STATISTICAL ANALYSIS OF PRESTRESS LOSSES FOR TWO HPC GIRDERS

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ABSTACT

Prestress losses are an inherent characteristic of prestressing concrete members. The concrete material property models which include modulus of elasticity (MOE), and creep and shrinkage time functions used in current prestress loss methods typically address normal strength concrete (NSC). There are very limited data in current literature of calibrating the adequacy of these methods for high performance concrete (HPC) girders. In this paper, a time-step (T-S) procedure was applied to estimate losses at different times of interest for two long-span HPC prestressed I-girders exceeding 11,000 psi. Monte Carlo Simulation was used to investigate the variances of the predicted and the measured losses due to the measurement randomness in inputs. Four cases of different predictions of losses using measured properties and different material models were compared with the measured losses from actual test data.

Keywords: Prestress Loss, HPC Girder, Time-Step Method, Concrete Modulus of Elasticity, Concrete Creep, Concrete Shrinkage, Variances, and Monte Carlo Simulation.

INTRODUCTION

Prestress loss estimation is an important step in the design process of a pre-tensioned or post-tensioned concrete member to determine expected deflections and cracking moments. Numerous methods and design recommendations have been proposed to estimate prestress loss. For a pre-tensioned concrete member, prestress losses are due to a complex interaction between elastic shortening, concrete creep, concrete shrinkage and steel relaxation.

Most of prestress loss estimation methods use simple empirical equations to account for the separate contribution of each source, and are known as lump sum methods. Methods in this category, including AASHTO LRFD[1], AASHTO 16th ed. Standard Specifications[2], PCI Committee on Prestress Losses – Simplified Method[3] and the PCI Design Handbook[4], predict prestress loss at the end, and not at specified times of service life. The time-dependencies of concrete properties, such as concrete compressive strength gain with time, concrete modulus of elasticity (MOE), creep and shrinkage growth, are only generalized.

Another category of prestress loss estimation methods is the time-step approach, which includes PCI Committee on Prestress Losses – General Method[3], and a time-step method[5]. These two methods are characterized by time interval steps that are used to calculate prestress loss cumulatively. However, only the time-step method takes into account some of the time-dependencies of concrete by using creep and shrinkage time functions. In addition, the time function is used for the loss component due to steel relaxation. Because of the time functions used in this procedure for the three long-term losses due to creep, shrinkage and steel relaxation, the total losses can be calculated at any time of interest.

In most cases, the ACI 209 creep and shrinkage time functions are used in the time-step method[6], though the method has the potential to apply other creep and shrinkage models into its procedure, such as the CEB-FIB model[7] and models developed by Bažant and Panula[8]. The time-dependencies of concrete compressive strength and modulus of elasticity (MOE) are usually regarded as having slight effect on loss generation. A bi-linear model comprising two point estimates is usually applied for both compressive strength and MOE ($f'_{ci}, f'_{c-28day}, E_{ci}$, and $E_{c-28day}$) to simplify the time-step procedure. Because the time-step procedure has the flexibility of applying different creep and shrinkage models, and because it has been viewed as a more accurate method for predicating losses to date, the time-step procedure has been used here to study the prestress losses for two HPC girders. The *T-S procedure* used herein specifically refers to the method proposed by Naaman[5] in conjunction with several time-dependent material models.

The past decade has noted that high-performance concrete (HPC) prestressed bridge girders showed a great deal of advantages both economically and environmentally. However, the prestress loss prediction methods in current codes have not followed this development, which typically address normal strength concrete (NSC) prestressed girders. The adequacies of these methods need to be calibrated for HPC prestressed girders, including the comparisons between measured losses and predictions. Naaman and Siriaksorn[9] reported that the T-S procedure can be used for concrete prestressed girders with strength up to 10 ksi (68.9 MPa) through a comprehensive parametric study, in which ACI 209[6] concrete material models were used including MOE, creep and shrinkage time functions, and the corresponding correction factors. As mentioned earlier, the T-S procedure is able to generate prestress losses at any time of interest. This allows for a possibility to verify the T-S procedure and its associated material models for HPC girders by comparing the predictions with the measured losses at different age of girders.

LONG-SPAN HPC GIRDERS

For comparison to predicted losses, measured losses from two 45M Mn/DOT composite prestressed bridge test girders with spans of 132.75 ft (40.5 m) and nominal compressive strengths exceeding 11 ksi (75.8 MPa) were used[10]. The span-to-depth ratio for both girders was 35.4, an increase of nearly 50 percent over conventional designs. A 9 in (229 mm) composite deck with a 28-day compressive strength of 4 ksi (27.6 MPa) was designed according to Mn/DOT standard specifications for bridge girders (Figure 1).

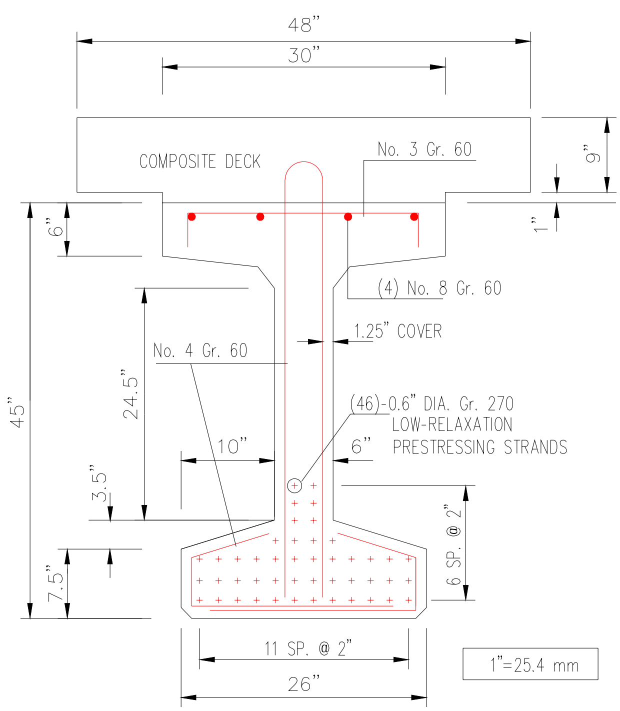

Figure 1: Test Girder Cross Section at Mid-span.

For the high strength mixes, Girder I used a limestone coarse aggregate and Girder II used glacial gravel with microsilica, though both used Type III cement, the same fine aggregate and superplasticizer. Resulting water-to-cementitious material ratios were 0.32 and 0.36 for Girder I and Girder II, respectively. Each girder was reinforced with forty-six 0.6 in (15.3 mm) Gr. 270 low-relaxation prestressing strands longitudinally and No. 4 Gr. 60 mild steel transversely. Harp points were located 40 percent of the overall length from each end.

