EFFECT OF DECK CRACKING ON PRESTRESS LOSSES

Sudarshan C Kasera
Richard Miller, PhD, PE, FPCI, University of Cincinnati
G. A. Rassati, PhD, University of Cincinnati
Ala Tabiei, PhD, University of Cincinnati

ABSTRACT

The AASHTO LRFD Bridge Design Specifications contain two methods for calculating loss of prestressing force, an approximate method and a refined method. The refined method predicts a gain in prestressing force due to differential shrinkage between the deck and girder. Some states do not allow engineers to use this gain and others only allow part of the gain to be included in the calculation of net prestressing force.

This study uses an ABAQUS finite element model of a Type III AASHTO girder with a deck. The results show that when the deck is placed at a very early age (10 days in this study), the gain in prestressing force is minimal. When the deck is placed at a later age (30 days), there is a gain in prestressing force as predicted in the refined method. When the deck is placed at a much later age (60 or 90 days), there is an initial gain in prestressing force. However, at some point the deck cracks and the stresses due to differential shrinkage are relieved. This causes most, but not all, of the gain in prestressing force to be lost. However, shrinkage and creep will cause an increase in tensile stresses at the bottom of the girder which must be considered.

Keywords: AASHTO Refined Method**,** Bridge, Camber, Cracking, Creep, Prestressed Concrete, Prestress Losses, Shrinkage

INTRODUCTION

In the 4th Edition of the American Association of State Highway and Transportation Officials (AASHTO) LRFD Specifications for Bridge Design[1], the methodology for calculating loss of prestressing force was changed. Early editions of the AASHTO LRFD Specifications used the method for calculating losses that had been in the old AASHTO Standard Specifications[2] which considered only relaxation of the prestressing steel and elastic shortening, creep and shrinkage of the girder. There was no consideration of the effect of adding a deck.

The new method, based on research reported in NCHRP Report 496[3], provides for two separate methods: an approximate method and a refined method. The approximate method still only considers relaxation of the prestressing steel and elastic shortening, creep and shrinkage of the girder, but uses updated coefficients. A later change in the AASHTO LRFD Specifications restricted the use of this method to bridges with composite decks.

The refined method calculates losses by an independent calculation for each of the following contributors:

- prestress loss due to shrinkage of girder concrete between transfer of prestressing force and deck placement
- prestress loss due to creep of girder concrete between transfer of prestressing force and deck placement
- prestress loss due to relaxation of prestressing strands between transfer of prestressing force and deck placement
- prestress loss due to relaxation of prestressing strands in composite section between time of deck placement and final time
- prestress loss due to shrinkage of girder concrete between time of deck placement and final time
- prestress loss due to creep of girder concrete between time of deck placement and final time
- prestress gain due to shrinkage of deck in a composite section

Of these, it is the prestress gain due to shrinkage of the deck in composite action that is the subject of some controversy. Some states do not allow this gain to be considered in calculations of prestress losses. Others allow accounting for the gain, but some require that conservative assumptions about the time of deck placement be used. Still other states only allow some percentage of the gain to be counted.

The premise is that when the deck is placed, there is a differential shrinkage between the younger deck concrete and the older girder concrete. Because the deck is usually well connected to the girder in order to achieve composite action for bending, the differential shrinkage of the deck causes axial compression and positive bending to occur in the girder.

The bending moment effect is usually larger than the axial compression effect so there is a net tension in the bottom of the girder, creating a gain of prestressing force.

The gain in prestressing force due to shrinkage of the deck is usually small. In design example 9.1 in the Precast/Prestressed Concrete Institute (PCI) *Bridge Design Handbook*[4], the total effective prestressing stress after all losses is 166 ksi. The gain in prestressing stress is only 1.2 ksi, less than 1% of the total effective prestressing stress. Note that this occurs when the deck is placed 90 days after the girder is cast, so the effect of differential shrinkage will be large. If the deck is placed when the girder is younger, the effect of differential shrinkage will be less pronounced.

The method also ignores the possibility of deck cracking. The deck is in a state of restrained shrinkage, so tensile stresses will develop and the deck may crack. Although reinforcement will limit the opening of the crack, the presence of the crack will reduce the tensile stresses in the deck and that will result in a reduced gain of prestressing force.

This paper uses finite element analysis to explore the effect of deck placement on loss or gain of prestressing force.

ANALYTICAL MODEL

This project began as an attempt to model a two span, continuous for live load bridge and see the effects of creep and shrinkage on the connection at the continuity diaphragm. NCHRP Report 579 was the basis for the current specifications on this type of bridge so the two span specimen tested in that project was to be used as the basis for the study. However, before modeling the more complex two span system, a single span model was created to assure the analysis would run with the creep and shrinkage models. That single span model is the basis of this paper.

