Bridge Design and the Creep Conundrum

By: David Goodyear

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INTRODUCTION

This paper presents an argument for modifying structural design practice to consider the variance in time-dependent concrete material properties within the context of reliability-based design codes. The author's primary reference is to bridge design. However, the discussion is generally applicable to structural design wherever the time-dependent properties of concrete can affect structural performance.

The discussion focuses on concrete creep, recognizing that the assignment of time-dependent concrete strains under long-term loading to creep or shrinkage can be a consideration in assigning variance to any particular design protocol. Much of the discussion is based on the *fib* Model Code 2010[1] formulation for forecasting creep and shrinkage as the appropriate basis for bridge design. Other methods including prior CEB-FIP methods, ACI 209, and research methods such as B3 and B4 are instructive for the assessment of variance in design and the potential impact on codified assignments for design reliability.

BACKGROUND

The AASHTO Standard Specifications (LRD design basis, prior to 1994) contained a topical reference to creep without recommendations for evaluating creep strains other than through scalars applied to initial deflections and modular ratios applied to composites. There was reference to "more comprehensive analysis" as a designer's option, but otherwise, a uniform factor of 4 was applied to initial elastic section deflection computations. There was no commentary with the Standard Specifications, so there was no explanation of how the scalars should be incorporated into the effective modulus behavior affecting changing statical systems. Creep was accounted for as a load (R + S + T) with a load factor of 1.

The AASHTO LRFD Code initially carried treatment of creep forward from the Standard Specifications as a separate load effect. Later editions of LRFD incorporated creep as an element of dead load within the reliability format of the Code.

The challenge with formulating design reliability for concrete structures is that concrete creep is not a load. Creep is a material property, just as the 28-day modulus is a concrete material property. Concrete response to permanent load is nonlinear over time. Creep is an element of modulus—an age-adjusted modulus—for the concrete material within a concrete or composite member. Creep can affect the distribution of loads within an indeterminate structure or within a member section. However, while creep strain does not affect load equilibrium for a structural system, it can affect reliability for section design due to redistribution of section forces applicable to design.

When performing structural analysis to determine demands for design, the modulus is not considered as a load, but the effect of modulus on the distribution of loads into member forces is considered for indeterminate sections and systems. The treatment of creep as a load is an artifact of the linear analysis methods used for bridge design. By bracketing the effect of creep on member response due to the self-equilibrating effects of creep over time, the nonlinearity of the concrete modulus is bound so as to assess the redistribution of internal forces over time. The change in modulus over time changes the distribution of forces over time, and thereby alters the reliability (β for demand versus resistance) on a section or member level, which can affect the controlling system reliability. It then becomes challenging to ascertain the effect of creep on the reliability of section strength associated with external loading (because it is not a load) or the resistance of a concrete or composite

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member without considering a confidence level for the age-adjusted modulus due to creep.

In the case of statically determinate concrete structures, modulus is primarily a factor in deflections; therefore, other than for assessing post-tensioning losses in a determinate beam, the age-adjusted modulus has been addressed as a serviceability consideration. The evaluation of creep is anchored to service limit state analysis because material behavior and forecasting methods are bounded by service limit state stresses in concrete—generally below $0.40f_c'$. For statically indeterminate structures, particularly those subject to changing statical systems during and after construction, the nonlinear material effects can have a direct influence on the reliability of concrete and composite bridge design for both the service and strength limit states.

The argument for adopting a design approach that addresses material nonlinearity for concrete and composite bridge structures has parallels with the recent changes in AASHTO[2] for the limit state analysis of wind. In the case of wind design, the historical approach for extreme winds was to apply a load factor to 100-year return period loads for strength, assuming that a load factor would address reliability for strength design. The corresponding limit state wind speed was much higher than the nominal design wind speed, so the implicit assumption was that structural demand would scale linearly using the load factor. However, AASHTO recognized that the aeroelastic effects of the higher wind speed differ from the 100-year return wind speed case (wind demand is nonlinear with wind speed for a flexible structure and does not scale linearly with a load factor), so AASHTO corrected the design basis to provide reliability through return wind speed rather than a load factor and required that analysis incorporate the strength limit wind speed directly.