The two girders were built in the summer of 1993 and monitored for stress changes and load responses until ultimate flexural testing in 1996. Test data including the measurements of material properties and the readings from the embedded strain gages were well documented. For the losses comparison study presented herein, the measured values of parameters required by the T-S procedure for both girders are tabulated in Table 1. Because of the existence of random errors due to measurements and to investigate the statistics of the predicted and measured losses, the data for the properties are expressed by their mean values and standard deviations based on the measured data and some simple assumptions (for the geometric properties). The probability distributions for all parameters are assumed to be Normal except for the parameters used as constants.

Table 1: Statistics of All Parameters for Girder I and Girder II.

Parameters	Girder I		Girder II		Source and Note
	Mean	Cov.	Mean	Cov	
Initial MOE (E_{ci})	4380 ksi	0.02	4750 ksi	0.02	Test data Ahlborn [11]
MOE at 28-day ($E_{c-28day}$)	4810 ksi	0.02	4800 ksi	0.02	
Ult. creep coeff. (best-fit) (C_u)	2.4	0.03	2.89	0.02	The measured data from cylinder specimens and coefficients from nonlinear regression.
Ult. shrinkage (best-fit) ($\varepsilon_{sh,u}$)	226	0.11	202	0.13	
Moment of Inertia (I_c)	163400 in^4	0.003	Same as Girder I		Assuming the precision of measurement for dimensions is 0.001in
Girder Section Area (A_c)	613 in^2	0.001			
Section Perimeter (P_c)	180 in	0.001			
Strands Eccentricity (e_c)	17.28 in	0.003			
Jacking stress (f_{pj})	191.6 ksi	0.03			Test data Ahlborn[11]
MOE of Strands (E_{ps})	29100 ksi	0.008			
Yielding Strength (f_y)	239 ksi	0.01			
Area of Strands (A_{ps})	10.5 in^2				Constant
Time at transfer (t_t)	96.50 hour				Constant; From jacking;
Age at loading (t_a)	1 day				Constant; From concrete casting
Span (L_n)	132.75 ft				Constant

MATERIAL MODELS INVOLVED IN T-S PROCEDURE

In general, the mechanical behaviors of concrete in most specifications and literature include compressive strength age function, the stress-strain relationship, MOE model, tensile splitting strength model, modulus of rupture model, and creep and shrinkage time functions. For the T-S procedure, the MOE model, which usually is expressed as a function of the compressive strength and the unit weight of concrete, and the creep and shrinkage time functions are included into its structure. This paper particularly focuses on the impact that these three material models have on prestress losses.

MODULUS OF ELASITICITY

ACI Building Code 318-02[12] reports that for normal weight concrete, the MOE can be defined as:

$$E_c = 33 w_c^{1.5} \sqrt{f_c^{'}} \quad (1)$$

where w_c is the unit weight of concrete and $f_c^{'}$, the concrete compressive strength, corresponds to the calculated E_c at the same age.

For HPC with higher compressive strengths, ACI Committee 363[13] recommends the following equation.

$$E_c = \left[40,000\sqrt{f_c^{'}} + 1.0\times10^6\right]\left(\frac{w_c}{145}\right)^{1.5} \quad (2)$$

In the T-S procedure, there are two MOEs, the initial MOE at release, denoted as E_{ci}, and the 28-day MOE, denoted $E_{c-28day}$. As expressed in Eq. 1 and 2, the predictions for MOE include the measured unit weight values and the corresponding compressive strength values. In this study, the measured mean values of MOE as well as the measured compressive strengths and unit weights are listed in Table 2, in which the predicted MOEs using Eq. (1) and (2) are given respectively to compare with the measured MOE values.

Table 2: The Measured and Predicted Mean Values of MOE.

Property	Age	Girder I	Girder II
Unit weight (measured)	w_c (Constant)	152 pcf	153 pcf
Compressive strength (measured)	At release ($f_{ci}^{'}$)	9300 psi	10400 psi
	At 28-day ($f_{c-28day}^{'}$)	12100 psi	11100 psi
MOE (measured)	At release (E_{ci})	4380 ksi	4750 ksi
	At 28-day ($E_{c-28day}$)	4810 ksi	4800 ksi
MOE (ACI 318[12] prediction)	At release (E_{ci})	6140 ksi	6500 ksi
	At 28-day ($E_{c-28day}$)	7000 ksi	6710 ksi
MOE (ACI 363[13] prediction)	At release (E_{ci})	5370 ksi	5610 ksi
	At 28-day ($E_{c-28day}$)	5970 ksi	5760 ksi

CREEP AND SHRINKAGE MODELS

The time-dependent creep and shrinkage growth directly impact prestress losses. They are generally expressed in the following forms for the creep and shrinkage at any time in standard conditions,

$$C_t = \frac{t^\beta}{\alpha + t^\beta} C_u \quad (3)$$

$$\varepsilon_{sh,t} = \frac{t}{\alpha + t}\varepsilon_{sh,u} \quad (4)$$

where α and β are constants for a given shape and size which define the time-ratio part, C_u is the ultimate creep coefficient, $\varepsilon_{sh,u}$ is the ultimate shrinkage strain, and t is the time after loading in Eq. (3) and the time from the end of the initial curing in Eq. (4). Values of

α, β, C_u and $\varepsilon_{sh,u}$ can be determined by fitting the data from specimens cured and loaded in standard conditions.

Ahlborn[11] used a nonlinear regression method to fit the creep and time functions using the basic forms of Eq. (3) and (4). The measured creep and shrinkage data were obtained from the 6×12 in (150×300 *mm*) cylinder specimens cast from the girder concrete, and cured and housed in the same environment as the two girders. The resulting constant parameters are summarized in Table 3. To account for the randomness of the measured creep and shrinkage, the parameters C_u and $\varepsilon_{sh,u}$ were assigned different level of variances shown in Table 1, which were calculated from the difference between the fitted predictions and the measured data. These 'best-fit' parameters were specifically proposed for the Girder I and Girder II in the original research and not as general expressions for HPC.

Table 3: Basic Parameters for Creep and Shrinkage Time Functions

Models		Creep			Shrinkage	
		α	β	Cu	α	$\varepsilon_{sh,u}$
Girder I	Best-Fit[11]	17.3	0.38	2.40	375	226
	ACI 209[6]	10.0	0.60	1.12	55	400
	Mokhtarzadeh[15]	10.47	0.40	2.28	65	530
Girder II	Best-Fit	18.5	0.39	2.89	147	202
	ACI 209	10.0	0.60	1.34	55	400
	Mokhtarzadeh	7.87	0.56	2.56	65	530

To study the significance of the creep and shrinkage models on the predicted losses using the T-S procedure, two additional categories of constant parameters for Eq. (3) and (4) were also considered. The first category was characterized by the parameters in the time-ratio parts that were recommended by ACI Committee 209[6]. The ultimate creep coefficients were obtained by interpolation using the creep coefficient for varying concrete strength recommended by Nilson[14] and the ultimate shrinkage strain was taken as $400\mu\varepsilon$ for both girders[9]. All these parameters are listed in Table 3. While the ACI 209 recommended parameters in the time-ratio parts were originally developed for NSC, Naaman had used these parameters to calculate prestress losses for concrete prestressed girders up to 10 ksi (68.9 MPa) with the consideration of correction factors[9].