The model is a Type III AASHTO I girder reinforced with 20, 0.6 inch diameter prestressing strands. There is a 96 inch x 7.5 inch composite deck (Figure 1) reinforced with two layers of #5 bars @ 12 inch centers in both directions. The overall length of the girder is 51 feet and the center of bearing to center of bearing span is 50 feet. Material properties are shown in Table 1. Steel was modeled as an elastic-perfectly plastic material. For compression, the concrete was modeled using the damaged plasticity model available in ABAQUS. The tension model allowed for post peak, softening behavior.

Solid, 8-node brick elements with reduced integration and hourglass control were used to model the girder and slab and embedded truss elements were used to model strands and reinforcing bars. Initial prestressing of strands, as well as time-dependent creep and shrinkage effects were applied through user subroutines developed for the single span model. The analyses were run statically in subsequent steps using Newton-Raphson iterations, first by applying the required pretension force to the strands, followed by a step allowing the girder to undergo creep and shrinkage up to the desired time. At that point, the full dead load of the deck was applied to the girder, and the deck was added and allowed to come up to strength, and subsequently undergo creep and shrinkage. Midspan deflection, stresses at top and bottom fiber of girder, as well as deck and strand stresses, were monitored as a function of time. Additional models were run without allowing creep, shrinkage and cracking of the deck.

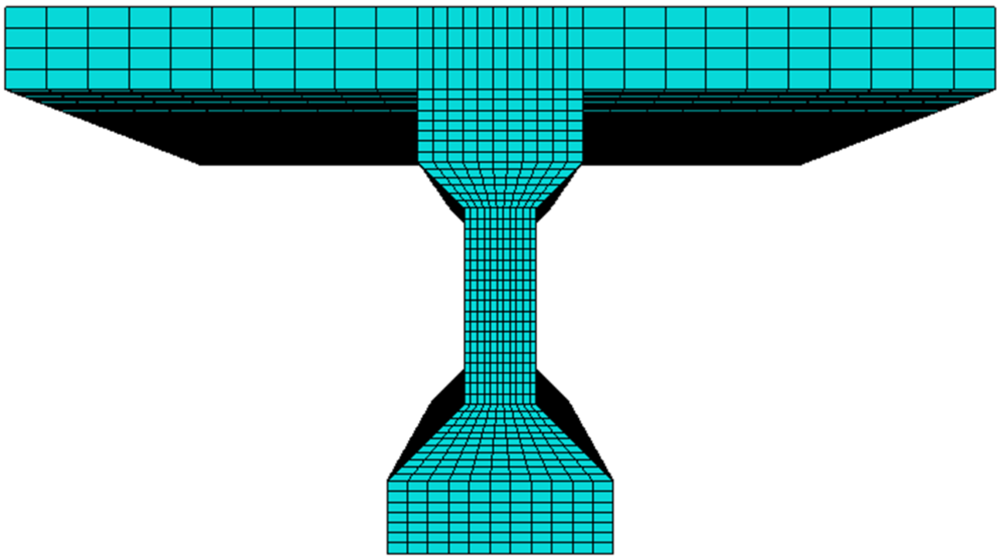

Figure 1 – Cross Section.

Table 1 – Material Properties

Girder		Deck	
Compressive Strength	9100 psi	Compressive Strength	9100 psi++
Tensile Strength	700 psi	Tensile Strength	400 psi
v/s ratio	4	v/s ratio	3.6
C_u	2.5	C_u	2.5
Creep correction factor+	0.831	Creep correction factor+	0.575
Age at first load	1 day	$\varepsilon_{sh,u}$	760×10^{-6}
$\varepsilon_{sh,u}$	760×10^{-6}	Shrinkage correction factor+	0.552
Shrinkage correction factor+	0.529		

+ Assumed: RH = 70%, slump=2.5 in (made workable with water reducer), 60% fine aggregate, 7% air entrained, cement content = 752 pounds/cy.
++ Deck has same compressive strength as beam to eliminate modulus mis-match and prevent spurious compressive failure.

CREEP AND SHRINKAGE MODELING

Before describing the modeling approach, it is important to discuss the challenges with modeling creep and shrinkage. Both creep and shrinkage are described by the potential. For creep, C_u is the ultimate creep coefficient which is the ratio of the potential maximum creep strain for concrete divided by the initial elastic strain. ACI Committee Report 209[5] states that this value may vary from about 1.3 to 3.0, although the Commentary of the AASHTO LRFD Specifications (C5.4.2.3.2) shows values from 0.5 to 4. For precast/prestressed concrete, values around 2.0 are often assumed. The maximum shrinkage potential is designated by $\varepsilon_{sh,u}$ and can vary from almost 0 for continuously cured concrete to over 1000 microstrain. Unfortunately, creep and shrinkage potentials are affected by a number of variables, including aggregate type, size, shape and volume, water/cement ratio, presence of pozzolanic materials, cement type, the chemical make-up of the cement, paste volume, air content and presence of admixtures. Even if the exact same mix design is used, natural day-to-day variations in the constitutive materials can cause wide variation in the creep and shrinkage properties of production mixes.

