ATINER CONFERENCE PRESENTATION SERIES No: CIV2024-0340

ATINER's Conference Paper Proceedings Series
CIV2024-0340
Athens, 29 October 2024

Proposed Formulas for Lump-Sum Prestress Losses

Nabil Al-Omaishi

Athens Institute for Education and Research
9 Chalkokondili Street, 10677 Athens, Greece

ATINER's conference paper proceedings series are circulated to promote dialogue among academic scholars. All papers of this series have been presented at one of ATINER's annual conferences according to its acceptance policies (http://www.atiner.gr/acceptance).

© All rights reserved by authors.

ATINER's Conference Paper Proceedings Series
CIV2024-0340
Athens, 29 October 2024
ISSN: 2529-167X

Nabil Al-Omaishi, Professor, The College of New Jersey, USA

Proposed Formulas for Lump-Sum Prestress Losses

The current AASHTO- LRFD (American Authorities of Highway and Transportation Officials) Approximate formula[1] *for estimating long-term prestress losses is the outcome of the research work presented in the NCHRP (*National Cooperative Highway Research Program) *Report 496*[2]*. It is produced by simplifying the detailed method and taking into account the variability of concrete properties and the interaction between precast girder and cast-in-place deck. It also introduced an Approximate method for elementary estimate of prestress losses that could be used at the conceptual design stage. The significance of this study is to improve the preliminary estimate of the current AASHTO-LRFD Approximate formula for long-term prestress losses of the different types pretensioned sections.*

Keywords: *pretensioned girders, prestress loss, creep loss, shrinkage loss*

Acknowledgments: *The author would like to thank Dr. M. Tadros for his valuable suggestions in the selection process of the parameters for this paper.*

Introduction

The Two detailed parametric studies, presented in this paper that are based on the average conditions for the design and construction of commonly used bridge girders. The girders examined are *Bulb Tee BT-54, Bulb Tee BT-72, I-Girder NU1100, I-Girder NU1600, I-Girder NU2000, Box Beam BI-48, Box Beam BIII-48, Inverted Tee IT600*, and *Slab Beam SIV-48*. Three spans and consequently three levels of prestressing for each section have been considered. The first study establishes the creep multiplier, N_c, while the second study evaluates the shrinkage multiplier, N_s. Both multipliers are used in the lump-sum formulas for estimating long-term prestress losses for different bridge girders. The multipliers produced by these studies are compared with that of the current *AASHTO-LRFD* approximate method, and new lump-sum formulas for long-term prestress losses are proposed.

Discussion

The variables used for the two parametric studies include: cross-section of beam; span and spacing of beams; and consequently, different deck thickness; concrete strengths at release and final times; and levels of prestressing. The nine sections selected for these studies are: *Bulb Tee BT-54*, *Bulb Tee BT-72*, *I-Girder NU1100*, *I-Girder NU1600*, *I-Girder NU2000*, *Box Beam BI-48*, *Box Beam BIII-48*, *Inverted Tee IT600*, and *Slab Beam SIV-48*. The design parameters are: levels of prestressing (low, medium and high) for three simple spans, three spacing for each girder, and three deck thicknesses. Half an inch reduction of deck thickness in computing composite section properties (for long term wear), haunch of 1-inch thick, low-relaxation strand (*Grade 270*) with a modulus of elasticity of 28,500 ksi (196,400 MPa) and a yield strength of 243 ksi (1,675 MPa). The jacking stress is 0.75 of the ultimate strength. The dead load includes: girder weight, deck weight, diaphragm weight, haunch weight, and two-inch thick asphalt wearing surface. Table 1 shows the section properties of the nine sections. The numerical values of material and design parameters for the nine sections examined are shown in Tables 2 and 3, respectively. Full explanation and numerical examples of the *AASHTO-LRFD Detailed Method*, including the material properties and prestress losses, can be found in the *PCI Journal* articles that were published in the fall 2009[3], and in the summer 2009[4], respectively.