In a similar fashion, creep in concrete can increase with permanent stresses above the $0.40f_c'$ level to a greater or lesser degree depending on the mixture design and compressive strength of the concrete.[3] Typical concrete structures may not see permanent strength limit state stresses significantly higher than $0.40f_c'$ across a general cross section, although composite members may see higher concrete stresses at the strength limit state prior to creep redistribution. The increasing nonlinear character of creep above the code-based stress level can add to the variance for strength and extreme limit state analyses in those cases where the strength limit state includes high long-term permanent load. This variance is nonlinear and should be considered directly in design.

Conventional design practice does not address the variance in concrete material modulus. The elastic modulus of concrete is generally referenced to a predictive equation based on concrete strength, with some formulae modified for aggregate type. The norm is generally based on a 28-day strength established using ASTM C469/C469M[5] with variations determined analytically for other maturities (or similar testing in European standards). The implication with the formulae for modulus is one of precision. Yet any broad testing program across a normal range of concrete mixture designs will show considerable scatter, similar to Fig. 1.

The 28-day reference is an arbitrary maturity for elastic analysis that provides for standardization of material specifications and design protocol. Yet permanent loads are often applied at earlier ages than 28 days, and always applied at later ages, requiring an age-adjusted modulus to be considered for structural behavior. The simple form for age-adjusted modulus is $E_{ci}/(1+\phi_{(t)})$, where E_{ci} is the modulus at loading and $\phi_{(t)}$ is the ratio of inelastic strain to elastic strain over time. This is the definition used in ASTM C512/C512M,[6] where creep strain ratio is referenced to initial loading age. Note that creep in MC 2010 is referenced to E28 instead of E_{ci}, however the general form for age-adjusted modulus is the same. The variance of interest is the net age-adjusted modulus, which by definition incorporates the combined variance of E_{ci} and ϕ.

There are several formulations that are often compared on a time scale showing the increase for inelastic strain over service life (that is, plots of the ϕ factor alone). Because these formulations are from different basic codes (such as ACI 209, AASHTO, CEB-FIP 78, CEB-FIP 90, and Model Code [MC] 2010) with different equations for computing E_c, comparison of creep factors alone is not meaningful without including the reference to the corresponding E_c value for elastic strain and for definition of creep coefficient. For instance, when comparing ACI 209[7] using the average creep factor of 2.35 to MC 2010 for a 6 in. (150 mm) slab loaded at 7-day maturity, a comparison of creep factors from MC 2010 and ACI 209[7] versus creep divided by the concrete modulus associated with each method leads to a significantly different interpretation when comparing the alternative methods (Fig. 2). The ACI 209 mean creep coefficient is referenced herein due to the common application of mean value per ACI 209. ACI 209 suggests a range of applicable coefficient from 1.3 to 4.5 and refers to ASTM C512/C512M[6] for

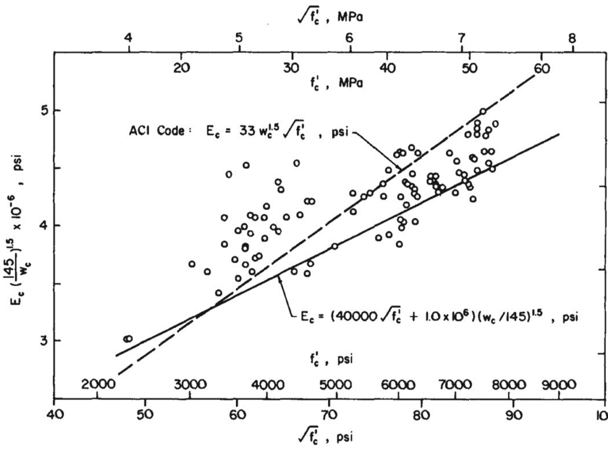


Fig. 1—Typical scatter of modulus testing.[4]

project-specific determination of appropriate factors. Few engineers evaluate the range provided in ACI 209.

Sources of variance in creep

There are two general sources of variance for creep effects in bridge design. The first is in the execution of the particular analytical method for computing creep strains (methods vary themselves, but this reference is to execution of any particular method). The second is the intrinsic variability of time-dependent material behavior—that is, the variance of actual material response relative to mean material response as it departs from the analytical method. Both partial variances are large relative to the more ordinary variances considered when establishing the reliability of codified design.[8]

ANALYTICAL VARIANCE

Forecasting methods

Modern codes for forecasting creep strains are based on material and environmental inputs that are assumptions at design time. Referring to MC 2010 for discussion, the primary environmental inputs are humidity and temperature. The primary material inputs include design strength (not target strength, which is often closer to the actual strength, and therefore better correlated with the empirical database), aggregate type, and cement type. MC 2010 commentary includes discussion on how the limitations on mixture design detail at design time established the framework for material inputs to the MC 2010 method.[9]