Both creep and shrinkage are affected by relative humidity, length of curing and volume-to-surface ratio of the member. Creep is also affected by the strength of the concrete at the time of application of the permanent stresses and their magnitude. Because of these factors, an exact prediction of the behavior of a concrete member due to creep and shrinkage is difficult. The Commentary to the AASHTO LRFD Specifications (C5.4.2.3.1) states the AASHTO equations "cannot be expected to yield results with an accuracy of less than $\pm$ 50%."

There are also several models for predicting creep and shrinkage as a function of time. The current AASHTO LRFD Specifications present a model based on NCHRP Report 496. Previous editions of the AASHTO LRFD Specifications contain the same model as the AASHTO Standard Specifications. ACI 209R2 presents other models. Additional models can be found in literature. It would be incorrect to state that any of these models is more accurate than another as all are accurate for the data used to derive them and all will display inaccuracies when used for other concrete mixes.

Because of this variation, the numerical results of any analysis can be changed based on the assumed model, the values of C_u and $\varepsilon_{sh,u}$ and assumptions about environmental conditions. However, by using reasonable models and values, the analysis can show the engineer qualitative information that can provide an understanding of the behavior the composite bridge girders and inform design decisions.

Creep and shrinkage of both the girder and the deck were modeled using the equations given in ACI Committee Report 209. The ACI 209R2-92 equations were used because there was an existing subroutine that could be modified for this project and because the equations allow for explicit assumptions of the creep and shrinkage potentials, C_u and $\varepsilon_{sh,u}$, of the concrete.

RESULTS

After a prestressed beam is cast and then stored, it will camber upward (growth in storage). When the deck is cast, the weight of the deck will cause an immediate downward deflection. At this point, the deck begins to shrink and differential shrinkage of the deck attempts to decamber (cause a downward deflection) the girder. Whether the net deflection is upward or downward depends on the interaction of the deck shrinkage and girder creep and shrinkage. If the girder is relatively young and very little creep and shrinkage has occurred and/or there is very little shrinkage of the deck, the girder behavior should dominate and there should be a net cambering of the system. On the other hand, if the girder is older at the time the deck is installed, such that most of the creep and shrinkage has already occurred, and/or the deck has a very high shrinkage, the net effect should be for the deck to dominate and the girder should decamber.

Data from Washington State DOT[6] (Figure 2) show the camber of five girders which were over 200 days old at the time the deck was cast. Since the deck is so much younger than the girders, the theory would seem to predict that the girders should decamber due to differential shrinkage. However, the deflection is actually almost constant. For two of the girders, there is a slight increase in camber and then the camber becomes essentially constant.

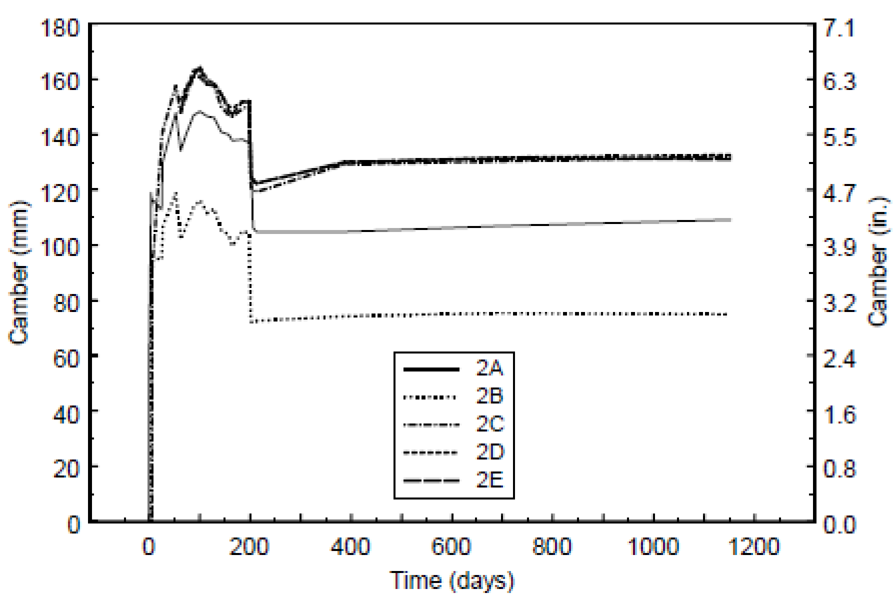

Figure 2 – Camber of girders with time (from Barr et al.[6])

Figure 3 shows the results of the current analysis. Note that if the deck is cast when the girder is only 10 days old, the creep and shrinkage of the girder will be dominant and the girder cambers up. If the girder is 30 days old when the deck is cast, the creep and shrinkage of the girder and the shrinkage of the deck seem to balance and the result is almost a constant camber. For both cases, the deck does not crack. For the cases where the girder is 60 or 90 days old when the deck is cast the effect of deck shrinkage is pronounced and there is a decambering of the girder due to deck shrinkage. However, in both cases the deck cracks and some, but not all, of the shrinkage effect is released. As a result, the girder regains some of the camber and, after a short time, the net camber becomes almost constant. Over time, the deck will also creep in tension (which was modeled) and this will also relieve some of the restraint provided by the deck. For all but the 30 day case, the long term camber is not much different than the camber value just after the deck is placed. For the 30 day cases, there is some net decambering, but it is small (<10%).