Table 1. *Section Properties of the Nine Section*

Section Property	BT-54	BT-72	NU1100	NU1600	NU2000	BIII-48	BI-48	IT600	SIV-48
A_g (in^2)	659.0	767.0	694.6	810.8	903.8	812.5	692.5	245.7	703.0
h (in)	54	72	43.3	63	78.7	39	27	23.6	21
I_g (in^4)	268,077	545,894	182,279	458,482	790,592	168,367	65,941	11,938	34,517
y_b (in)	27.6	36.6	19.6	28.4	35.7	19.3	13.4	8.3	10.5
Weight (kip/ft^3)	0.686	0.799	0.724	0.840	0.942	0.846	0.721	0.256	0.732

1.0 in. = 25.4 mm, 1.0 in^2 = 645 mm^2, 1.0 in^4 = 360,300 mm^4, 1.0 kip/ft^3 = 157 N/m^3

Table 2. *Girders and Decks Used in the AASHTO-LRFD Refined Estimate of Time-Dependent Losses*

Beam Sections	BT 54	BT 72	NU 1100	NU 1600	NU 2000	BIII 48	BI 48	IT 600	SIV 48
Span: Low, Medium & High, ft	100, 110, 110	110, 120, 130	70, 90, 110	100, 110, 130	110, 130, 150	60, 70, 100	50, 56, 60	44, 56, 70	28, 38, 46
V/S	2.96	2.96	2.95	2.95	2.95	3.44	3.36	2.60	3.47
H, %	70	70	70	70	70	70	70	70	70
f_{ci}, ksi	8	8	5.5	5.5	5.5	5.5	5.5	6.5	5.5
f_c, ksi	12	12	7.5	7.5	7.5	7	7	8	7
E_{ci}, ksi	5531	5531	4384	4384	4384	4362	4362	4790	4362
E_c, ksi	6774	6774	5120	5120	5120	4921	4921	5314	4921
t_i, day	1	1	1	1	1	1	1	1	1
ψ_{bid}	0.848	0.848	1.084	1.084	1.084	1.019	1.030	1.011	1.015
ψ_{bif}	1.123	1.123	1.556	1.556	1.556	1.463	1.478	1.406	1.457
Deck									
Width, ft	8, 8, 8	8, 8, 8	12, 8, 6	12, 10, 6	12, 10, 6	8, 8, 8	8, 8, 8	2, 2, 2	4, 4, 4
Thickness, in	8	8	8	8	8	8	8	8	3
f_d, ksi	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
E_d, ksi	3845	3845	3845	3845	3845	3845	3845	3845	3845
t_d, day	90	90	90	90	90	90	90	90	90
t_f, day	20000	20000	20000	20000	20000	20000	20000	20000	20000

1.0 ft = 304.8 mm, 1.0 ksi = 6.89 MPa

Table 3. *Three Spans, Spacing and Levels of Prestressing for Each Girder*

Level of Prestressing	BT 54	BT 72	NU 1100	NU 1600	NU 2000	BIII 48	BI 48	IT 600	SIV 48
Low									
No. of Strands	24-0.6 in.	30-0.6 in.	42-0.5 in.	54-0.5 in.	56-0.5 in.	23-0.5 in.	23-0.5 in.	8-0.5 in.	10-0.5 in.
A_p, in^2	5.208	6.510	6.426	8.262	8.568	3.519	3.519	1.224	1.530
Eccentricity, in.	24.63	33.00	16.22	24.24	31.34	17.29	11.37	6.49	8.25
Span and spacing, ft	100 @ 8	110 @ 8	70 @ 12	100 @ 12	110 @ 12	60 @ 8	50 @ 8	44 @ 2	28 @ 4
Medium									
No. of Strands	36-0.6 in.	40-0.6 in.	48-0.5 in.	56-0.5 in.	58-0.5 in.	35-0.5 in.	31- 0.5 in.	10-0.5 in.	15-0.5 in.
A_p, in^2	7.812	8.680	7.344	8.568	8.874	5.355	4.743	1.530	2.295
Eccentricity, in	23.41	31.70	15.91	24.04	31.08	16.60	10.85	6.49	8.25
Span and spacing, ft	110 @ 8	120 @ 8	90 @ 8	110 @ 10	130 @ 10	70 @ 8	56 @ 8	56 @ 2	38 @ 4
High									
No. of Strands	44-0.6 in.	50-0.6 in.	54-0.5 in.	58-0.5 in.	58-0.5 in.	46-0.5 in.	41-0.5 in.	18-0.5 in.	20-0.5 in.
A_p, in^2	9.548	10.850	8.262	8.874	8.874	7.038	6.273	2.754	3.06
Eccentricity, in.	21.81	29.08	15.44	23.78	31.08	16.29	10.49	5.80	8.25
Span and spacing, ft	110 @ 8	130 @ 8	110 @ 6	130 @ 6	150 @ 6	100 @ 8	60 @ 8	70 @ 2	46 @ 4

where

$f_c^{'}$ = specified compressive strength of girder concrete, ksi

f_d = specified compressive strength of deck concrete, ksi

h= depth of concrete girder, in.

I_g= moment of inertia of girder gross section, in^4

t_f= age of concrete at final time of load application, days

t_i= age of concrete at time of initial loading at release, days

V/S= volume-to-surface ratio of girder

y_b= eccentricity of bottom fibers with respect to centroid of gross girder section, in.

