Evaluation of AASHTO Provisions for Creep and Shrinkage of Prestressed UHPC Girders

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Abstract:

The use of ultra-high performance concrete (UHPC) for pretensioned bridge girders is appealing for bridge engineers due to its superior engineering properties. Design of pretensioned UHPC girders requires an accurate estimation of the prestress losses caused by creep and shrinkage. A review of the literature reveals a lack of information on creep and shrinkage behaviors of UHPC-class materials. As such, there does not exist an available model to estimate long-term prestress losses due to creep and shrinkage. The intent of this study is to address this gap. The main objectives of this research are as follows: (1) examine the current AASHTO equations for creep and shrinkage, (2) determine the applicability of parameters in the equations for UHPC-class materials, and (3) compare existing AASHTO models with measured creep and shrinkage of different UHPC-class materials. This paper briefly discusses existing models and the experimental research being conducted at Turner-Fairbank Highway Research Center to address the knowledge gaps.

Keywords: UHPC, Creep, Shrinkage, Prestressed girders, Long-term losses

1. Introduction

Deployment of ultra-high performance concrete (UHPC) in design of structural components has been gaining momentum in recent years due to its superior mechanical properties compared to conventional concrete. UHPC is a cementitious composite material with a water-to-cementitious material ratio less than 0.25, and is reinforced with at least 2% steel fibers by volume. The 28-day compressive strength of UHPC is greater than 21.7 ksi (150 MPa) and the tensile strength is greater than 0.7 ksi (5 MPa) (Graybeal, 2014). UHPC exhibits mechanical and durability properties that make it an ideal candidate for use in developing new solutions to pressing issues related to highway bridge design, construction, repair, and replacement (Graybeal, 2014).

Given the aforementioned properties, UHPC provides an opportunity for pretensioned girders to deliver longer span lengths or shallower structural depths compared to conventional concrete solutions. The design of pretensioned UHPC girders will require an accurate estimation of the long-term prestress losses due to creep and shrinkage of UHPC; losses will also be caused by relaxation of prestressing strands. A review of the literature reveals a lack of information related to the creep and shrinkage behaviors of UHPC-class materials. Specifically, there are not any available models to estimate the prestress losses due to creep and shrinkage of UHPC. The intent of this study is to address this gap. The main objectives of this research are as follows: (1) examine the current AASHTO equations for creep and shrinkage, (2) discuss the applicability AASHTO equations for UHPC-class materials, and (3) compare existing AASHTO models to measured creep and shrinkage data from different UHPC-class materials.

2. Creep Coefficient and Shrinkage

Creep is a deformation mechanism of concrete members caused by a sustained load that increases with time. The creep coefficient defines the ratio of the creep strain to instantaneous elastic strain after loading. Shrinkage is a deformation caused by hydration of cementitious materials and drying out of moisture in concrete members. Creep and shrinkage deformations are particularly important in prestressed girders because they cause gradual loss of prestress force and time-dependent deflections, which can lead to serviceability problems in bridges. The AASHTO LRFD Bridge Design Specification (AASHTO, 2017) provides equations to estimate the creep coefficient and shrinkage strain of conventional concretes up to compressive strengths of 15 ksi (103.4 MPa). Table 1 summarizes these equations.

Table 1 Creep coefficient and shrinkage strain equations

AASHTO LRFD Section 5.4.2.3 Equations		Eq.
Creep Coefficient	$\psi(t,t_i) = 1.9k_{hc}k_f k_s k_{td} t_i^{-0.118}$	(1)
Strain due to shrinkage	$\varepsilon_{sh} = 0.48\times10^{-3} k_{hs}k_f k_s k_{td}$	(2)
Humidity correction factor for creep	$k_{hc} = 1.56 - 0.008H$	(3)
Humidity correction factor for shrinkage	$k_{hs} = 2.0 - 0.014H$	(4)
Strength correction factor	$k_f = \dfrac{5}{1 + f'_{ci}}$	(5)
Size correction factor	$k_s = 1.45 - 0.13\left(\frac{v}{s}\right) \geq 1.0$	(6)
Time development correction factor	$k_{td} = \dfrac{t}{12\left(\frac{100 - 4f'_{ci}}{f'_{ci} + 20}\right) + t}$	(7)

where:

H = average annual ambient relative humidity (percent)

t = maturity of concrete (days), defined as age of concrete between time of loading for creep calculations, or end of curing for shrinkage calculations, and time being considered for analysis of creep or shrinkage effects

t_i = age of concrete at time of load application (days)

v/s = volume-to-surface ratio (in.)

f'_{ci} = design concrete compressive strength at time of prestressing for pretensioned members and at time of initial loading for non-prestressed members. If concrete age at time of initial loading is unknown at design time, f'_{ci} may be taken as 0.80 f'_c (ksi).