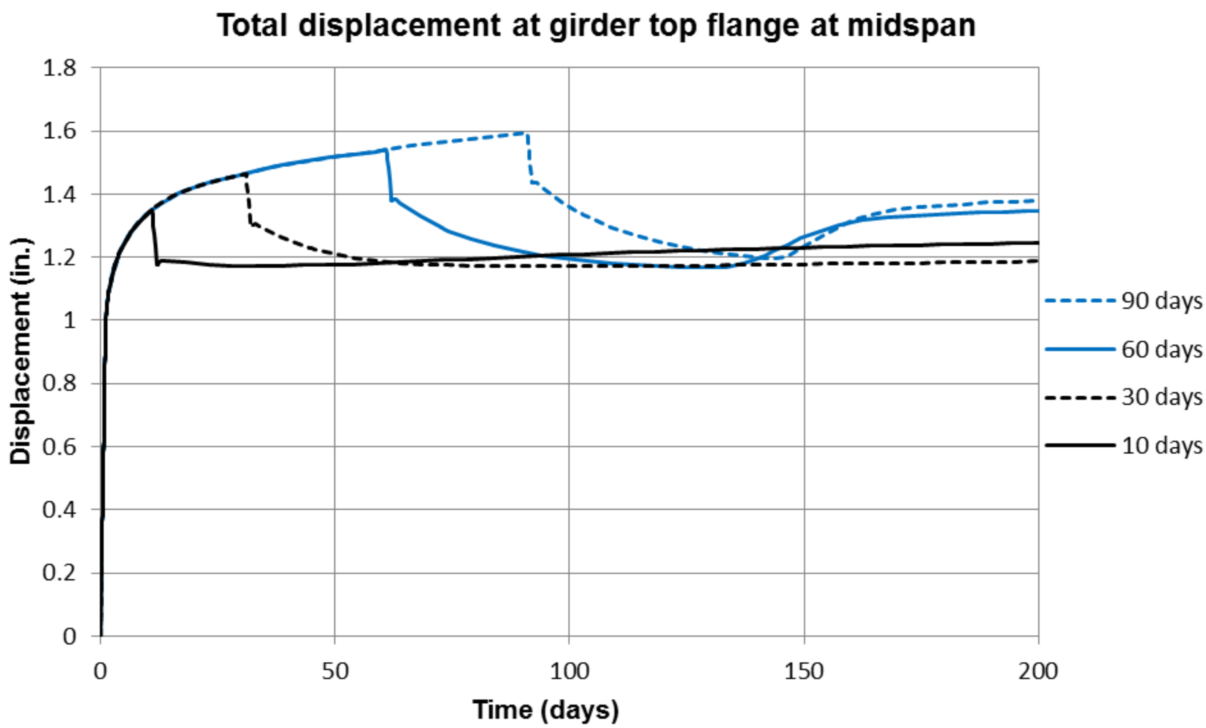

Figure 3 – Displacement of the top flange with time for decks cast at various ages.

The graph for the girder with deck placement at 90 days shows that deck cracking occurs in less time than for girder where the deck is placed at 60 days. Figure 4 shows the deck stress in relation to time. For the girder where the deck is placed at 90 days cracking occurs approximately 42 days after the deck is cast as opposed to 60 days after casting the deck when the deck is placed at 60 days. This is consistent with the fact that the later the deck is placed, the more differential shrinkage occurs and that will increase the stress in the deck more quickly. It is not unreasonable to assume that if the girders were quite old when the deck is placed and the deck shrank a large amount at an early age, cracking might occur quite soon after the deck is placed and camber curves like those in Figure 2 would not be unexpected.

As previously noted, cracking of the slab does not completely relieve all of the restraining effects of the deck. Figure 5 shows the camber for the case where the deck is placed when the girder is 90 days old. One line represents the camber when the deck is allowed to shrink, creep and crack. The other ignores creep, shrinkage and cracking. If cracking totally relieved the restraining effect of the deck, the lower and upper curves should come together soon after the deck cracks and they do not. In fact, they appear to tend toward parallel over time indicating some restraint from the deck.