For HPC with compressive strengths greater than 7000 psi (48.3 MPa), many researchers have analyzed data to fit the given Eq. (3) and (4) to describe the creep and shrinkage. Mokhtarzadeh[15] conducted a companion study to Ahlborn's girder tests[11] to consider the creep and shrinkage behavior of high strength concrete mixes of different aggregate combinations ranging from 7 ksi (48.3 MPa) to 15 ksi (103.4 MPa). The standard conditions for the specimens were relative humidity 50%, and steam-cured specimens loaded to 60% of one-day strength at one day. The resulting parameters listed in Table 3 correspond to a limestone mix similar to Girder I and rounded gravel with silica fume mix similar to Girder II.

The fitted parameters in Eq. (3) and (4) were developed based on test data from the cylinder specimens in ‘standard conditions’. If the information is to be used for a real prestressed concrete girder, a series of multiplicative correction factors must be applied. In general, they are expressed as:

$$C^{cr}{}_{t} = \frac{t^{\beta}}{\alpha + t^{\beta}} C_u K_{CH} K_{CA} K_{CS} \tag{5}$$

$$\varepsilon^{cr}{}_{sh,t} = \frac{t}{\alpha + t} \varepsilon_{sh,u} K_{SH} K_{SS} \tag{6}$$

where the factors are used to account for the deviations from non-standard conditions, including relatively humidity factors (K_{CH}, K_{SH}), shape and size factors (K_{CS}, K_{SS}), and age at loading factor for creep (K_{CA}). In addition, the superscript *cr* denotes the corrected creep and shrinkage functions.

Correction factors must be applied if the girders are in non-standard conditions relative to the test cylinders. Because the standard conditions for Mokhtarzadeh’s parameters for relative humidity and age of loading were same as the test cylinders for Girder I and Girder II, the factors of K_{CH}, K_{SH} and K_{CA} can be set at 1.0. However for the ACI 209 recommended parameters whose standard conditions can be found in reference 6, these factors must be incorporated. In this study, the computed factors were based on the relationships from Naaman[5]. The resulting correction factors and respective relationships are summarized in Table 4.

Table 4: Correction Factors of Creep and Shrinkage Estimations for Girders

	Girder I and Girder II	Equations[5]
ACI 209[6]	$K_{CH} = 0.935, K_{CA} = 1.130, K_{CS} = 0.834$	$K_{CH} = 1.27 - 0.0067 \cdot RH$ $K_{CA} = 1.25 t_a^{-0.118}$
	$K_{SH} = 0.900, K_{SS} = 0.834$	
Mokhtarzadeh[15] and the Best-Fit[11]	$K_{CH} = 1.0, K_{CA} = 1.0, K_{CS} = 0.834$	$K_{CS} = K_{SS} = 1.14 - 0.09 \frac{A_c}{P_c}$
	$K_{SH} = 1.0, K_{SS} = 0.834$	$K_{SH} = 1.4 - 0.01 \cdot RH$

Figures 2 and 3 illustrate the measured creep and shrinkage data from the cylinder specimens over time, and the predictions using Eq. (5) and (6) with three different categories of parameters accounting for the necessary corrections.

