situations where a more accurate early-age (less than 180 days) prestress loss estimate is needed, a logarithmic time factor can be used. The constants in Fig. 10 and Eq. (11) were calibrated based on the specimens of the experimental testing for this project (Fig. 1). These specimens represent a wide variety of concrete materials and exposure conditions (discussed previously and in Garber et al.[3,7]), so Eq. (11) can be used for standard designs and conditions.

Logarithmic time factor

$$k_{t,\ln} = 0.09 \ln t + 0.38 \qquad (12)$$

Conclusion and recommendations

The appropriate estimation of prestress loss is essential for the proper design of prestressed concrete members. An underestimated prestress loss may result in a prestressed girder prone to service-load-level cracking and durability concerns. Overestimated prestress loss may result in excessive cambers or the use of a greater amount of steel. A proper balance must be struck with accuracy, precision, and conservatism—a challenge because improved accuracy implies decreased conservatism. In addition, excessive complexity may be unnecessary (with the limited amount of knowledge at the time of initial design) and detrimental to the designer having a good understanding of the girder's behavior.

In the authors' opinion, additional complexity is warranted if a benefit from it can be derived in terms of accuracy and/or precision. The 2012 AASHTO LRFD specifications do not offer additional precision over the procedure proposed in this paper and is 10 times more computationally intensive. Approximately 600 mathematical operations are required for the AASHTO LRFD specifications' prestress loss procedure compared with the 60 operations required for the proposed procedure. This additional computational expense does not improve the *COV* or the standard deviation in relation to the proposed procedure when considering the behavior of the 140 specimens included in the prestress loss database.

On the basis of improved accuracy, reduced scatter, and increased computational efficiency, the proposed prestress loss calculation procedure put forth in this paper is viewed to be consistent with the spirit with which the AASHTO LRFD specifications were originally calibrated. The 7% increased bias for the proposed procedure (in other words, the average *E/M* value of 1.32 compared with 1.25) may be viewed as a slight disadvantage in relation to the refined AASHTO LRFD specifications procedure. That said, this slight disadvantage can be put into context by recognizing that the proposed procedure eliminates all of the grossly underpredicted data points (those with *E/M* values between 0.6 and 0.8 and those that are less than 0.6, as shown in Table 4).

Finally, for situations in which the development of prestress loss over time is needed, a simple time development factor can be used (supplementing the proposed loss procedure), as illustrated in this paper.

Note to readers

Additional information is available online in an appendix.

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The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of TxDOT.

References

1. Tadros, M. K. 2003. *Prestress Losses in Pretensioned High-Strength Concrete Bridge Girders*. NCHRP Report 496. Washington, DC: Transportation Research Board.

2. AASHTO (American Association of State Highway and Transportation Officials). 2005. *AASHTO LRFD Bridge Design Specifications, 3rd Edition—2005 Interim Revisions*. 3rd ed. Washington, DC: AASHTO.

3. Garber, D., J. Gallardo, D. Deschenes, D. Dunkman, and O. Bayrak. 2012. *Effect of New Prestress Loss Estimates on Pretensioned Concrete Bridge Girder Design*. Austin, TX: Texas Department of Transportation.

4. AASHTO. 2012. *AASHTO LRFD Bridge Design Specifications*. 6th ed. Washington, DC: AASHTO.

5. AASHTO. 2004. *AASHTO LRFD Bridge Design Specifications*. 3rd ed. Washington, DC: AASHTO.

6. PCI Industry Handbook Committee. 2010. *PCI Design Handbook: Precast and Prestressed Concrete*. MNL-120. 7th ed. Chicago, IL: PCI.

7. Garber, D., J. Gallardo, D. Deschenes, and O. Bayrak. 2015. "Experimental Investigation of Prestress Losses in Full-Scale Bridge Girders." *ACI Structural Journal* 112 (5): 553–564.

8. Garber, D., J. Gallardo, D. Deschenes, and O. Bayrak. 2016. "Prestress Loss Database for Pretensioned

Concrete Members." *ACI Structural Journal* 113 (2): 313–324.

9. Garber, D. 2014. "Effect of New Prestress Loss Estimation Procedure on Precast, Pretensioned Bridge Girders." PhD diss., University of Texas at Austin.

10. Gallardo, J. 2014. "Model of Strain-Related Prestress Losses in Pretensioned Simply Supported Bridge Girders." PhD diss., University of Texas at Austin.

11. Texas Department of Transportation. Accessed [date]. "Bridge Standards." http://www.txdot.gov/insdtdot/orgchart/cmd/cserve/standard/bridge-e.htm.

12. Birrcher, D. B., O. Bayrak, and M. E. Kreger. 2010. "Effects of Increasing Allowable Compressive Stress at Prestress Transfer." *ACI Structural Journal* 107 (1): 21–31.

13. Bazant, Z. P., and S. Baweja. 2000. "Creep and Shrinkage Prediction Model for Analysis and Design of Concrete Structures: Model B3." In *The Adam Neville Symposium: Creep and Shrinkage—Structural Design Effects*, SP194, pp. 1–84. Farmington Hills, MI: ACI (American Concrete Institute).

14. Wendner, R., M. Hubler, and Z. Bazant. 2013. "The B4 Model for Multi-decade Creep and Shrinkage Prediction." Paper presented at CONCREEP-9, Massachusetts Institute of Technology, Cambridge, MA.

15. ACI Committee 209. 2008. *Guide for Modeling and Calculating Shrinkage and Creep in Hardened Concrete*. ACI 209.2R-08. Farmington Hills, MI: ACI.