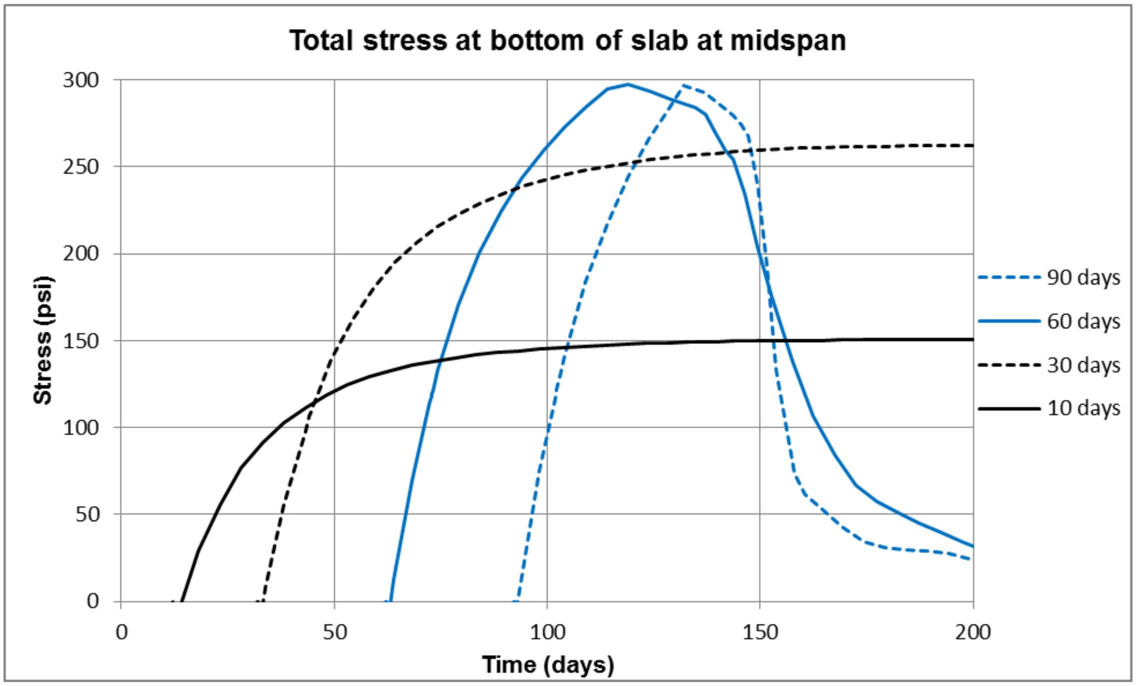

Figure 4 – Stress at the bottom of the slab vs. time for decks placed at different girder ages.

The effect of deck shrinkage and cracking on the loss of prestressing force is of great interest and importance. In theory, shrinkage of the deck causes a gain in prestressing force which would increase the cracking resistance of the member and the allowable service load. The refined method of calculating loss of prestressing force in the AASHTO LRFD Specifications includes a calculation for this gain. However, not all states all this gain to be counted and some allow only part of it.

Figure 6 shows the loss of prestressing stress as a function of time for cases where the deck is placed at different girder ages. It is interesting to note that, until the deck cracks, all of the curves tend to the same value of prestressing stress. This could be due to the fact that the only difference is the differential shrinkage of the deck, which has only a small effect on the total prestressing force. This is could also be an artifact of choosing the values of C_u and $\varepsilon_{u,sh}$ to be the same for both the deck and girder so more analyses are needed. What is clear is that once the deck cracks there is some relief of the restraint and some of the prestressing gain due to deck shrinkage is lost.