While the MC 2010 creep provision addresses an array of influences on creep behavior, some effects are invoked or ignored at the discretion of the designer. The designer's election of inputs can create a variance due to analytical rigor, with the designer's process also influenced by the

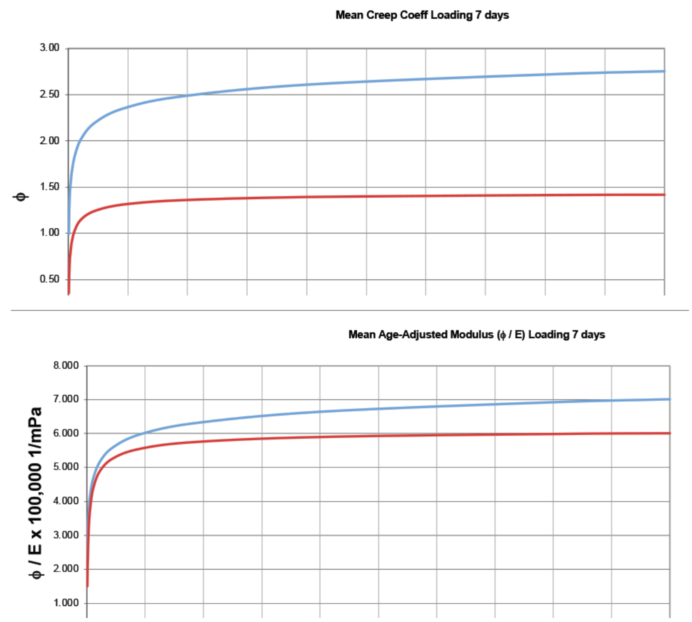


Fig. 2—Comparison of creep coefficients versus effective modulus for alternative methods.

speculative nature of some input parameters.

For example, temperature is included in the input parameters for estimating creep strain. While service temperature is related to material behavior as well as maturity,[1] the more significant temperature effect for cast-in-place segmental design is during the early age for concrete, where cantilever construction dead loads are applied as early as possible to advance construction. MC 2010 provides for an adjusted age at loading (an increased maturity) that is a function of curing temperature. Cement and aggregate type are also inputs to computations for creep. However, the assignment of curing temperature within the design analysis for creep is not common and selection of cement and aggregate is often arbitrary at the design stage.

A simple increase in curing temperature from ambient of 68°F (20°C) to in-form of 122°F (50°C) advances a 3-day nominal age to a 10-day effective age—a change which can alter the target creep by 10 to 20% by MC 2010 methods. The geometric influences on temperatures within the cross section add further to this uncertainty. Neither curing temperature nor operating temperature are deterministic at the time of design. For most of the continental United States, the predicted effect of operating temperature over time is nominal in comparison to the effect of curing temperature. Selections for cement and aggregate[9] can affect creep forecast by 10 to 20% and total strains (elastic plus creep) by 30 to 40%. These effects of design variables for creep should be factored into the variance, even if the analytical formulation for the effects of temperature, aggregate, and cement on creep is assumed to be precise. The binary nature of these potential analytical variances (binary being the designer's choice to include or omit a particular effect) has a strong influence on the reliability of creep forecasts.

Engineering methods

Contemporary practice for concrete bridge design is based on the use of space frame beam models for concrete girder spans that include section property variations along a span, account for the sequence of construction and include a forecasting method for computing time-dependent deflections and associated stages of force, and displacement demands from construction to the end of service. The use of discrete solid element models (such as finite element analysis [FEA]) of cross sections is generally limited to local analysis or academic studies.

Commercial programs used for analysis and design vary in analytical approach. The variances due to options in programs are compounded by the way that different engineers apply the features of any particular computer program, making it difficult to assume a consistent design baseline for any method or software routine.

These variances, both in computer software algorithms and in user application of software, can add to the variability of a designer's application of methods for creep effects and should be combined when considering the variability associated with creep in design.

There are two potentially significant analytical inputs that can meaningfully affect computations, but which are not consistently applied by designers.