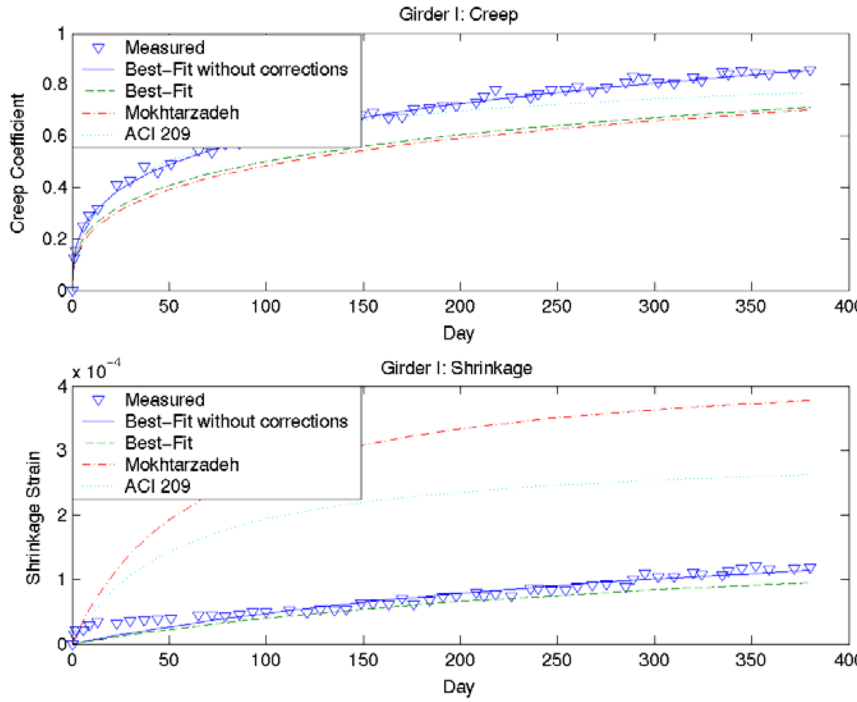

Figure 2: Measured Creep and Shrinkage Predictions for Girder I

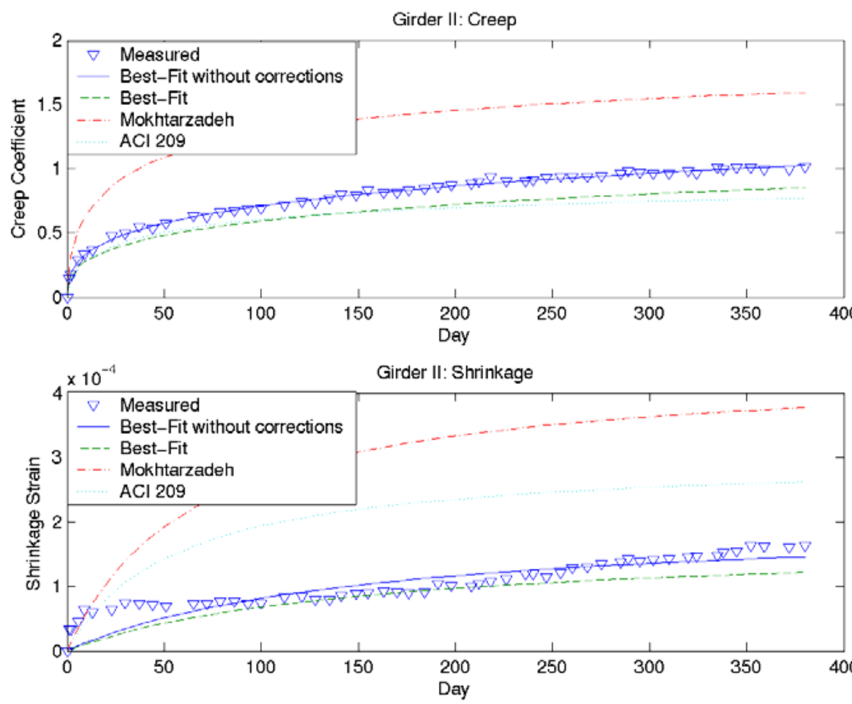

Figure 3: Measured Creep and Shrinkage Predictions for Girder II

MEASURED AND PREDICTED LOSSES

The two HPC girders were instrumented with vibrating wire gages to determine concrete strains at the girder mid-span. Strains were measured at several times, including (but not all inclusive) immediately after transfer, 28 days, before deck casting, prior to cracking testing and finally prior to ultimate flexural testing. The deterministic 'measured' prestress losses were then computed using the measured strains and fundamental mechanics with the average values of material and geometric properties[11].

To predict prestress losses using the T-S procedure, a computer program was implemented. The program outputs prestress loss at any specified time from the time of release to the end of service, i.e., the total prestress losses and its four components can be plotted over time continuously. Theoretically, the accuracy of prediction can be improved by increasing the number of time steps and optimizing the scheme of time steps. A scheme of time steps—sixty steps spanning 50 years—was used, which had been shown to have the sufficient computational efficiency and convergence rate[16]. By using the average values of the measured material and geometric properties and the corrected best-fit creep and shrinkage parameters, the deterministic predicted prestress losses at any time of interest for each girder were generated by the computer program.

All input parameters for computing losses have inherent variances due to the randomness in measurement, which leads to the propagated variances for both the measured and predicted losses. According to the first-order approximation theory, the deterministic measured and predicted prestress losses above can be numerically viewed as the estimates of the corresponding mean losses, therefore the deterministic measured and predicted losses share the same columns as the mean values of the corresponding losses in Table 5. All losses are displayed in percent and referenced to initial jacking stresses.

Table 5: Statistics of Measured and Predicted Losses for Girder I and Girder II.

Age (day)	Design Case Losses^{+}	Measured Losses				Predicted Losses			
		Girder I		Girder II		Girder I		Girder II	
		Mean^{++}	Std.$^{+++}$	Mean	Std.	Mean	Std.	Mean	Std.
Initial at release (1day)	11.2%	15.5%	2.8%	18.6%	2.7%	15.3%	0.8%	14.3%	0.7%
28-day	22.9%	21.6%	2.4%	22.2%	2.4%	19.3%	1.1%	18.9%	1.0%
Deck Casting (201day)	33.2%	23.9%	2.4%	23.3%	2.4%	22.6%	1.3%	22.9%	1.3%
Cracking Testing (378/690day)	35.9%	26.6%	2.3%	25.8%	2.3%	23.9%	1.4%	25.6%	1.4%
Ultimate Flexure Test (860day)	36.4%	27.2%	2.3%	26.3%	2.3%	25.6%	1.5%	26.0%	1.5%
End of service (50years)	38.1%	—	—	—	—	30.0%	1.8%	30.5%	1.8%

$^{+}$ Design Case Losses were predicted based on nominal design properties with the time-step method[11].
$^{++}$ The 'Mean' represents both the deterministic and the mean of predicted and measured losses.
$^{+++}$ Std. = Standard Deviation.

Also included in Table 5 are losses predicted from nominal design properties. The differences between these design expectations and measured or predicted losses using actual material properties have been shown by others to be relevant, especially in HPC girders. The poor estimates from the design case losses stated here only reiterate the need for designers to understand the material behavior if accurate predictions of losses are expected. Furthermore, accurately predicting losses leads to more accurate estimates of deflections and stresses under service conditions[10].

To investigate the propagated variances of the measured and predicted losses, Monte Carlo Simulation method was chosen because of the structural complexity of the T-S procedure and the calculation formulas of measured losses. A parametric statistics study had been conducted for all parameters using the required information as summarized in Table 1. It is noted that some parameters were used as constants because the variances of some parameters have a very small contribution to the variance of output according to an uncertainty importance study conducted by Chen for the T-S procedure[16]. Latin Hypercube sampling was applied so that the sampling size was taken as low as 1000. Using the mean and standard deviation of each normally distributed parameter, a set of samples was simulated for each parameter listed in Table 1. The computer program of the T-S procedure was called 1000 times for Girder I and Girder II, respectively, to solve predicted losses for both girders. The continuous means and standard deviations of predicted losses over time were determined for each girder. A similar process was also performed on the procedure of measured prestress losses, in which the statistics of the involved parameters were taken from Table 1 and the measured average strains were used as constants. The standard deviations of predicted and measured losses at times of interest are tabulated in Table 5. Figures 4 and 5 illustrate the predicted means and standard deviations of losses over time. The deterministic predicted losses over time and the distributions at the times of interest are also plotted. The distribution type of the simulated prestress losses at any time of interest was solved by probability plotting. In this study, Normal or Lognormal distribution are representative of the output prestress loss distribution shown in Figures 4 and 5.