The current *AASHTO-LRFD Refined Estimate of Time-Dependent Losses,* which is the result of the extensive research work presented in the *NCHRP Report 496*[2], is used to compute the long-term losses using its concrete creep and shrinkage formulas. In the detailed method, the transformed section coefficients K_{id} and K_{df} , equations 1 and 2, respectively, are used to reflect the interaction between concrete and prestressing stands (transformed-section effects) and the softening effect of creep on that transformed section (as opposed to instantaneous elastic analysis). Thus, the transformed section coefficients may be viewed as the creep-adjusted transformed-section coefficient.

$$K_{id} = \frac{1}{1+\frac{E_p A_{ps}}{E_{ci} A_g}\left(1+\frac{A_g e_{pg}^2}{I_g}\right)(1+0.7\psi_{bid})} \qquad \textit{LRFD Eq. 5.9.5.4.2a-2} \qquad (1)$$

$$K_{df} = \frac{1}{1+\frac{E_p A_{ps}}{E_{ci} A_c}\left(1+\frac{A_c e_{pc}^2}{I_c}\right)\left(1+0.7\psi_{bif}\right)} \qquad \textit{LRFD Eq. 5.9.5.4.3a-2} \qquad (2)$$

where

A_c = area of composite section at service, in^2

A_g = area of gross section of girder, in^2

A_{ps} = area of prestressing steel, in^2

e_{pg} = eccentricity of strands with respect to centroid of gross section of girder, always taken as positive, in.

e_{pc} = eccentricity of strands with respect to centroid of composite section at service, always taken as positive, in.

E_{ci} = modulus of elasticity of girder concrete at transfer, ksi

E_p = modulus of elasticity of prestressing steel, ksi

I_c = moment of inertia of composite section at service, in^4

I_g = moment of inertia of gross section of girder, in^4

K_{id} = transformed-section coefficient that accounts for the interaction between concrete and steel between prestress transfer and deck placement times

K_{df} = transformed-section coefficient that accounts for the interaction between concrete and steel between deck placement and final times

ψ_{bid} = girder creep coefficient between initial (release) and deck placement times

ψ_{bif} = girder creep coefficient due to sustained load applied at initial time (release), and kept constant until final time

Table 4. *Transformed Section Coefficients, K_{id} and K_{if}*

Beam Sections	**BT 54**	**BT 72**	**NU 1100**	**NU 1600**	**NU 2000**	**BIII 48**	**BI 48**	**IT 600**	**SIV 48**
Creep Ψ_{bid}	0.848	0.848	1.084	1.084	1.084	1.019	1.030	1.011	1.015
Creep Ψ_{bdf}	1.123	1.123	1.556	1.556	1.556	1.463	1.478	1.406	1.457
Level of Prestressing									
Low									
K_{id}	0.861	0.850	0.825	0.808	0.813	0.895	0.882	0.914	0.945
K_{df}	0.855	0.843	0.809	0.788	0.794	0.887	0.876	0.914	0.938
Medium									
K_{id}	0.814	0.817	0.808	0.802	0.809	0.854	0.854	0.895	0.92
K_{df}	0.805	0.807	0.789	0.782	0.789	0.843	0.846	0.895	0.91
High									
K_{id}	0.795	0.797	0.794	0.800	0.809	0.824	0.821	0.839	0.896
K_{df}	0.783	0.785	0.772	0.777	0.788	0.809	0.81	0.834	0.884
Average K_{id}	0.823	0.821	0.809	0.803	0.810	0.858	0.852	0.883	0.920
Average K_{df}	0.814	0.812	0.790	0.782	0.790	0.846	0.844	0.881	0.911

The last two rows illustrate the highest calculated values of K_{id} and K_{df} for the three levels of prestressing based of different beams.

Study I: Concrete Multiplier for Creep Loss N_c

The concrete creep multiplier, N_c, is taken as equal to 10 in the first term of equation 3 of the *AASHTO-LRFD Approximate Estimate of Time-Dependent Losses*. Relative humidity and concrete compressive strength factors are shown in equations 4 and 5, respectively:

$$\Delta f_{pLT} = 10\left(\frac{f_{pi}A_{ps}}{A_g}\right)\gamma_h\gamma_{st} + 12\gamma_h\gamma_{st} + 2.4$$ *LRFD Eq. 5.9.5.3-1* (3)

$$\gamma_h = 1.7 - 0.01H$$ *LRFD Eq. 5.9.5.3-2* (4)

$$\gamma_{st} = \frac{5}{1+f'_{ci}}$$ *LRFD Eq. 5.9.5.3-3* (5)

where
f'_{ci} = specified compressive strength of concrete at transfer, ksi
f_{pi} = stress in prestressing strands immediately before initial transfer, ksi
H = average annual ambient relative humidity, %
γ_h = correction factor for relative humidity of the ambient air
γ_{st} = correction factor for specified concrete strength at initial time
Δf_{pLT} = total long-term prestress loss that occurs between initial time and final condition, ksi