Many large concrete segmental bridges include deep structural sections over pier supports that taper toward more slender sections near the midspan. Figure 3 shows such a section near the pier for a U.S. concrete segmental bridge. Elements within the cross section have significantly different notional thicknesses, and element response within the cross section will exhibit different time-dependent drying creep and shrinkage strains.

Following the methods of Ghali and Favre,[10] an evaluation of the cross section as a layered member will result in eigenstresses that impart curvature to the section for both creep and shrinkage—curvature that is real but ignored in a line-element analysis. Restraint of differential shrinkage can also lead to moment curvature within a discretized section.

A similar effect of restraint computation applies to reinforcement within each element, compounding the layered analysis from that of a line element. Axial restraint of creep and shrinkage from embedded reinforcement is proportional to $1/(1+\rho N)$. In elements with high reinforcing ratios (ρ) such as columns, towers, or composite decks, the restraint effect can alter strain forecasts by 10 to 20% or more. Few engineers routinely apply design algorithms that include layering and embedded steel restraint effects, which adds further to the variance of creep computations in design.

MATERIAL VARIANCE

The variability of concrete material properties is widely recognized in construction specifications that have been developed for production control and acceptance. Production controls vary by project and may include target or minimum values for 28-day compression strength, durability factors, density, elastic modulus, or mean creep coefficient. There is no corresponding recognition in design specifications for how the variability of material properties beyond minimum acceptance standards can affect reliability for either service or strength limit states in design.

Creep versus shrinkage in design

The methods used to forecast concrete material behavior are largely empirical. Different methods have evolved from a common empirical database. With reference to the MC 2010 method, both creep and shrinkage include two-component formulations. Creep is separated into basic creep and drying creep, and shrinkage is separated into basic shrinkage and drying shrinkage. Both drying elements are a function of notional thickness of concrete elements exposed to an environment, whereas the basic elements are a function of the material alone. The MC 2010 formulation stands in contrast to other code formulations (ACI 209 and past CEB-FIP formulations, in particular) that have single-component creep or shrinkage or relate most time-dependent response to notional thickness and environment. As discussed earlier (refer to Fig. 3), the difference in component assignment to creep versus shrinkage can lead to a difference in outcome for time-dependent displacement forecast as applied in design, particularly as it relates to how shrinkage is typically considered for beam design. The development of alternative formulations for forecasting creep and shrinkage should be considered as part of the variance in material properties that serve to forecast mean values by any method.

There are several publications that address the reliability of theoretical formulations against the empirical database for concrete creep and shrinkage. The database most often referenced is the RILEM database that grew out of the Northeastern University database from 1978. A majority of the data sets are relatively short-term, far less than bridge service life. One long-term study of particular note is that from Brooks,[11] which presents results from a 30-year study on the ascension of creep, which is consistent with the character of basic creep described in MC 2010.

ACI 209.2-08[12] includes a survey of creep and shrinkage forecasting models as of the 2008 publishing date. ACI 209.2 addresses mixture design elements that affect creep, and most are not specified at design time.

Table 4.3 of ACI 209.2 presents a range of deviation from mean values for creep associated with prediction methods covered within the report. Wendner et al.[13] report variance for alternative creep prediction methods against the RILEM database, showing that variances vary from 26 to 59% depending on the method. The more comprehensive methods—those requiring more details for mixture design and environment—generally correspond with lower variances. However, a correlation with more extensive material definition contrasts with the limited material knowledge base at design time.

MC 2010 (published after ACI 209.2) Commentary 5.1.9.4.3 suggests a 25% variance for MC 2010, while Bažant et al.[14] found a 34% variance for MC 2010 with an extended database.

The variances that are presented for predictive methods for mean creep should be considered as variances in material behavior relative to the mean creep response based on the method used for forecasting creep input to bridge design. The creep curve for concrete is not deterministic.

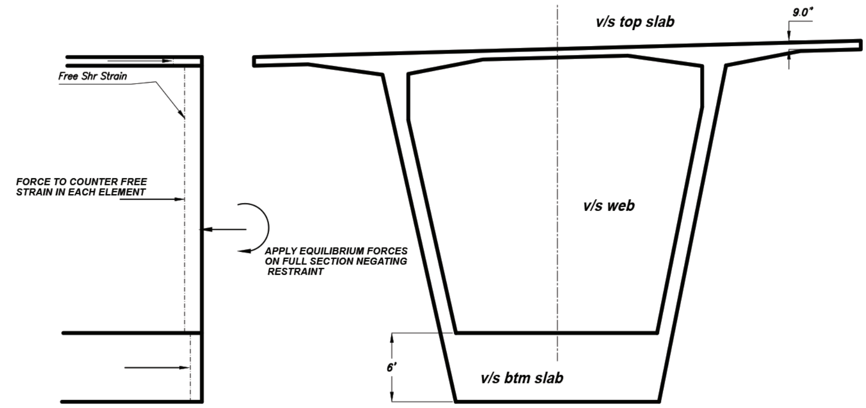


Fig. 3—Typical concrete segmental section-layer analysis.