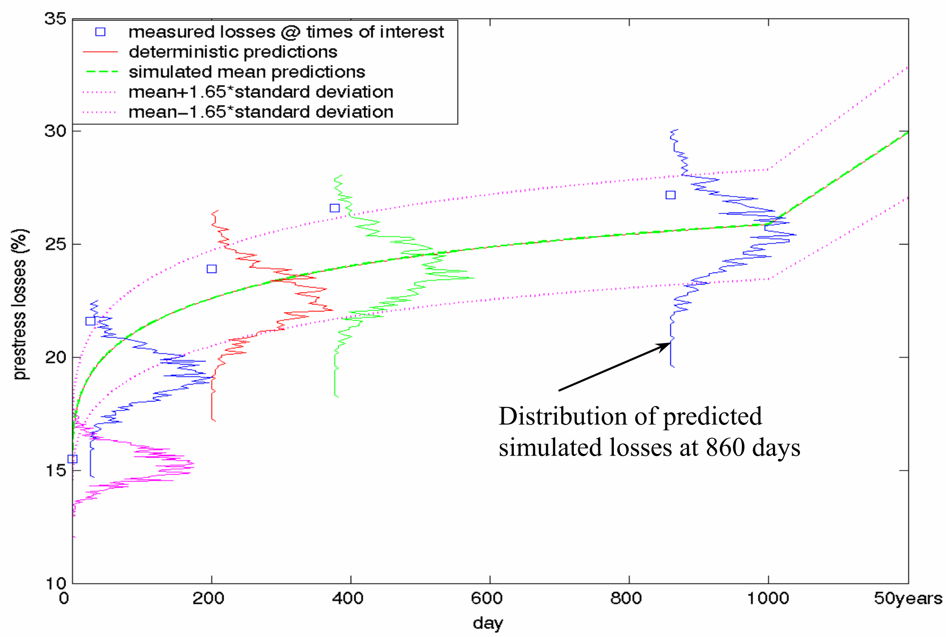

Figure 4: Simulated Prestress Losses For Girder I

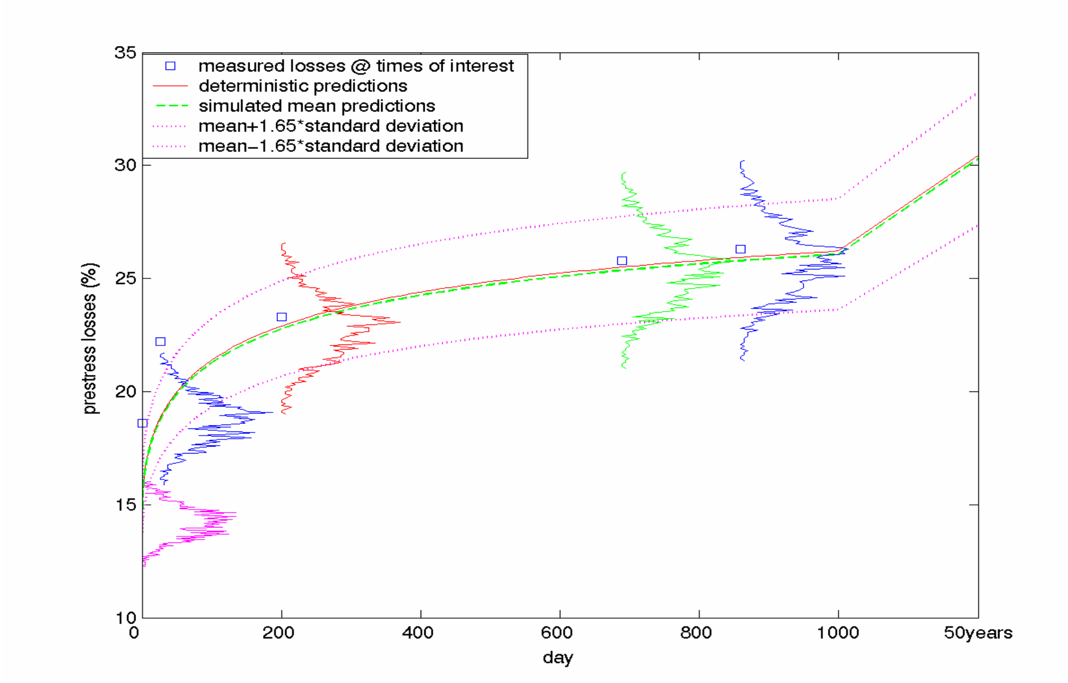

Figure 5: Simulated Prestress Losses For Girder II

In Figures 4 and 5, it can be seen that the deterministic predicted losses are nearly the same as the simulated mean losses over time as have been applied in Table 5. The standard deviations of the predicted losses increases with time; however, the coefficients of variance (standard deviation divided by mean) for losses varying with time are almost unchanged, for both Girder I and Girder II, which are about 0.05~0.06. This indicates that the T-S procedure is stable in the propagated variances of losses as well as in the deterministic losses.

It is of interest to establish whether the predicted mean (deterministic) losses are sufficient representatives of the measured mean (deterministic) losses at times of interest, thus the predicted loss at the end of service can be used as the final prestress loss in design. It can be stated from both Table 5 and Figures 4 and 5 that the predicted losses are good predictions at times of interest because of their relatively small gaps at all times of interest by comparing their mean values. However, it is noted that the variances of measured losses are greater than those of the predicted losses for both girders. In Figures 4 and 5, the predicted bandwidth of 3.3 times the standard deviation centered on the mean losses represents a ninety-percentile probability interval over time. At the age of 50 years, the predicted losses within this interval can range from 27% to 33% for Girder I and from 27.5% to 33.5% for Girder II. Awareness may arise that these variances underlying the predicted losses can impact the predicted values of deflections or stresses under service conditions.

COMPARISON STUDY USING DIFFERENT MATERIAL MODELS

From Table 5, it can be seen that the predicted losses are close to the measured losses, as expected because "best-fit corrected" models were used to compute predicted losses. Because the significant changes for the prestress loss prediction of HPC prestressed girders lie in the material models discussed earlier including MOE, creep and shrinkage functions, it is important to investigate the significance of these models in the T-S procedure for predicting prestress losses. In this study, a case-based comparison study was conducted. Four different combinations of material models, namely Case I ~ Case IV were used in this study. The deterministic losses were generated for all cases and are tabulated in Tables 6 and 7 for both girders. The cases are as follows:

I. The measured properties including the best-fit creep and shrinkage equations;
II. The measured properties with MOE predicted by ACI 363 and the corrected best-fit creep and shrinkage equations;
III. The measured properties with the corrected ACI 209 creep and shrinkage equations;
IV. The measured properties with the corrected Mokhtarzadeh's creep and shrinkage equations.

The comparisons were conducted first between the measured losses and the predicted losses in each case. The statistical hypothesis tests were not used herein; instead, the root mean square error (RMSE) between the five deterministic (mean) measured losses and the five deterministic (mean) predicted losses at different ages for the same girder were used. The RMSE is defined as:

$$RMSE = \sqrt{\sum_{i=1}^{5}\left(p_i - m_i\right)^2 / 5} \tag{7}$$

where p_i and m_i are the predicted and measured prestress loss at a certain time. This method allows for a straightforward comparison of which case or cases provide "good" predictions based on a low RMSE value.