The impacts of type of girder and level of prestressing have been assessed. The process of analysis starts with computing the creep loss at the three levels of prestressing for each of the nine cross-sections using the *AASHTO-LRFD Refined Estimate of Time-Dependent Losses*. The value of creep loss is influenced by the cross-section configuration, magnitude and duration of stress, creep coefficient of concrete, level of prestressing, and the maturity of concrete at the time of loading. Equation 6 is used for computing the total creep component of the long-term prestress losses:

$$\Delta f_{pC} = \Delta f_{pCR} + \Delta f_{pCD1} + \Delta f_{pCD2}$$ (6)

where:
Δf_{pC} = total creep component of long-term prestress loss between initial (release) and the final times, ksi
Δf_{pCD1} = creep component of long-term prestress loss between deck placement and final times, due to initial loads, ksi
Δf_{pCD2} = creep component of long-term prestress loss between deck placement and final times, due to deck weight and superimposed dead load, *SIDL*, ksi
Δf_{pCR} = creep component of long-term prestress loss between initial (release) and deck placement times, ksi

The maximum, medium and minimum values of the creep losses, based on the three levels of prestressing, for the nine sections are shown in **Table 5**. When the *AASHTO-LRFD Approximate Estimate* is used, the total long-term creep prestress loss, Δf_{pC} is represented by the first term of the formula as follows:

$$\Delta f_{pC} = N_c \frac{f_{pi} A_p}{A_g} \gamma_h \gamma_{st}$$

Table 5. *Computed Values of Long-term Prestress Losses due to Creep, ksi*

Level of Prestressing	**BT 54**	**BT 72**	**NU 1100**	**NU 1600**	**NU 2000**	**BIII 48**	**BI 48**	**IT 600**	**SIV 48**
Low									
Δf_{pCR}	10.47	11.72	17.14	17.92	17.35	9.25	10.72	7.64	5.10
Δf_{pCD1}	3.37	3.37	7.31	7.61	7.38	3.99	4.64	2.98	2.21
Δf_{pCD2}	4.44	3.77	6.20	7.22	6.70	3.52	4.07	2.47	0.80
Total Creep Δf_{pC}	18.27	19.27	30.66	32.76	31.43	16.75	19.43	13.09	8.11
Medium									
Δf_{pCR}	14.36	14.37	17.40	17.80	16.44	12.86	13.24	8.48	6.94
Δf_{pCD1}	4.60	4.60	7.39	7.55	6.98	5.52	5.71	3.31	2.99
Δf_{pCD2}	5.14	4.35	6.67	7.28	7.38	4.63	4.89	3.71	1.37
Total Creep Δf_{pC}	24.10	23.31	31.46	32.64	30.80	23.01	23.84	15.50	11.30
High									
Δf_{pCR}	16.29	15.87	17.14	16.56	14.85	13.06	16.35	13.26	8.61
Δf_{pCD1}	5.20	5.06	7.26	7.01	6.29	5.58	7.02	5.15	3.70
Δf_{pCD2}	5.01	4.70	7.13	6.37	6.27	7.70	5.58	5.22	1.93
Total Creep Δf_{pC}	26.50	25.62	31.53	29.95	27.41	26.34	28.95	23.63	14.24

The concrete creep multiplier can, therefore, be calculated using equation 7, and as follows:

$$N_C = \frac{\Delta f_{pc} A_g}{f_{pi} A_p \gamma_h \gamma_{st}} \qquad (7)$$

For Bulb-Tee 54 and low level of prestressing, with section properties and area of prestressing strands shown in Table 6.

Table 6. *Bulb Tee BT-54 Section Properties at Initial Time*

	Gross Section	**Transformed Section**
Area, in^2	659	691
Centroid of strands from the bottom fiber, in	27.63	26.54
Moment of Inertia, in^4	268,077	284,820
Eccentricity of strands, in.	23.41	22.32

The total long-term creep prestress loss, Δf_{pC} is equal to 18.27 ksi (125.8 MPa). The value of N_c can be calculated using the section properties and the design parameters shown in Tables 2 and 3.

$$N_c = \frac{18.27(659)}{202.5(5.208)0.556} = 20.5$$

N_c is taken as 10 in the *AASHTO-LRFD Approximate Estimate* equation which is quite different from the computed value of 20.5, when the total long-term creep loss is estimated using the *AASHTO-LRFD Refined Estimate*. All the computed long-term losses due to concrete creep are shown in Table 7 shown below.