2.1. Creep and Shrinkage Equation Coefficients

The equation coefficients of 1.9 in Eq. 1 and $0.48 x 10^{-3}$ in Eq. 2 were determined using average ultimate creep coefficient and ultimate shrinkage strain of conventional concrete specimens in standard conditions, respectively (Tadros et al., 2003). Here, the standard conditions for creep testing were defined as a relative humidity (RH) of 70%, a volume-to-surface ratio (V/S) of 3.5 in., a specified concrete compressive strength (f'_{ci}) of 4 ksi, a loading age of 1 day for accelerated curing and 7 days for moist curing, and a loading duration of infinity. According to the measured UHPC creep and shrinkage data reported in literature, the ultimate creep and shrinkage strain of UHPC is relatively lower than that of conventional concrete (Haber et al., 2018). Therefore, the coefficients in Eq. 1 and Eq. 2 may not be applicable for UHPC.

Experimental testing would likely be required to develop new, UHPC-specific coefficients for Eq. 1 and 2; assuming the form of the UHPC creep and shrinkage equations remains the same. This could be done using an approach similar to that noted above. Experiments could be executed to determine the average ultimate creep coefficients and shrinkage strains of different UHPC-class materials in standard conditions. New coefficients could be proposed once these values are determined.

2.2. Humidity Correction Factor

The humidity correction factors k_{hc} (Eq. 3) and k_{hs} (Eq. 4) for creep and shrinkage, respectively, were determined using an average linear relationship, which was determined from data points measured at different relative humidity (RH) environments (Tadros et al., 2003). Measured data has shown that conventional concrete has less ultimate creep and shrinkage in high humidity environments (Alusi et al., 1972; Li and He, 2018). Therefore, the creep coefficient and shrinkage strain of concrete need to be modified according to the RH of service environment. According to Eq. 3 and Eq. 4, the humidity correction factor at RH equal to 70% is 1.0; this factor is inversely proportional to RH. It is anticipated that these equations could be conservatively used for UHPC-class materials. UHPC has a denser microstructure and a more disconnected pore structure compared to conventional concrete. Therefore, humidity should have a lesser effect on the creep and shrinkage properties of UHPC-class materials. A refined solution could be developed through execution of a series of experiments in low and high humidity environments.

2.3. Strength Correction Factor

Experimental data has shown that higher compressive strength concretes have less ultimate creep and shrinkage. The strength correction factor, k_f (Eq. 5), is a reduction factor that modifies the ultimate creep and shrinkage strain of concrete based on the compressive strength at the time of loading. According to AASHTO (2017), k_f is valid for compressive strengths up to 15 ksi (103.4 MPa). The strength correction factor equation (Eq. 5) is normalized to a value of 1.0 assuming a compressive strength of 4 ksi (27.6 MPa) at release and a final compressive strength of 5 ksi (34.5 MPa) at service (Tadros et al., 2003). This equation in its present form is not likely to apply to UHPC-class materials. UHPCs will have considerably higher compressive strengths at release and service compared to conventional concretes.

2.4. Size Correction Factor

The size and shape of a concrete member influences the rate at which moisture moves into or out of the concrete, and therefore influences the rate of creep and shrinkage (Hansen and Mattock, 1996). The size correction factor, k_s (Eq. 6), was determined from creep and shrinkage data collected from samples with different volume-to-surface ratios (Tadros et al., 2003). Since UHPC has a denser microstructure and a more disconnected pore structure compared to conventional concrete, the rate at which moisture moves into or out of UHPC is reduced. Therefore, UHPC members are not expected to be significantly impacted by the size and shape effect. Conservatively, it is anticipated that the current AASHTO provision can be used for UHPC members to account for size and shape effects.