16. ACI–ASCE Joint Committee 323. 1958. *Tentative Recommendations for Prestressed Concrete*. Chicago, IL: Portland Cement Association.

17. Swartz, B. D., A. Scanlon, and A. J. Schokker. 2012. "AASHTO LRFD Bridge Design Specifications Provisions for Loss of Prestress." *PCI Journal* 57 (4): 108–132.

18. ACI Committee 423. 2014. *Guide to Estimating Prestress Loss*. Farmington Hills, MI: ACI.

Notation

A_g = area of gross concrete section

A_{ps} = total area of prestressing strands

COV = coefficient of variation

e_p = eccentricity prestressing strands at girder midspan of gross concrete section

E_{ci} = modulus of elasticity of concrete at time of release

E_p = modulus of elasticity for prestressing strands

E/M = estimated-to-measured loss ratio

f_c' = specified or measured ultimate strength of concrete

$f_{c,bottom}$ = initial bottom fiber stress of concrete member

f_{cgp} = stress in concrete at the centroid of the prestressing strands

f_{ci}' = concrete strength at release of prestress

f_{pi} = initial stress in prestressing steel

f_{pj} = stress in prestressing steel at jacking

f_{pt} = stress in prestressing strands immediately after transfer (proposed to be taken as $0.7f_{pu}$)

f_{pu} = ultimate strength of prestressing strands

f_{py} = yield strength of prestressing strand

h = section or specimen height

H = ambient relative humidity, %

I_g = moment of inertia of gross section

k_f = factor for the effect of concrete strength

k_s = shape factor (accounting for the effect of the volume-to-surface ratio of the component)

k_{td} = time development factor (found in 2012 AASHTO LRFD specifications procedure)

$k_{t,ln}$ = time factor based on logarithmic relationship

K_1 = correction factor for source aggregate (taken as 1.0 unless determined by physical tests)

K_{id} = transformed section coefficient (accounting for time-dependent interaction between concrete and bonded steel)

K_L = strand type factor = 30 for low relaxation strands and 7 for other prestressing steel, unless more accurate manufacturer's data are available

L_{beam} = total girder length

L_{max} = maximum length achievable using a specific section type and strand layout

L_{span} = total distance from center to center of supports

M_g = moment at midspan of girder due to self-weight

M_{sd} = moment at midspan of girder due to deck weight and superimposed loads

n = number of strands

N_{total} = total number of specimens

R^2 = correlation coefficient

RH = relative humidity

t = age of concrete at time of interest

t_d = age of concrete at time of deck placement

t_f = age of concrete at final time considered

t_i = age of concrete at time of release for pretensioned construction or age of concrete at time of load application

Δf_{cd} = change in concrete stress at centroid of prestressing strands due to long-term losses between transfer and deck placement combined with deck weight and superimposed loads

$\Delta f_{cd,DL}$ = change in concrete stress at centroid of prestressing strands due to deck weight and superimposed loads

$\Delta_{fcd,\Delta P}$ = change in concrete stress at centroid of prestressing strands due to long-term losses between transfer and deck placement

Δf_p = prestress loss

Δf_{pCD} = prestress loss due to creep of girder concrete between time of deck placement and final time

Δf_{pCR} = prestress loss due to creep of girder concrete (for 2012 AASHTO LRFD specifications taken as loss due to creep between time of transfer and time of deck placement)

$\Delta f_{pCR}(t)$ = prestress loss due to creep of girder concrete between time of transfer and time of interest

Δf_{pES} = prestress loss due to elastic shortening

Δf_{pLT} = long-term prestress loss

Δf_{pR} = prestress loss due to relaxation of prestressing strand

Δf_{pSR} = prestress loss due to shrinkage of the girder concrete

$\Delta f_{pSR}(t)$ = prestress loss due to shrinkage of girder concrete between time of transfer and time of interest

Δf_{pSS} = stress gain in prestressing strands due to shrinkage of deck in composite section

Δf_{pT} = total prestress loss

$\Delta_{strands}$ = difference in strands between two different designs (compared with 2004 AASHTO LRFD in most instances of this paper)

ε_{bdf} = shrinkage strain of girder concrete between time of deck placement and final time

ε_{bid} = shrinkage strain of girder concrete between time of transfer and time of deck placement

ε_{bif} = shrinkage strain of girder concrete between time of transfer and final time

ψ_{bdf} = girder creep coefficient at final time due to loading at deck placement

ψ_{bid} = girder creep coefficient at time of deck placement due to loading introduced at transfer

ψ_{bif} = girder creep coefficient at final time due to loading introduced at transfer

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Abstract

The estimation of prestress loss is required for design and analysis of prestressed concrete bridges and buildings. A proper balance must be struck between accuracy, precision, and conservatism for prestress loss estimation in order to safely and efficiently design prestressed concrete members. An extensive research project was undertaken in which 30 full-scale bridge girders with a variety of applicable design parameters were instrumented, constructed, monitored, and tested; a comprehensive experimental database containing data from 140 full-scale bridge girders was assembled; and an extensive analytical program was conducted to investigate the sensitivity of current estimation methods and implications of loss estimation on final designs. Through the work of this project, a prestress loss estimation procedure was developed that is simple to use, precise, and offers an appropriate level of conservatism. This procedure can be used for both time-dependent and final prestress loss estimation.

Keywords

Bridge, experimental database, full-scale testing, girder, prestress loss, prestress loss estimation.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

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