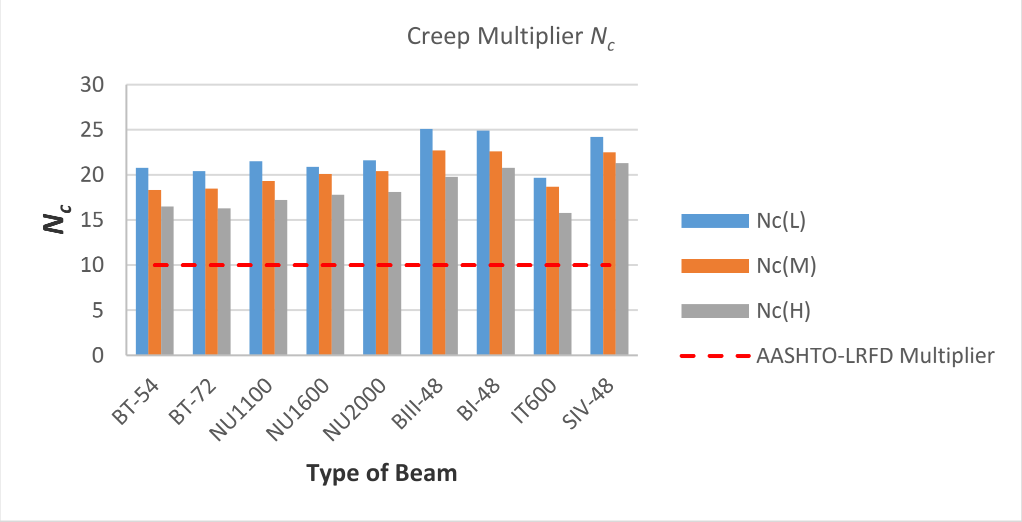
Table 7. *Parametric Study - Creep Multiplier N_c*

Level of Prestressing	**BT 54**	**BT 72**	**NU 1100**	**NU 1600**	**NU 2000**	**BIII 48**	**BI 48**	**IT 600**	**SIV 48**
Low									
Creep loss, ksi	18.27	19.26	30.66	32.76	31.43	16.75	19.43	13.09	8.11
H	70	70	70	70	70	70	70	70	70
ψ_h	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
ψ_{st}	0.556	0.556	0.769	0.769	0.769	0.769	0.769	0.667	0.769
$\gamma_h \gamma_{st}$	0.556	0.556	0.769	0.769	0.769	0.769	0.769	0.667	0.769
A_p / A_g	0.0079	0.0085	0.0093	0.0102	0.0095	0.0043	0.0051	0.0050	0.0022
N_c	20.8	20.4	21.5	20.9	21.6	25.1	24.9	19.7	24.2
Medium									
Creep loss, ksi	24.10	23.31	31.46	32.64	30.80	23.01	23.84	15.5	11.30
$\gamma_h \gamma_{st}$	0.556	0.556	0.769	0.769	0.769	0.769	0.769	0.667	0.769
A_p / A_g	0.0119	0.0113	0.0106	0.0106	0.0098	0.0066	0.0069	0.0062	0.0033
N_c	18.3	18.5	19.3	20.1	20.4	22.7	22.6	18.7	22.5
High									
Creep loss, ksi	26.50	25.62	31.53	29.95	27.41	26.34	28.95	23.63	14.24

$\gamma_h\ \gamma_{st}$	0.556	0.556	0.769	0.769	0.769	0.769	0.769	0.667	0.769
A_p / A_g	0.0145	0.0142	0.0119	0.0109	0.0098	0.0087	0.0091	0.0112	0.0044
N_c	16.5	16.3	17.2	17.8	18.1	19.8	20.8	15.8	21.3
Average N_c	18.5	18.4	19.4	19.6	20.0	22.5	22.8	18.1	22.7
AASHTO-LRFD Multiplier	10	10	10	10	10	10	10	10	10

Furthermore, this table is showing that all the values of N_c are consistently higher for low level of prestressing than that for high level of prestressing where large number of strands are used. The values of N_c range from 20.8 to 18.3 for Bulb Tee with an average of 19.55. From 21.6 to 19.3 with an average of 20.45 for NU I-Girder. From 25.1 to 22.5 with an average of 23.8 for Box Beams. From 19.7 to 18.1 with an average of 18.9 for Inverted Tee, and from 24.2 to 22.5 with an average of 23.35 for Slab Beam. Again, this is in contrast with the constant value of 10 used in the *AASHTO-LRFD Approximate Estimate of Time-Dependent Losses* which does not reflect the cross-sectional configuration as well as the level of prestressing. Figure 1 presents a summary chart of the values of N_c for high, medium and low level of prestressing for the four girder types and slab. This kind of chart is useful to designers at the early stage of design.

