Calculation of Prestress Loss and Beam Concrete Stress Due to Shrinkage of Deck Concrete

by Richard Brice, Washington State Department of Transportation

The American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[1] refined estimates of time-dependent prestress losses (LRFD Eq. 5.9.3.4.1-1) includes a term for prestress gain due to shrinkage of deck concrete Δf_{pSS} (LRFD Eq. 5.9.3.4.3d-1). This term accounts for the elongation of the prestressing strand due to the mechanical action of deck concrete creep and shrinkage as well as the time-dependent change in prestressing force due to creep of the beam concrete induced by the same mechanical action. The introduction of this gain in prestress as part of the total prestress loss has caused a lot of confusion and is often misapplied in design calculations for pretensioned beams.

Design examples in Chapter 9 of the upcoming fourth edition of the Precast/Prestressed Concrete Institute's *PCI Bridge Design Manual*[2] introduce a more rational method of stress analysis by using transformed section properties appropriate to the time when the prestressing force and *external* loads are applied. Gross (nontransformed) concrete section properties are used for redistribution of *internal* forces due to time-dependent prestress losses from creep and shrinkage of concrete and relaxation of prestressing reinforcement. The use of nontransformed section properties provides a reasonable approximation for the net concrete section properties required for initial strain analysis.

An appendix to Chapter 8 of the fourth edition *PCI Bridge Design Manual* provides a detailed mathematical explanation of how prestress loss and beam concrete stresses due to shrinkage of deck concrete are accounted for in the AASHTO LRFD specifications and how these topics are treated differently in the fourth edition *PCI Bridge Design Manual*. This article summarizes the main points of that appendix. The reader is directed to the appendix of Chapter 8 of the fourth edition of the *PCI Bridge Design Manual* for a more thorough and detailed discussion.

Shrinkage of Deck Concrete: PCI Recommendation

When the concrete deck is composite with the prestressed concrete beam, the shrinkage deformation of the deck causes deformations throughout the composite cross section. Internal self-equilibrating forces in the prestressing reinforcement and concrete section are then developed.

The self-equilibrating internal forces associated with shrinkage of the deck concrete can be determined by performing an initial strain analysis. This analysis is similar to the procedure that would be carried out for temperature changes.

The initial strain analysis is accomplished with the following steps:

1. Remove the bond between the deck and beam concrete, allowing the deck to deform freely: ε_{ddf} in **Fig. 1**.
2. Restore compatibility by applying a restoring force P_{dsr} to the deck, which returns the deck strain to zero (**Fig. 2**). Note that under the sustained restraining force, the deck concrete undergoes creep, so it is the total creep and shrinkage strain that is brought to zero by the restoring force.
3. Restore the bond between the deck and beam concrete and restore equilibrium by applying an equal and opposite restoring force P_{ds} to the composite section using the age-adjusted modulus of elasticity (**Fig. 3**).

This analysis results in a change in the stresses in the concrete section and a gain in the stress of the prestressing strand. Use of the age-adjusted modulus of elasticity in step 3 accounts for both the initial strain

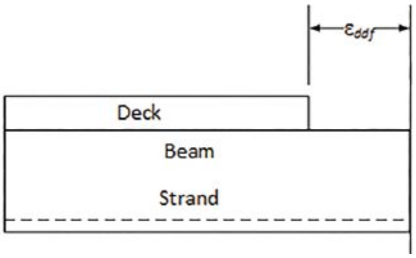


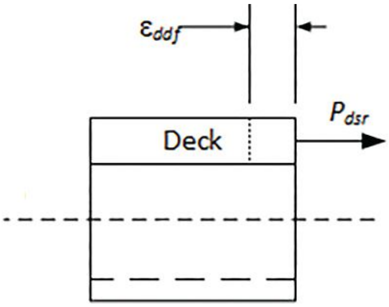
Figure 1. For step 1 of the initial strain analysis, the bond between deck and beam concrete is removed, allowing the deck to deform freely. All Figures: Washington State Department of Transportation.

caused by the internal self-equilibrating force in the net composite concrete section and the creep strain in the concrete that occurs over time due to the internal force developed in the net concrete section.