2.5. Time-Development Correction Factor

The time-development correction factor, k_{td} (Eq. 7), is used to estimate creep and shrinkage of conventional concrete as a function of time. According to Mertol et al. (2010), the time-development correction factor in AASHTO (2017) is applicable for concretes with strengths up to 18 ksi (124 MPa). Since UHPC has a high volume of fiber reinforcement and a more compact microstructure, the creep and shrinkage behavior of UHPC-class materials as a function over time are different compared to conventional and high-strength concrete. This behavioral difference has been attributed to the low water-to-binder ratio and the high fiber volume that potentially generates internal restraint within the cementitious matrix (Haber et al., 2018). Therefore, the time-development correction factor in Eq. 7 may not be appropriate for UHPC-class materials.

2.6. Loading Age Correction Factor

The creep behavior of concrete also depends on the maturity and age of the concrete when load is initially applied. Compressive strength and elastic modulus of concrete increases over time, particularly at early ages. Consequently, the ultimate creep of concrete loaded at an early age is usually higher than that of the concrete loaded at a mature age. The loading age correction factor, $t_i^{-0.118}$ contained within Eq. 1, is a reduction factor that considers the maturity of concrete at the time of loading or prestress transfer.

Haber et al. (2018) conducted creep tests of five different UHPC-class materials, which were loaded at either early and mature ages. The early-age specimens were cured for 7 days or less prior to loading and had compressive strengths between 13 ksi (90 MPa) and 16.5 ksi (114 MPa). The mature UHPC specimens were cured for 56+ days prior to loading and had compressive strengths greater than 17 ksi (117 MPa). Results showed that the ultimate creep of the early-age specimens was nearly twice that of the mature-age specimen. The early-age specimens were still gaining strength and had not completely undergone self-desiccation, which lead to an increase in measured creep compared to the mature-age specimens. Based on the findings in Haber et al. (2018), it is proposed that the loading age correction factor in Eq. 1 can be conservatively applied to UHPC-class materials. However, more experiments are required to verify the loading age effect in creep of UHPC-class materials.

3. Comparison of AASHTO and Measured UHPC Data

The measured creep and shrinkage data collected by Haber et al. (2018) was used herein to compare measured UHPC creep and shrinkage data with the existing AASHTO prediction models.

Figures 1 and 2 show the measured creep responses of four different UHPC-class materials loaded at early age and mature age, respectively. The plots denote the loading age, L_a (days), compressive strength at the beginning of testing, f'_{ci} (ksi)[MPa], and sustained stress, σ (ksi)[MPa]. Each plot shows a best-fit curve for the measured data, which was report by Haber et al. Lastly, each plot also shows the AASHTO-predicted creep curve. This was determined using Eq. 1 and measured UHPC material properties reported by Haber et al.

Results indicate that the current AASHTO provision-based predictions for creep coefficient cannot appropriately estimate the creep coefficient of UHPC-class materials; the predicted values are far below the measured data. This result is expected because the AASHTO model was developed for conventional concrete and is not calibrated to predict the performance of a material with substantially different mechanical properties. UHPC has a compact microstructure, low water-to-binder ratio, disconnected pores, high volume of fiber reinforcement, and high compressive strength and elastic modulus compared to conventional concrete. These parameters effect the behavior of UHPC-class materials under a sustained load over time.

Figure 3 shows measured strain due to shrinkage for the four UHPC-class materials. The data shown depicts the total shrinkage strain measured after the specimens were removed from their molds at 24 hours per ASTM C157 (Haber et al., 2018); total shrinkage strain includes drying and autogenous shrinkage. The measured data points were connected with straight lines to aid visualization. It should be noted that the abrupt changes in shrinkage strain were caused by slight variations in the laboratory environmental conditions. The AASHTO shrinkage model is also shown in Figure 3. The current AASHTO provisions underestimate the strain due to shrinkage of UHPC-class materials.

Based on the data shown in Figures 1 through 3, the AASHTO provisions for creep and shrinkage behavior need to be modified to capture the response of UHPC-class materials and members.