Figure 1. *Values of Creep Multiplier N_c*



Study II: Concrete Multiplier for Shrinkage Loss N_s

The parameters used in this study are exactly the same as those adopted in Study I. The main objective of the study is to evaluate the value of 12 that represents the concrete shrinkage multiplier, N_s, in the second term of equation 3 (*LRFD Eq. 5.9.5.3-1*) in the *AASHTO-LRFD Approximate Estimate of Time-Dependent Losses*. The change in concrete stress at the centroid of prestressing steel due to shrinkage is calculated with the *AASHTO-LRFD Refined Estimate* *of Time-Dependent Losses*, for the three levels of prestressing of each of the nine cross-sections. Prestress loss due to shrinkage is a function of the cross-section configuration, shrinkage strain of concrete, level of prestressing, ambient relative humidity, and the compressive strength of concrete. Equation 8 is used for computing the total shrinkage component of the long-term prestress losses:

$$\Delta f_{pS} = \Delta f_{pSR} + \Delta f_{pSD} + \Delta f_{pSS} \qquad (8)$$

where

Δf_{pS} = total shrinkage component of the long-term prestress loss that occurs between initial (release) and final times, ksi

Δf_{pSD} = shrinkage component of the long-term prestress loss that occurs between deck placement and final times, ksi

Δf_{pSR} = shrinkage component of the long-term prestress loss that occurs between initial (release) and deck placement times, ksi

Δf_{pSS} = deck-slab shrinkage component of long-term prestress loss that occurs between deck placement and final times, ksi

Another departure from the current *AASHTO LRFD* is in the computation of Δf_{pSS}. Differential shrinkage between shrinkage of cast-in-place deck and the precast girder, (ε_{ddf} - ε_{bdf}) should be used instead of the shrinkage of deck for the same time period, ε_{ddf} since shrinkage of girder has already been accounted for in the long-term loss. The change in concrete stress at the level of the strands' centroid will therefore be computed using equation 9:

$$\Delta f_{cdf} = \frac{(\varepsilon_{ddf} - \varepsilon_{bdf})\, A_d E_{cd}}{(1 + 0.7\psi_{ddf})} \left(\frac{1}{A_c} - \frac{e_{pc} e_d}{I_c} \right) \qquad \text{Modified } \textit{LRFD Eq. 5.9.5.4.3d-2} \qquad (9)$$

where

Δf_{cdf} = change in concrete stress at the level of the strands centroid between deck placement and final times, ksi

A_d = area of concrete deck, in^2

E_{cd} = modulus of elasticity of deck concrete at service, ksi

e_d = eccentricity of deck with respect to transformed composite section at the time of application of superimposed dead load, in.

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

ε_{ddf} = shrinkage strain of deck between deck placement and the final time

ψ_{ddf} = creep coefficient of deck due to a sustained load applied at deck placement time, t_d, and kept constant until final time, t_f

The maximum, medium and minimum values of the shrinkage losses, based on the three levels of prestressing, for the nine sections examined are shown **in Table 8.**

Table 8. *Computed Values of Long-term Prestress Losses due to Shrinkage, ksi*

Level of Prestressing	BT 54	BT 72	NU 1100	NU 1600	NU 2000	BIII 48	BI 48	IT 600	SIV 48
Low									
Δf_{pSR}	5.36	5.29	6.57	6.43	6.47	6.70	6.67	6.79	7.05
Δf_{pSD}	1.72	1.70	2.80	2.73	2.75	2.89	2.89	2.65	3.05
Δf_{pSS}	1.16	1.10	0.91	0.87	0.92	1.30	1.31	1.03	0.84
Total Shrinkage Loss Δf_{pS}	8.25	8.09	10.28	10.03	10.14	10.88	10.86	10.47	10.93
Medium									
Δf_{pSR}	5.07	5.09	6.43	6.39	6.44	6.39	6.46	6.64	6.86
Δf_{pSD}	1.62	1.63	2.73	2.71	2.73	2.75	2.78	2.60	2.96
Δf_{pSS}	0.97	0.96	0.79	0.83	0.86	1.13	1.15	1.01	0.81
Total Shrinkage Loss Δf_{pS}	7.67	7.68	9.96	9.92	10.03	10.27	10.39	10.25	10.62
High									
Δf_{pSR}	4.95	4.97	6.32	6.37	6.44	6.17	6.21	6.23	6.68
Δf_{pSD}	1.58	1.58	2.68	2.69	2.73	2.64	2.67	2.42	2.87
Δf_{pSS}	0.79	0.75	0.67	0.68	0.73	0.98	1.02	0.77	0.79
Total Shrinkage Loss Δf_{pS}	7.32	7.30	9.67	9.74	9.90	9.79	9.90	9.42	10.34