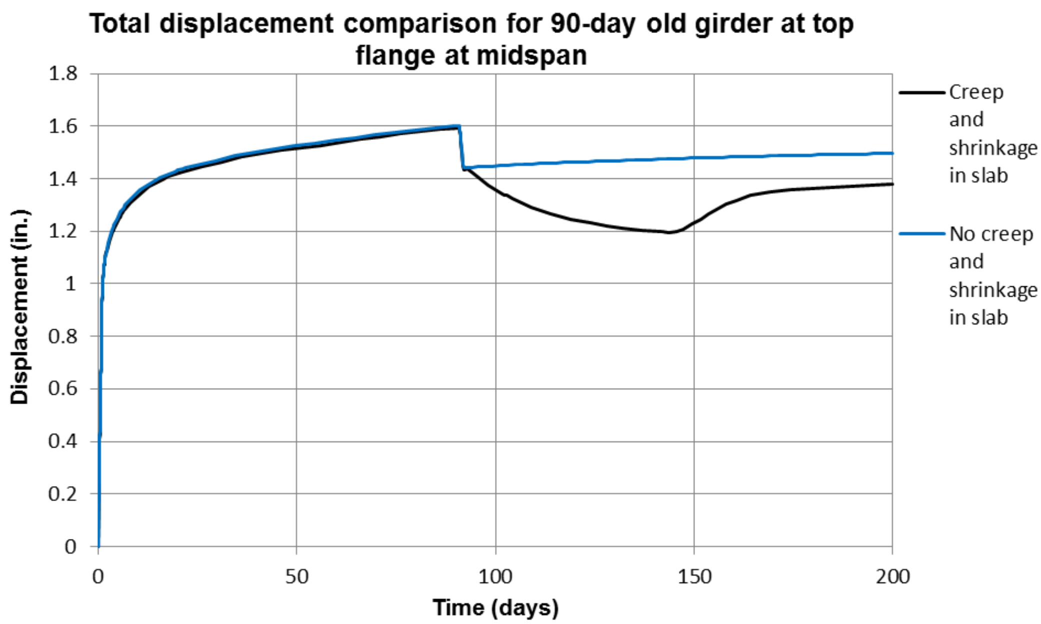

Figure 5 – Camber of the girder considering and ignoring creep, shrinkage and cracking of the deck.

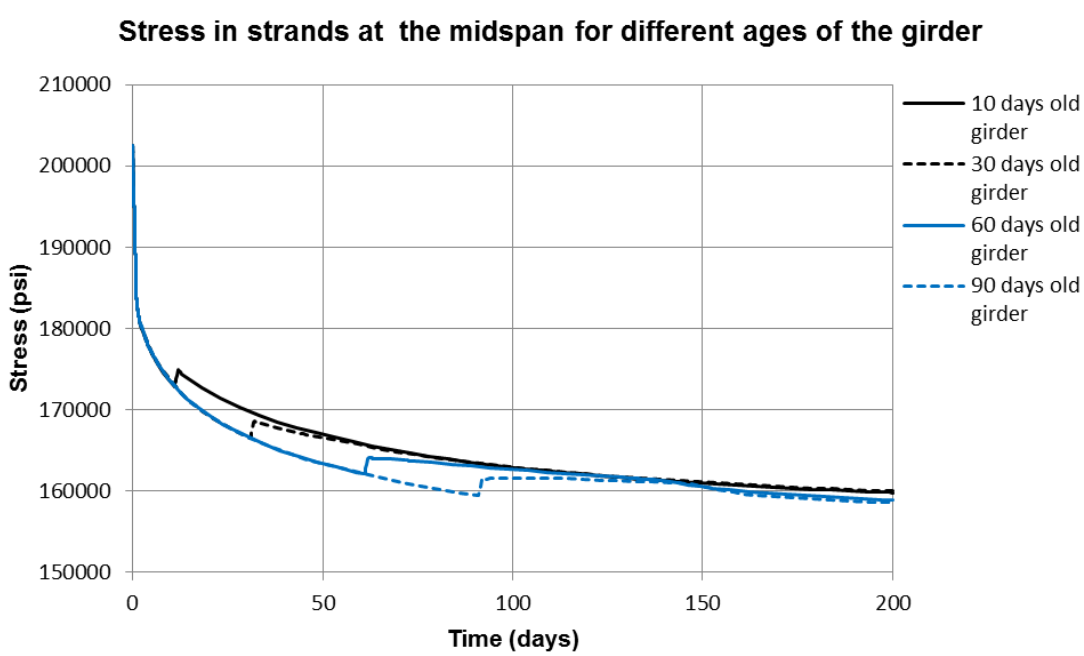

Figure 6 – Variation of prestressing stress with time for decks placed at different ages of the girder.

However, not all of the gain is lost. Figure 7 shows a comparison of the curves both considering creep and shrinkage of the deck and ignoring creep and shrinkage of the deck for the case where the deck is placed at a girder age of 30 days. The deck does not crack. The figure shows that at 200 days there is a gain of prestressing stress due to deck shrinkage of approximately 1.3 ksi. The equation in the AASHTO LRFD specifications would predict a gain of 1.7 ksi, so the values are reasonable.