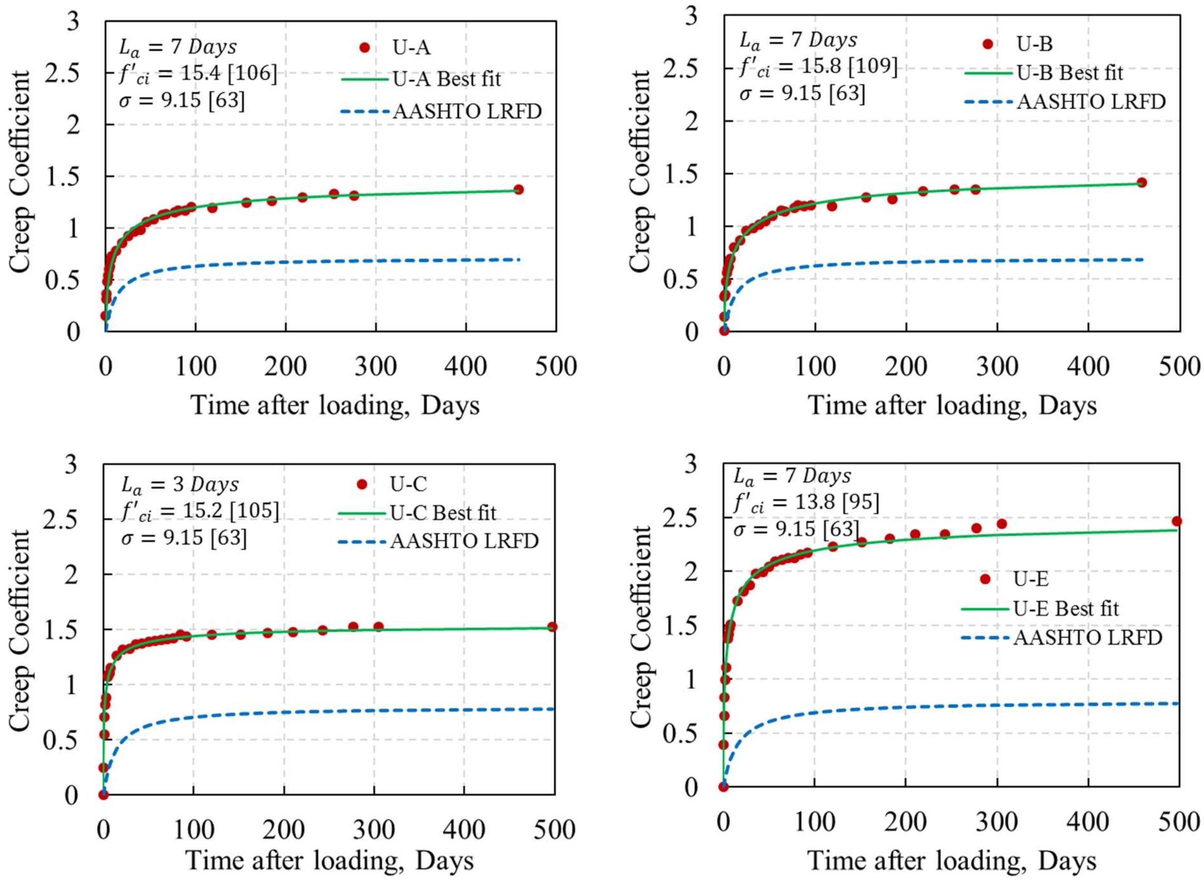

Figure 1. Creep coefficient of UHPC loaded at an early age

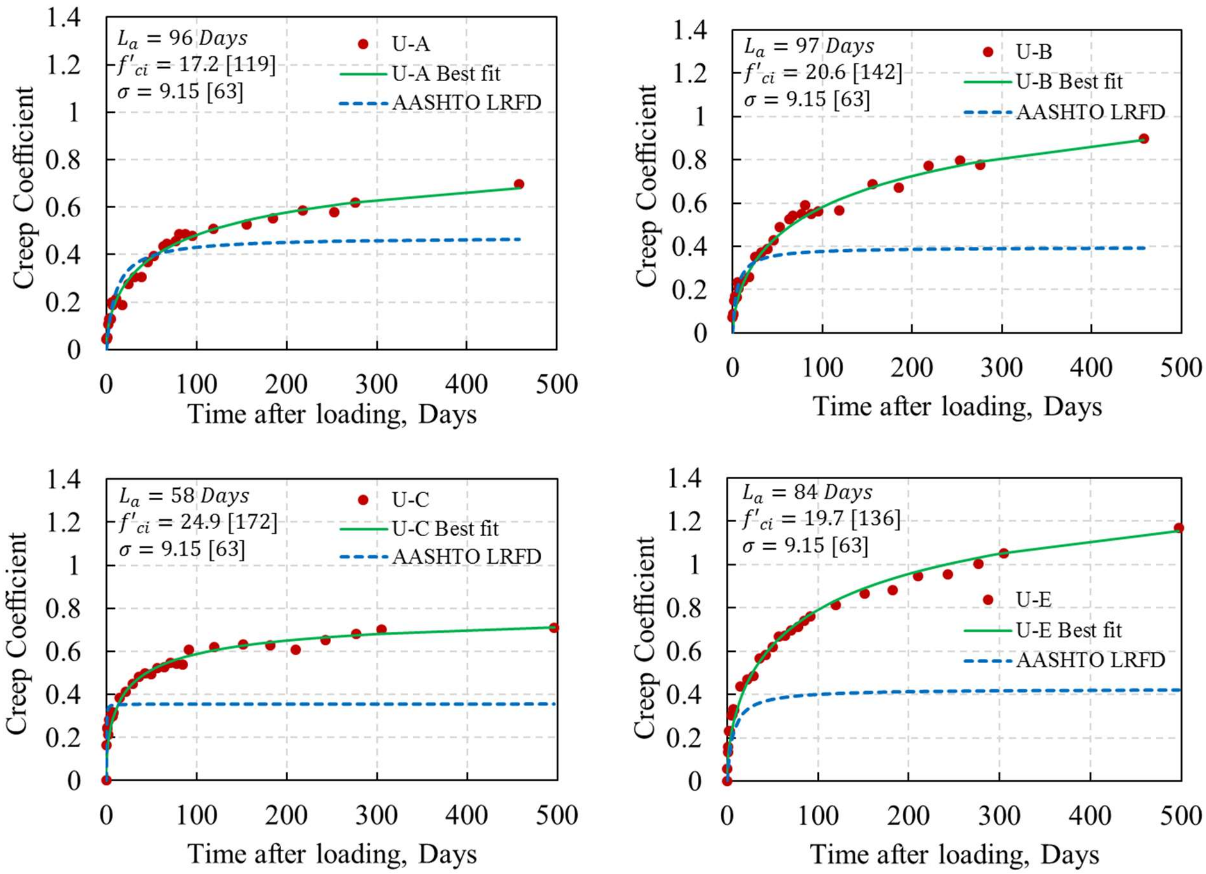

Figure 2. Creep coefficient of UHPC loaded at a mature age

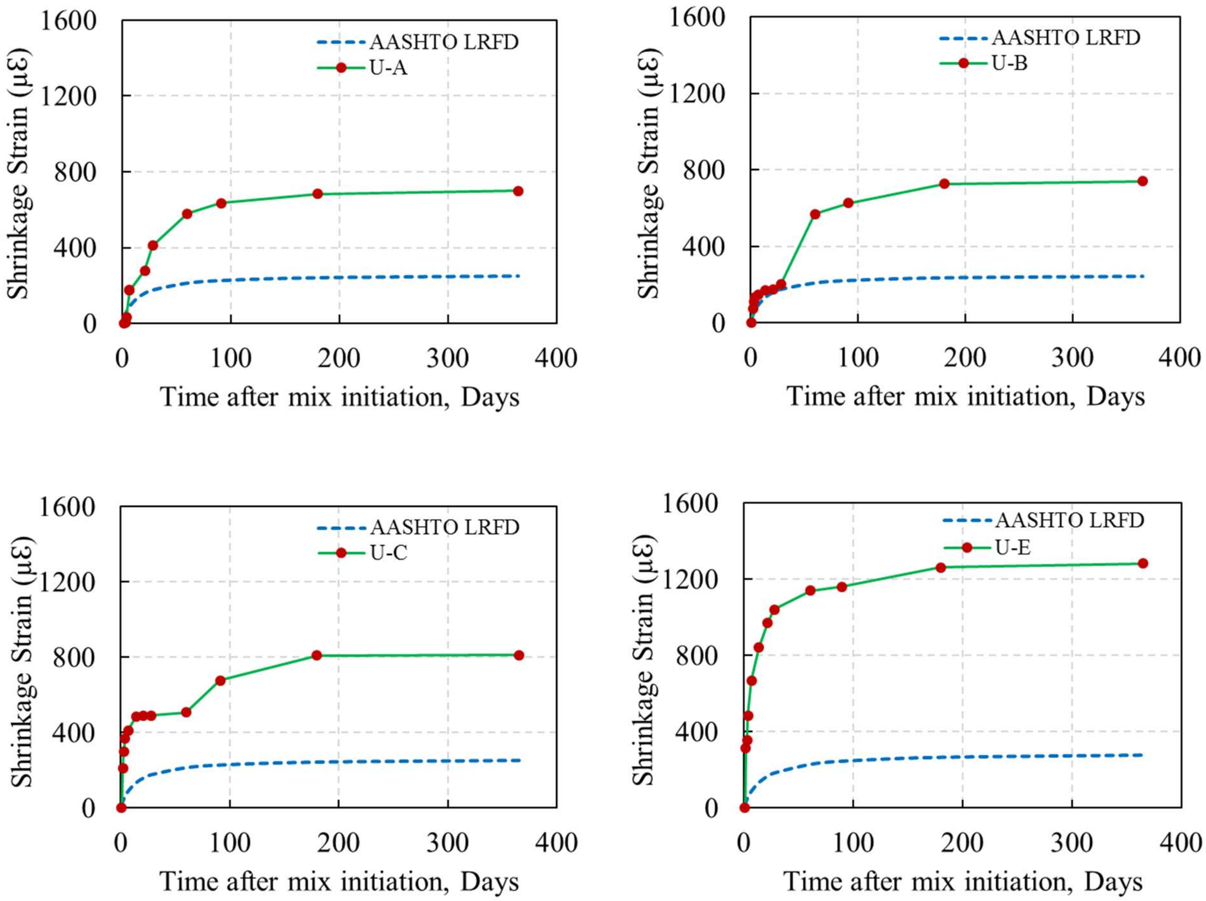

Figure 3. Strain due to total shrinkage of UHPC

4. Future Work

A new series of creep and shrinkage experiments are being conducted on different UHPC-class materials at FHWA's Turner-Fairbank Highway Research Center to address the research gaps discussed in this paper. Figure 4 shows a picture of creep testing that is underway. The experimental variables include sustained stress level, relative humidity, and UHPC type. Unlike previous studies on creep and shrinkage of UHPC, this series of tests will investigate the effect of different environmental conditions on creep and shrinkage of UHPC-class materials: conditions include relative humidity of 80% (Frame 1), relative humidity of 50% (Frame 2 and 4), and a sealed condition (Frame 3). The creep room temperature is maintained at 73.4 ± 3.6 ºF (23 ± 2 ºC).