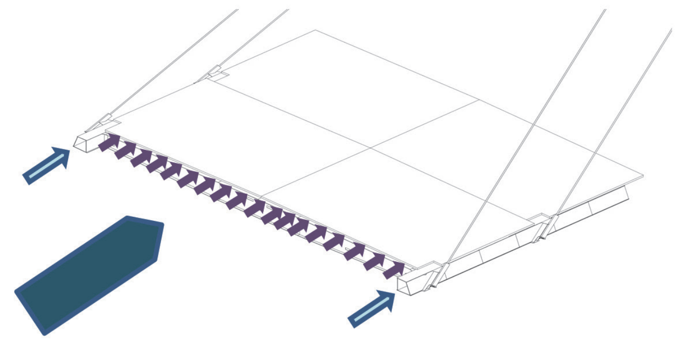


Fig. 4—Typical composite cable-stayed deck.

IMPACT OF CREEP ON DESIGN

While creep does not affect global equilibrium, creep can affect the distribution of forces in concrete frames and composite members that define the design basis for member sections. Perhaps the clearest case is the design of an axially loaded composite member. This is a common design configuration for a composite cable-stayed bridge in the United States (Fig. 4). The stiffness-adjusted area ratio of concrete deck to steel edge girder results in most permanent axial load from stays being resisted by the concrete for typical precast deck designs. Creep in the deck sheds axial load to the steel edge girders. Design reliability for the steel edge girders is influenced by the reliability of the creep coefficient-based force distribution associated with the concrete deck.

The more common application for creep influence on design is associated with segmental concrete bridge construction—particularly for free cantilever construction where the construction stage requires deflection control, and design for the final continuous statical system is based on the degree to which creep redistributes moments from the cantilever towards the final statical system. Less common but equally significant is the design of concrete arch bridges (Fig. 5), where the final grade is controlled by creep and spandrel column moments are affected by creep in both the arch (higher arch creep producing higher demand) and in the spandrel columns (lower column creep producing higher demand).

Variance in creep is less relevant for the construction case because settings for deflection during construction are targeted to mean values for reliability of deflection control. However, the effect of creep on strength design for all types of structural frames and composite members may not have an obvious controlling bias (high or low).

Reliability

The response of a concrete structure is determined by the age-adjusted modulus. The age-adjusted modulus for concrete does not provide the same reliability as a narrow-band, stable elastic modulus similar to steel, yet the elastic design approach in the AASHTO Code treats both cases the same.

The potential impact on reliability of a bridge element where creep moments dominate demand, such as the region of contraflexure in a continuous frame or the spandrel moments over a concrete arch, is illustrated in Fig. 6.

The resulting reliability for these and similar conditions is not reflected in the calibration for the Code. To the extent that such sections can control either serviceability or strength, and therefore limit the utility of a bridge, design protocol needs to include more explicit accounting for the variance in creep.

The AASHTO Code association of creep with dead load is a proper association in terms of behavior because the age-adjusted modulus of concrete material is fundamental to computing the time history of limiting strain and stress distribution for indeterminate structures. However, the effect of creep on the reliability of dead load demand is not consistent with the reliability formulation for the AASHTO Code, so a separate approach is needed for creep, just as is the case for any other fundamentally nonlinear material.

RECOMMENDATIONS

Concrete member strength is incorporated into the reliability formulation for the AASHTO LRFD Code as outlined in Kulicki et al.[8] and combined with an assignment of the variance in external loads to confirm a target reliability (β). By ignoring the variance in creep, the implicit assumption is that the variance in creep will not limit the serviceability of a bridge over its service life and that creep will not influence functional section design strength. History shows that neither assumption is always correct.[14,15]

The large variance in concrete material behavior creates a conundrum for concrete bridge design. Creep affects the distribution of dead load forces for composite structures and indeterminate concrete structures erected under changing statical systems, even though creep does not change dead load equilibrium.