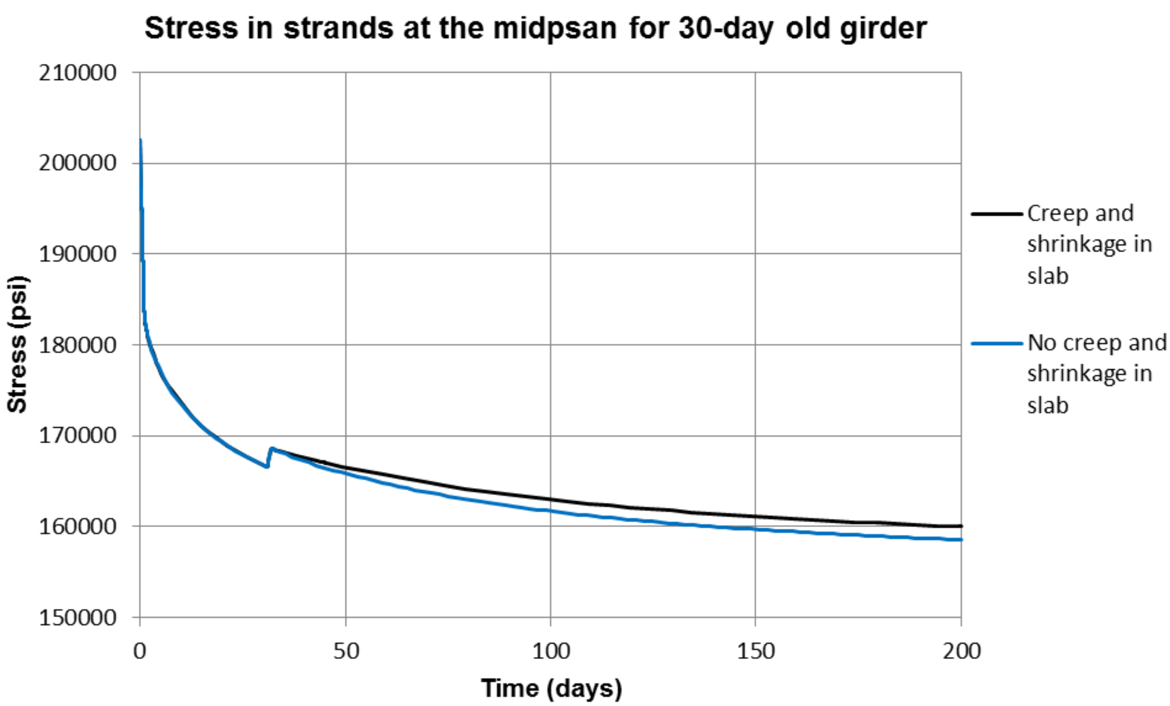

Figure 7 – Prestressing stress vs time for the case of deck slab placement at a girder age of 30 days; considering and ignoring creep and shrinkage of the slab.

Figure 8 shows the same comparison, except it is for the case where the deck is placed when the girder is 90 days old. Here, there is still a gain of 0.60 ksi over the case where shrinkage and creep of the slab are ignored. The AASHTO equation would predict a gain of 1.4 ksi. Thus, allowing the engineer to use half of the prestressing gain due to deck shrinkage, as is done in some states, seems reasonable and allows for cases where the deck cracks.

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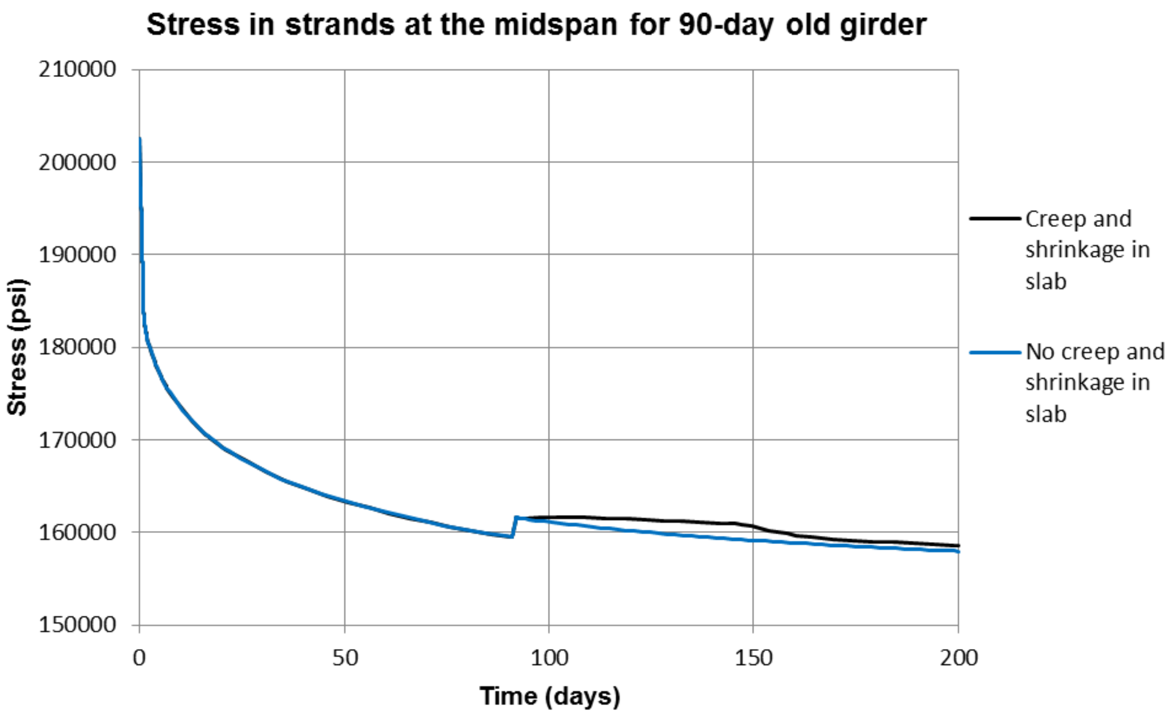

Figure 8 – Prestressing stress vs time for the case of deck slab placement at a girder age of 90 days; considering and ignoring creep and shrinkage of the slab.