Treatment of Deck Shrinkage in the AASHTO LRFD Specifications

The prestress gain due to shrinkage of deck concrete Δf_{pSS} (LRFD Eq. 5.9.3.4.3d-1) in the time-dependent losses equation (LRFD Eq. 5.9.3.4.1-1) from the AASHTO LRFD specifications is obtained directly from the initial strain analysis. However, the change in beam concrete stress is not directly accounted for in the AASHTO LRFD specifications and is often overlooked. Treating the shrinkage of deck concrete as an external force is a simple method of estimating the effect shrinkage of the deck concrete has on the beam section. When the beam concrete stress is computed using transformed sections,

Figure 2. In step 2 of the initial strain analysis, deck concrete strain is restored to zero by applying force P_{dsr}.



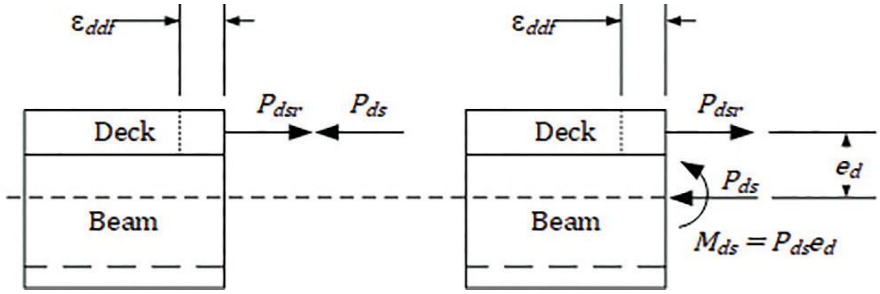


Figure 3. In step 3 of the initial strain analysis, equilibrium is restored by applying an equal and opposite restoring force P_{ds} to the composite section using the age-adjusted modulus of elasticity.

the effect of bond and strain compatibility between the prestressing steel and concrete is implicitly considered; hence this effect is called the "implicit elastic gain." For deck shrinkage, the implicit elastic gain is directly included in Δf_{pSS}. When using transformed section analysis, the implicit elastic gain due to shrinkage of the deck concrete is accounted for twice: once in Δf_{pSS} and once in the transformed section stress analysis.

Excluding Δf_{pSS} from the time-dependent prestress losses corrects a double-counting issue when transformed section analysis is used. However, Δf_{pSS} also includes the change in prestress due to beam concrete creep induced by the tension stress in the beam from deck shrinkage. These creep strains elongate the strand, resulting in an increase in the effective prestress and a change in the beam concrete stress. Excluding Δf_{pSS} eliminates this effect from the stress analysis; however, the effect can be captured by computing the beam concrete stress using age-adjusted composite transformed area and section modulus. Because this contribution to the overall beam concrete stress is small, nontransformed section properties may be used without appreciable loss of accuracy.

Conclusion

PCI recommends that the prestress gain caused by deck shrinkage Δf_{pSS} be excluded in the calculation of time-dependent prestress losses because the calculated magnitude of deck shrinkage strains may not develop in the presence of deck cracking and deck reinforcement. The gain in prestress due to deck shrinkage modeled in Δf_{pSS} accounts for both elastic and beam concrete creep-induced elongation of the strand. When transformed section analysis is used, the elastic gain is incorrectly accounted for twice. Excluding Δf_{pSS} corrects this issue but excludes the effect of beam concrete creep induced by the shrinkage of deck concrete.

PCI also recommends that the effect of deck shrinkage should be analyzed by considering it as an external force applied to the nontransformed composite section. This force is applied at the center of the deck with an eccentricity from the center of the deck to the center of gravity of the composite section.

This approach to computing stresses in the beam concrete is used for the design examples presented in Chapter 9 of the forthcoming fourth edition *PCI Bridge Design Manual*.

References

1. American Association of State Highway and Transportation Officials (AASHTO). 2020 *AASHTO LRFD Bridge Design Specifications*. 9th ed. Washington, DC: AASHTO.
2. Precast/Prestressed Concrete Institute (PCI). Forthcoming. *Bridge Design Manual*. MNL-133. 4th ed. Chicago, IL: PCI.