Table 6: Deterministic Predictions from Case I to Case IV for Girder I

Age	Measured Losses	Predictions			
		Case I	Case II	Case III	Case IV
1day	15.5%	15.3%	11.8%	14.2%	14.2%
28day	21.6%	19.3%	15.4%	20.0%	19.6%
201day	23.9%	22.6%	18.5%	24.1%	25.2%
378/690day	26.6%	23.9%	19.8%	25.7%	26.7%
860day	27.2%	25.6%	21.3%	26.6%	28.3%
50years	—	30.0%	25.4%	28.0%	32.0%
RMSE		0.018	0.057	0.010	0.013

Table 7: Deterministic Predictions from Case I to Case IV for Girder II

Age	Measured Losses	Predictions			
		Case I	Case II	Case III	Case IV
1day	18.6%	14.3%	11.3%	14.3%	14.3%
28day	22.2%	18.9%	15.4%	20.7%	24.2%
201day	23.3%	22.9%	19.2%	25.4%	30.7%
378/690day	25.8%	25.6%	21.6%	27.2%	32.9%
860day	26.3%	26.0%	22.0%	27.4%	33.2%
50years		30.5%	26.2%	28.7%	34.6%
RMSE		0.024	0.055	0.024	0.059

Figures 6-9 illustrate the predicted losses over time in comparison with the measured losses at five different times for the four previous defined cases. To investigate the insights of total losses, the varying predicted loss components are also plotted.