When the *AASHTO-LRFD Approximate Estimate* is used, the total long-term shrinkage prestress loss, Δf_{pS} is represented by the second term of the formula and as follows:

$$\Delta f_{ps} = N_s \gamma_h \gamma_{st}$$

Therefore, the concrete shrinkage multiplier can be computed using equation 10:

$$N_s = \frac{\Delta f_{ps}}{\gamma_h \gamma_{st}} \qquad (10)$$

For beam *BT-54* and low level of prestressing, the total long-term shrinkage prestress loss, Δf_{pS} is equal to 8.25 ksi. The value of N_s can, therefore, be calculated using the section properties and the design parameters shown in Tables 2 and 3:

$N_s = \frac{8.25}{0.556}$=14.8

N_s is taken as 12 in the *AASHTO-LRFD Approximate Estimate* equation which is quite different from the estimated value of 14.8 when the total long-term shrinkage loss is estimated using the *AASHTO-LRFD Refined Estimate*.

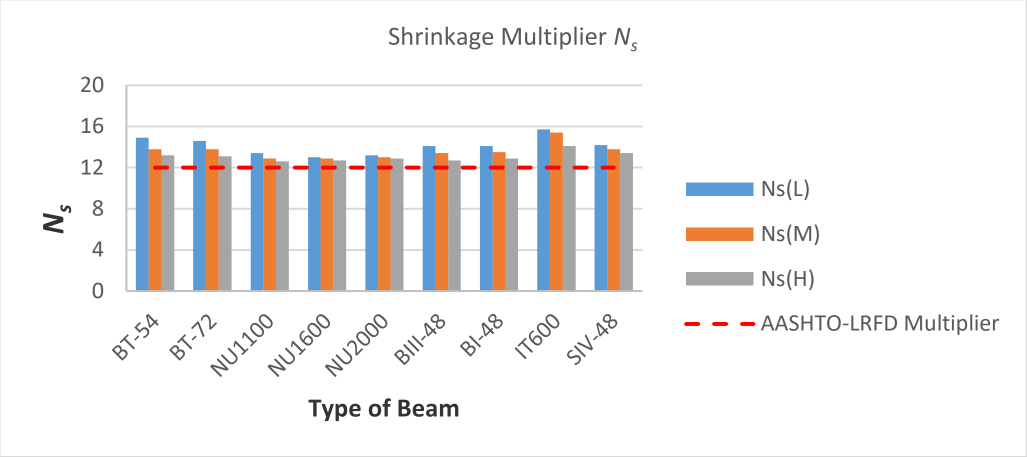
Table 9. *Parametric Study - Shrinkage Multiplier N_s*

Level of Prestressing	**BT 54**	**BT 72**	**NU 1100**	**NU 1600**	**NU 2000**	**BIII 48**	**BI 48**	**IT 600**	**SIV 48**
Low									
Shrinkage loss, ksi	8.25	8.09	10.28	10.03	10.14	10.88	10.86	10.47	10.93
γ_h γ_{st}	0.556	0.556	0.769	0.769	0.769	0.769	0.769	0.667	0.769
N_s	14.9	14.6	13.4	13.0	13.2	14.1	14.1	15.7	14.2
Medium									
Shrinkage loss, ksi	7.67	7.68	9.96	9.92	10.03	10.27	10.39	10.25	10.62
γ_h γ_{st}	0.556	0.556	0.769	0.769	0.769	0.769	0.769	0.667	0.769
N_s	13.8	13.8	12.9	12.9	13.0	13.4	13.5	15.4	13.8
High									
Shrinkage loss, ksi	7.32	7.30	9.67	9.74	9.90	9.79	9.90	9.42	10.34
γ_h γ_{st}	0.556	0.556	0.769	0.769	0.769	0.769	0.769	0.667	0.769
N_s	13.2	13.1	12.6	12.7	12.9	12.7	12.9	14.1	13.4
Average N_s	13.9	13.8	13.0	12.9	13.0	13.4	13.5	15.1	13.8
AASHTO-LRFD Multiplier	12	12	12	12	12	12	12	12	12

These data show that the values of N_s are consistently higher for low level of prestressing than that for high level of prestressing when the concrete compressive strength and the ambient relative humidity are constants. The average values of N_s multiplier range from 14.9 to 13.8 with an average of 14.35 for Bulb-Tees. From 13.4 to 12.9 with an average of 13.15 for NU I-Girder. From 14.1 to 13.4 with an average of 13.75 for Box Beams. From 15.7 to 15.1 with an average of 15.4 for Inverted Tee, and from 14.2 to 13.8 with an average of 14.0 for Slab Beam.