This paper is not recommending a separate partial load factor for creep because creep is not a load. The approach of this paper is to evaluate a confidence level for the age-adjusted modulus used in analysis sufficient to eliminate a significant error in the coefficient of variation for concrete dead load demand that is the basis for AASHTO LRFD load factors.

The character of time-dependent material stiffness in design has more in common with soil than with steel. The design challenge is similar to that for seismic design, where foundation stiffness can vary widely depending on how soil responds to ground

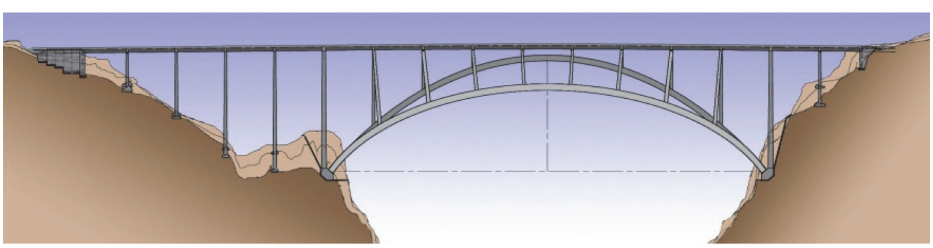
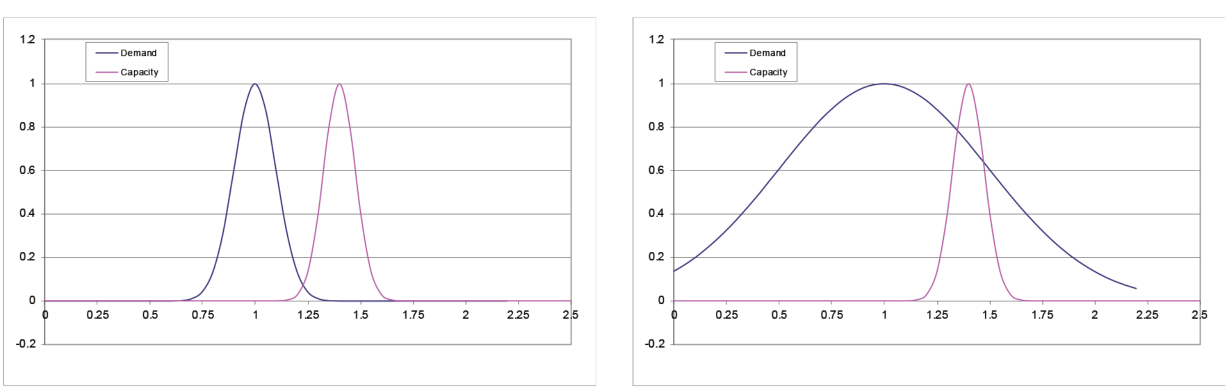


Fig. 5—Spandrel column moments due to creep deflection.



β for AASHTO Concrete Dead Load Variance

Impact of V=50% in Creep Change to Dead Load

Fig. 6—Impact on reliability where creep moments dominate demand.

Table 1—Variance recommendations for creep

Analytical variance	V
Temperature assumptions	0.05
Model refinement	0.1
Mixture design assumptions	0.1
Material variance	
Method correlation to database	0.25
Variance for forecast of creep strains (sum)	0.5

Table 2—Creep multiples for reliability

Confidence band	Multiple on computed mean for $V = 0.5$
95% bracket	0.17/1.83
95% upper bound	1.98

motion. The method used for seismic design is to envelope design forces associated with liquefied and non-liquefied soil properties. In the case of soil liquefaction, the stiffness range is large—so large relative to the permanent load variance embedded in the Code that the reliability framework for Code-based design is applied for each extreme stiffness rather than adjusting the permanent load design basis. The same situation should apply to concrete bridge design for creep.

Based on the material presented in this paper and based on application of MC 2010 to design, partial variances against the forecast of mean creep can be in the ranges shown in Table 1.

The variance (V) assumed within AASHTO for dead weight of cast-in-place (CIP) concrete[8] is 0.10, which typically accounts for 85% or more of the load for a long-span concrete segmental bridge (V is 0.08 for factory precast). Code calibration does not include specific consideration for refined structural analysis of either the demand or resistance computations, so any effect of creep variance should fall within the reliability framework for dead load (for example, reliability of the creep forecast should be sufficiently large so as not to affect reliability of dead load demand assumed in design).