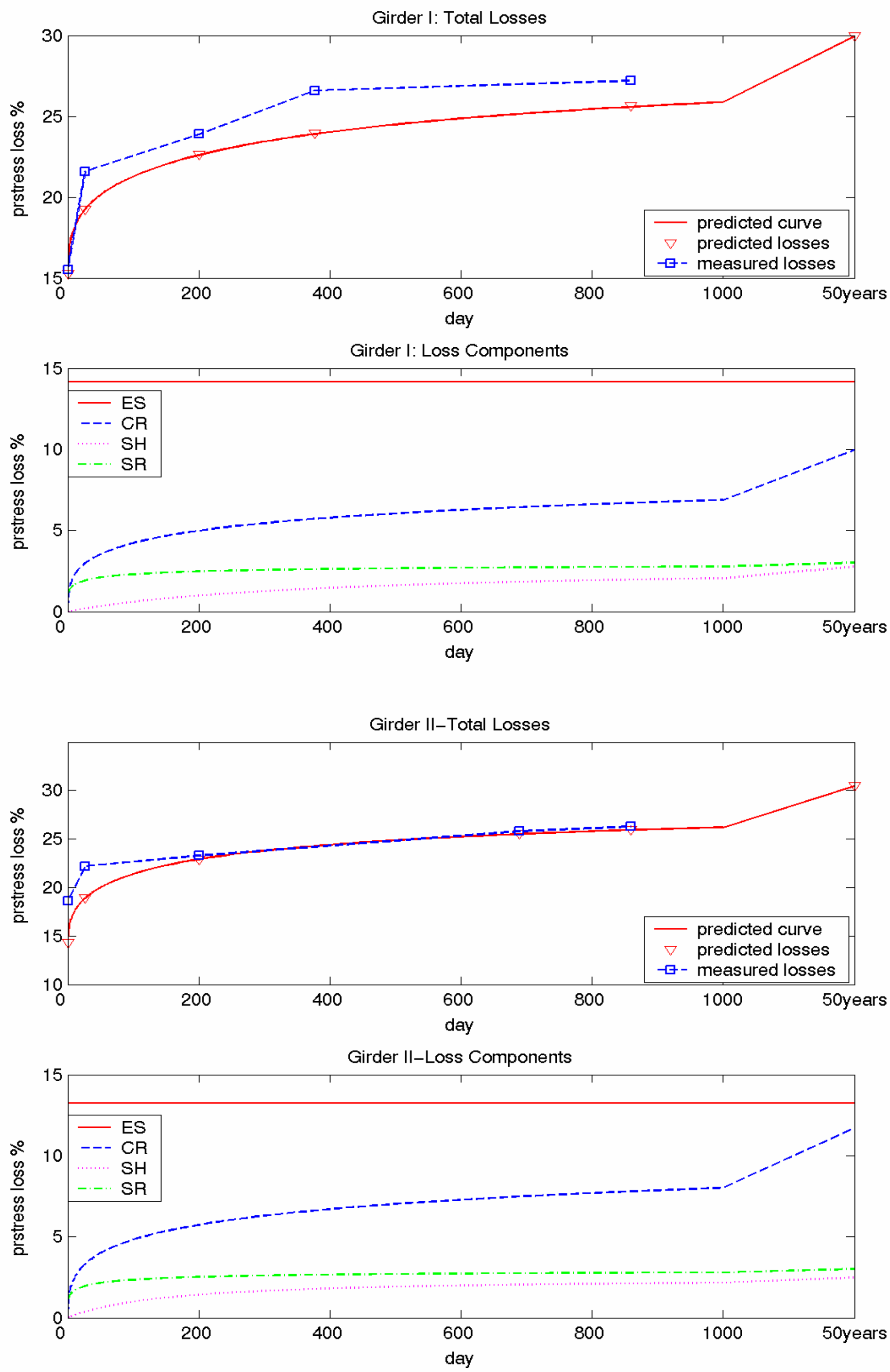

Figure 6: Case I–Measured Losses and Predicted Total Losses and Components

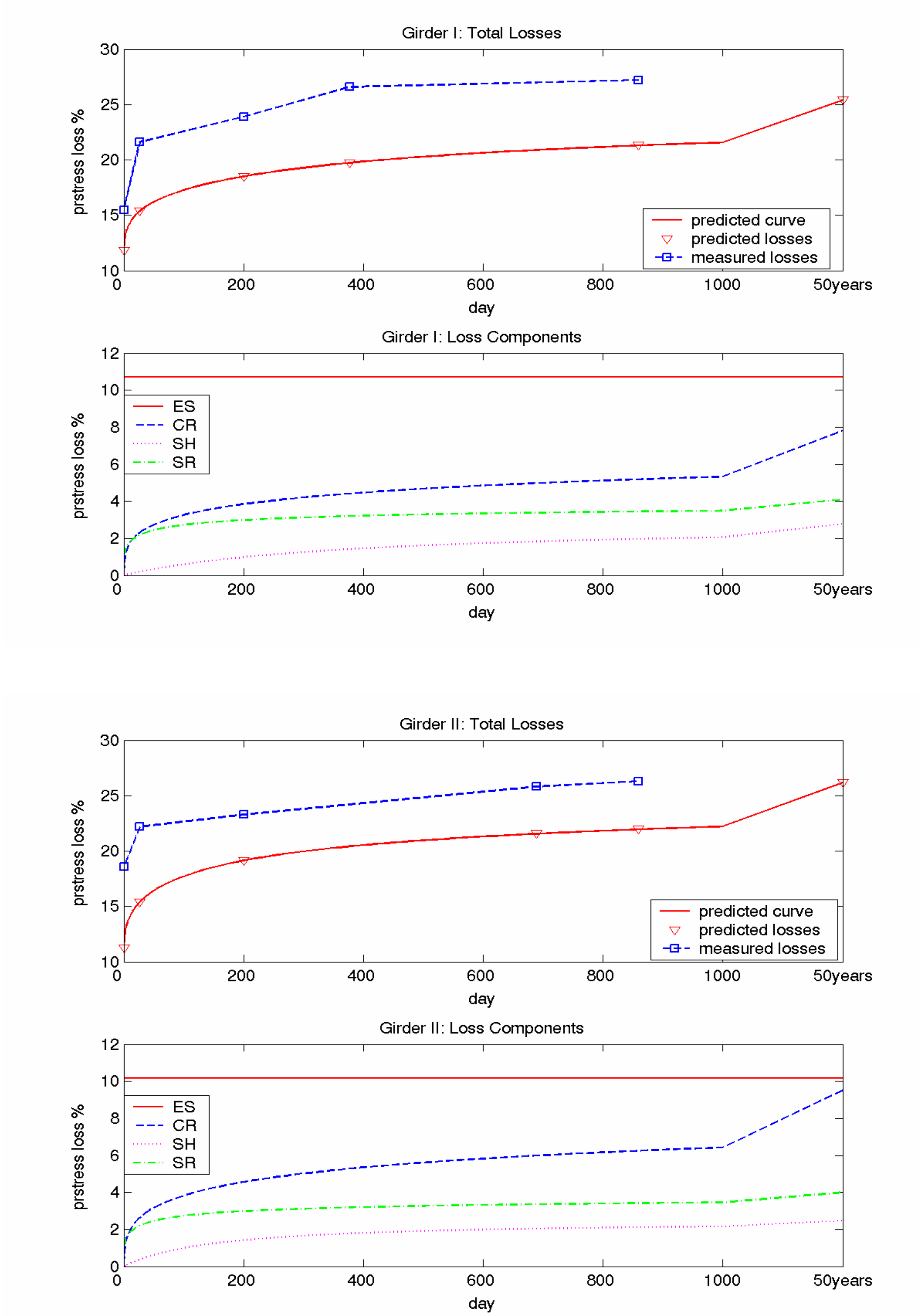

Figure 7: Case II–Measured Losses and Predicted Total Losses and Components

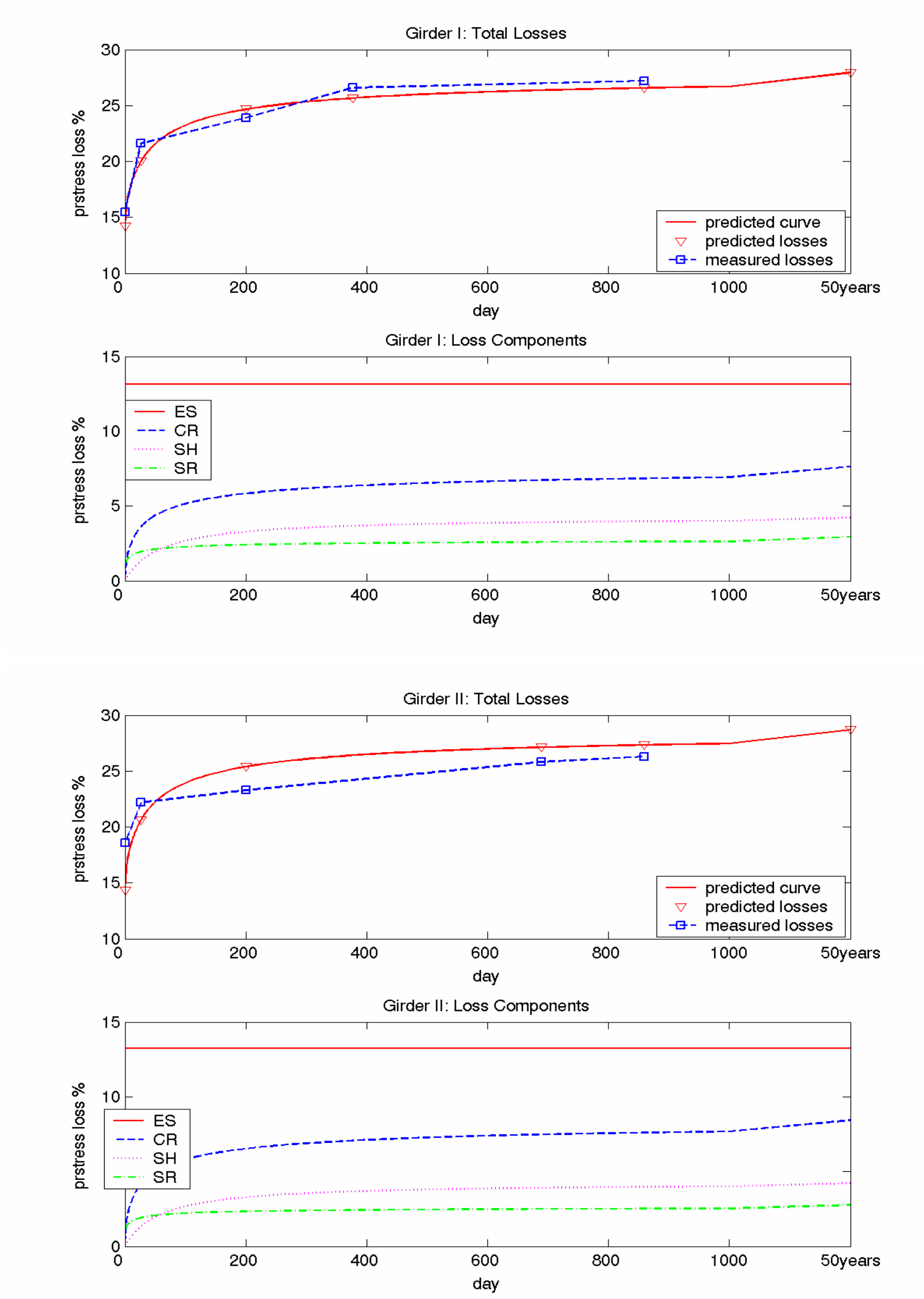

Figure 8: Case III–Measured Losses and Predicted Total Losses and Components

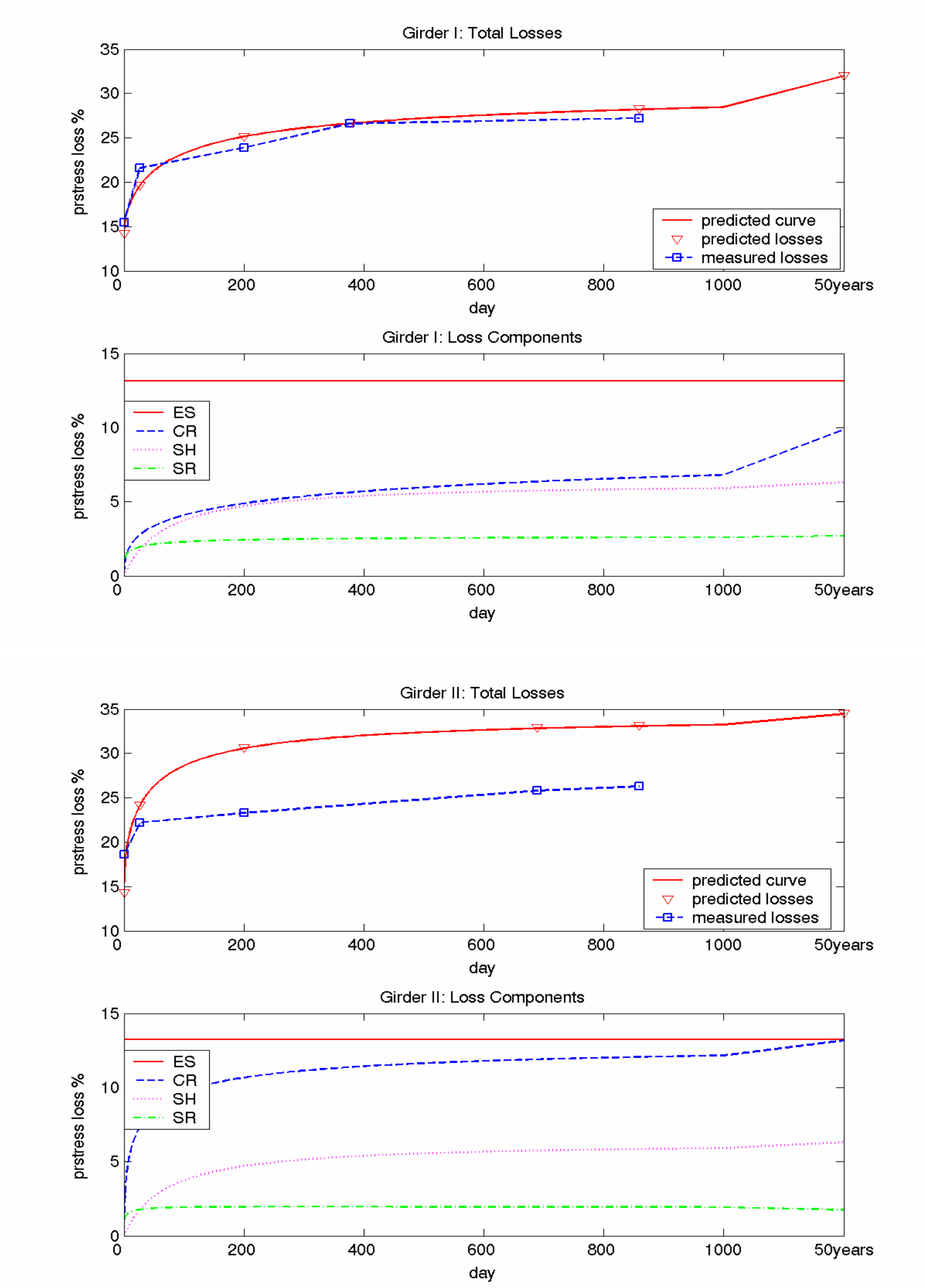

Figure 9: Case IV–Measured Losses and Predicted Total Losses and Components

The direct observations can be made from both Tables 6 and 7 and Figures 6-9 as follows. Relative to measured losses, the predictions for Case I are good for both Girder I and Girder II in which all inputs were measured values and the creep and shrinkage functions were the corrected best-fit time functions. However, doubt may exist that the results just happened to be good predictions considering the fact that material data from only two girders, and more specifically these two girders, were applied herein.

The predictions in Case II have considerable bias when comparing to measured losses for both Girder I and Girder II. The difference of Case I and Case II is that in Case II, the predicted MOEs using ACI 363 equations were used. This result reveals that the MOEs have a significant effect on the prestress loss outputs of the T-S procedure.

Case III also gave good results for both girders when comparing measured losses to predicted losses that used the corrected ACI 209 creep and shrinkage time functions. From Figures 2 and 3, it can be seen that the corrected ACI 209 creep equation is very close to the corrected best-fit equations for both girders; however, the ACI 209 shrinkage functions was not close to their best-fit counterparts. By comparing the shrinkage loss component in Case I and Case III (Figures 6 and 8), it can be shown that the shrinkage loss did not change much from Case I to Case III, i.e., the shrinkage time equations have a slight effect on the total loss output.

In Case IV, only the predictions for Girder I had good results when compared to measured losses. In this case, the corrected creep and shrinkage functions from Mokhtarzadeh were applied. From Figures 2 and 3, as the ACI 209 equations did, these shrinkage functions did not predict well when comparing with the best-fit shrinkage functions. Furthermore, Mokhtarzadeh's creep equations only gave a good prediction for Girder I. Considering Figures 6 and 9, the creep losses constitute a large portion of total losses, thus total losses are sensitive with the applied creep functions.