This is in contrast with the corresponding constant value of 12 used in the *AASHTO-LRFD Approximate Estimate of Time-Dependent Losses* regardless of the effects of the cross-section configuration of the beams. Figure 2 shows a summary chart of the values of N_s for high, medium and low level of prestressing for the nine beam types.

Figure 2. *Values of shrinkage multiplier* N_s



Proposed Lump-Sum Formulas

The following proposed Lump-sum formulas, equations 11 through 15, represent the average conditions of time-dependent losses due to creep and shrinkage of concrete, and relaxation of steel strands for each of the beam examined:

- Bulb-Tee: $\Delta f_{pLT} = 19.6\left(\frac{f_{pi}A_{ps}}{A_g}\right)\gamma_h\gamma_{st} + 14.4\gamma_h\gamma_{st} + 2.4$ (11)
- I-Girder: $\Delta f_{pLT} = 20.5\left(\frac{f_{pi}A_{ps}}{A_g}\right)\gamma_h\gamma_{st} + 13.2\gamma_h\gamma_{st} + 2.4$ (12)
- Box Beam: $\Delta f_{pLT} = 23.8\left(\frac{f_{pi}A_{ps}}{A_g}\right)\gamma_h\gamma_{st} + 13.8\gamma_h\gamma_{st} + 2.4$ (13)
- Inverted Tee: $\Delta f_{pLT} = 18.9\left(\frac{f_{pi}A_{ps}}{A_g}\right)\gamma_h\gamma_{st} + 15.4\gamma_h\gamma_{st} + 2.4$ (14)
- Slab Beam: $\Delta f_{pLT} = 23.4\left(\frac{f_{pi}A_{ps}}{A_g}\right)\gamma_h\gamma_{st} + 14.0\gamma_h\gamma_{st} + 2.4$ (15)

The Lump-sum formulas are useful for computing the time-dependent losses in the preliminary design stage while the final estimated loss should be recalculated in the final design stage.

Conclusions

Based on the results of these parametric studies, the following conclusions are drawn:

- The values of K_{id} and K_{df} vary substantially based on the geometry and configuration of each beam. However, the values of K_{id} and K_{df} for the same beam are consistently lower for higher level of prestressing.
- The current *AASHTO-LRFD Approximate Estimate* of time-dependent losses does not reflect the impact of beam configuration on the creep and shrinkage multipliers.
- The computed creep multiplier N_c is significantly higher than that of the *AASHTO-LRFD Approximate Estimate* of 10. The creep multiplier decreases with the increased level of prestressing and vice versa. This trend is observed in all nine beams analyzed in this study.
- The value of the shrinkage multiplier N_s decreases slightly with the increased level of prestressing and vice versa. This trend is observed in all the nine beams analyzed in this study. The shrinkage multiplier is close to that of the *AASHTO-LRFD Approximate Estimate* of 12.
- Five proposed Lump-sum formulas have been presented for estimating the long-term prestress losses that account for the commonly used beams.

References

1. AASHTO, American Association of State Highway and Transportation Officials, "*AASHTO-LRFD Bridge Design Specifications*". 6th ed. Washington, DC, 2012.
2. Tadros, M. K., N. Al-Omaishi, S.J. Seguirant, and J.G. Gallt, "*NCHRP Report 496 Prestress Losses in Pretensioned High-Strength Concrete Bridge Girders*". NCHRP, Washington, DC, 2003.
3. Al-Omaishi, N., Tadros, M.K, and Seguirant, S.J., "*Estimating Prestress Loss in Pretensioned High Strength Concrete Members*", Precast Concrete Institute, PCI Journal, Chicago, Illinois, fall 2009.
4. Al-Omaishi, N., Tadros, M.K, and Seguirant, S.J., "*Elasticity Modulus, Shrinkage and Creep of High Strength Concrete as adopted by AASHTO*", Precast Concrete Institute, PCI Journal, Chicago, Illinois, summer 2009.