As with the case for foundation stiffness in seismic design, the envelope approach to addressing creep in design can be based on the current code conventions for reliability. The open question is how to determine the appropriate confidence level for creep-based, age-adjusted modulus. The assignment of net variance indicated in Table 1 is general, and complicated by limited data, by the differences in alternative computational methods, and by the binary nature of design methods. Grouping all computational variances into one factor would result in a summation of individual variances in Table 1. The election of refined analyses could justify a more limited cumulative statistical variance for analytical items, alternatively applying the SRSS (Square Root of Sum of the Squares) of the individual items. In either case, the variance can be significant for design.

Few structural reliability criteria are accepted at a threshold less than 95% non-exceedance, which equates to $1.96V$ for an upper-bound analysis over the mean for designs where maximum creep will control demand—for instance, a segmental girder system supported on bearings. Designs of complex composite sections and continuous frames that require a bracketed analysis rather than just an upper bound (refer to discussion on Fig. 5) should be reviewed for a 5%/95% differential to envelop the maximum dead load demand that comes from restraint of creep within a structural system (refer to Table 2). Designers must apply their knowledge of system behavior to determine how the assignment of upper- and lower-bound values maximize demands from creep. This assignment is generally obvious for a given structural system and range of concrete types specified for construction.

The reliability concepts in this paper are fundamental to strength design. In many cases, it can be difficult to separate strength design from serviceability because serious serviceability effects can compromise member strength. A 95% confidence for non-exceedance addresses the cumulative normal distribution, which equates to β of 1.96. For $V = 0.5$, the upper-bound multiplier is then $1 + 1.96 \times 0.5 = 1.98$. For a bounded evaluation of both extremes (high versus low), the 5%/95% confidence band represents a partial β of approximately 1.65 for an upper factor of $1 + 1.65 \times 0.5 = 1.83$ and a lower factor of $1 - 0.83 = 0.17$. Serviceability considerations for deflections often have no high or low bias, so warrant targeting the mean values for creep. However, even in serviceability cases, the designer and contractor can be better informed through a review of how the variance in creep can affect targets for deflection or crack control and offer guidance on how the service limit state targets can be more reliably achieved during construction.

Developing a simple solution to a complex problem is part of the art of engineering. Virtually all major bridge analysis is now automated through either commercial or proprietary design software. The effort to address the reliability bandwidth for age-adjusted modulus is trivial for a software solution, needing only to expand the enveloping process for demand according to the upper- and lower-bound values prior to proceeding with the conventional design algorithms. This simple change to design criteria will improve the quality of long-span post-tensioned concrete bridge design and expand the market for innovative concrete bridge structures.

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David Goodyear, *PE, SE, NAE, joined the Olympia, WA, office of Arvid Grant and Associates in 1980 as a bridge engineer and began his association with PTI in 1983 as AGA's representative on the newly formed PTI Committee on Cable-Stayed Bridges. He continued PTI Committee work with the ad-hoc committee on Design and Construction for Segmental Concrete Bridges, assembled to deliver the 20-7/32 Guide Specification of the same name in 1988. He formed his own engineering practice of DGES in 1987, which became part of T.Y. Lin International in 1996. Goodyear was the Chief Bridge Engineer for T.Y. Lin International until December 2018. He is now a consulting structural engineer in Olympia, WA. While the Segmental Guide Spec was turned over to AASHTO for incorporation into the Code, the PTI Committee on Cable-Stayed Bridges has continued under the leadership of PTI as Committee 45 since its founding. Goodyear has served on that committee for the past 40 years, including 10 years as Chair. He has led the design of a number of major bridges, including the Mike O'Callaghan–Pat Tillman Memorial Bridge at Hoover Dam; the Port Mann Bridge in Vancouver, BC, Canada; and the Crooked River, Sellwood, and Tilikum Bridges in Oregon. While working for Arvid Grant in Olympia, he was a lead engineer for the East Huntington cable-stayed bridge in West Virginia.*

Goodyear has served as President of the Structural Engineers Association of Washington and has been actively involved in AASHTO Bridge Code committee developments for major bridge design. He is a recipient of the Beavers Organization's Outstanding Engineering Award for his work in engineering for construction of arch and cable-stayed bridges, is a member of the National Academy of Engineering and the National Academy of Construction, and is a Fellow of the Post-Tensioning Institute.