This experimental program will aim to determine new coefficients for the creep and shrinkage equations, new humidity correction factors, and a new strength correction factor for UHPC-class materials. In addition, the new results are expected to provide insight on the time-development and loading age correction factors of UHPC-class materials. Newly-collected data will be integrated with data from previous studies to develop AASHTO-like provisions for creep and shrinkage of UHPC-class materials to estimate long-term losses of prestressed UHPC girders.

Figure 4. Creep cylinders in load frames

5. Discussion and Conclusions

The intent of this study was to briefly describe the important parameters influencing the creep and shrinkage models for conventional concrete in AASHTO LRFD (2017), and examine the applicability of these parameters for UHPC-class materials. UHPC has superior mechanical properties, a low water content, and a high volume of fiber reinforcement, which influence the creep and shrinkage behavior compared to conventional concrete. The current AASHTO prediction models for creep coefficient and shrinkage strain do not consider the properties of UHPC. AASHTO equations do not accurately estimate the creep coefficient and shrinkage strain of UHPC-class materials based on comparisons with experimental data. However, it is likely that some parameters in the AASHTO equations can be conservatively used for UHPC-class materials including the humidity correction factor, the size correction factor, and the loading age correction factor. Other parameters including the equation coefficients, the strength correction factor, and the time-development correction factor may require recalibration for UHPC-class materials.

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