These comparison studies above indicate that good representatives of the HPC properties have significant impact on the prestress loss output using the T-S procedure. It is worthy to point out that this study did not intend to correct or propose any HPC material models, for example, the ACI 209 recommended creep and shrinkage time functions cannot be concluded that they are appropriate for all HPC girders. Also it is not appropriate to conclude that the ACI 363 MOE model cannot be used.

CONCLUSIONS

This paper studied the prestress losses for two HPC I-girders, in which the measured losses were viewed as representatives of real losses at different times up to the age of 860 days and a time-step prestress loss procedure was applied to obtain predicted losses. A Monte Carlo Simulation based approach was applied to estimate the variability of output losses for a cumulative time-step loss method; the variances of the measured losses were also investigated.

It was found that the variances of the measured losses were relatively greater than those of the predicted losses using the T-S procedure. The coefficients of variance of the predicted losses remained approximately constant for the losses over the service life of girders. Designers should consider that the variability of predicted losses using the measured properties can translate into a large range of expected deflections and stresses under service conditions.

The case-based comparison study showed that the material property models used in the T-S procedure have a great impact on the output of prestress losses for HPC I-girders, including the MOE model, and the creep and shrinkage time-dependent models. It was shown from this study that the creep model is more significant than the shrinkage model because of the shrinkage model's relatively low contribution to the total loss.

The computer-implemented program of the T-S procedure is very flexible, as characterized by the capacity of using any material models and generation of losses at any specified time. It is reasonable to conclude that it can be used for any HPC type prestressed girders provided that the material models involved are sufficiently accurate.

The results in Case III using the corrected ACI 209 models, in which the correction factors accounted for the relative humidity, age of loading time and the shape and size effect, yielded very good predictions of prestress losses. For other cases, only the corrected factor of shape and size was applied. However, the formulas for these factors were based on some simplified empirical equations for normal NSC. The calibration of these factors for HPC prestressed girders may be necessary.

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