Although the gain in prestressing force due to shrinkage and creep of the slab is small and it is likely relieved by cracking, the effect of deck creep and shrinkage should not be completely ignored. Figure 9 shows the stress at the bottom flange of the girder, at midspan, for the case of a slab placed at 30 days; the latest placement of the deck where the deck does not crack. This graph shows compressive stresses because only the effects of prestressing, dead load and creep/shrinkage effects are shown. The graph must be interpreted by assuming that barrier weight, additional wearing surface weight and live loads will be applied. Thus, although the graph shows net compressive stresses, it must be assumed the application of additional loads will result in a net tensile force.

There are two lines. One shows the effect if there is no shrinkage or creep in the deck and the other accounts for shrinkage and creep. The graph shows that shrinkage and creep of the deck results in a reduction of compressive stress (i.e. an additional tensile stress) of about 150 psi. Thus, if the application of additional service loads resulted in a net tensile stress at the bottom of the girder, shrinkage and creep of the deck would increase this stress. In theory, this could crack the girder, but whether this cracking would actually occur is not certain. Consider that:

a) The allowable stress is $0.19\sqrt{f_c'}$ and the modulus of rupture (cracking strength) is $0.24\sqrt{f_c'}$. There is some allowance made for additional stress due to other factors.

b) The MOR of $0.24\sqrt{f_c'}$ is a lower bound and the actual cracking strength is probably greater.
c) Figure 9 considers the case where the deck is placed as late as possible and still does not crack. This may not be the usual case.

Figure 10 shows what happens if the deck is placed at 90 days. Again, the two lines represent cases where shrinkage and creep are and are not considered. Here, shrinkage and creep effects cause a tensile stress of about 220 psi just before the deck cracks. When the deck cracks, the differential stress is about 75 psi, so the high stress is a temporary condition.

Whether this additional stress needs to be considered is a matter of the engineer's judgement and the DOT policy.

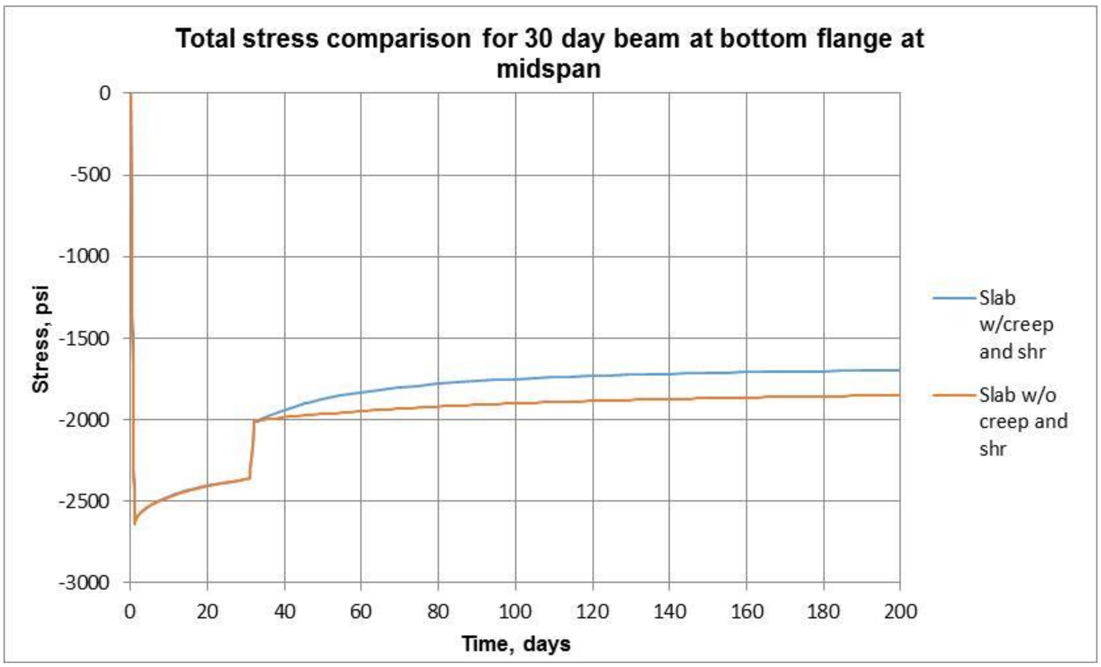

Figure 9 – Stress in the bottom flange at midspan for the case of placing the deck at 30 days.

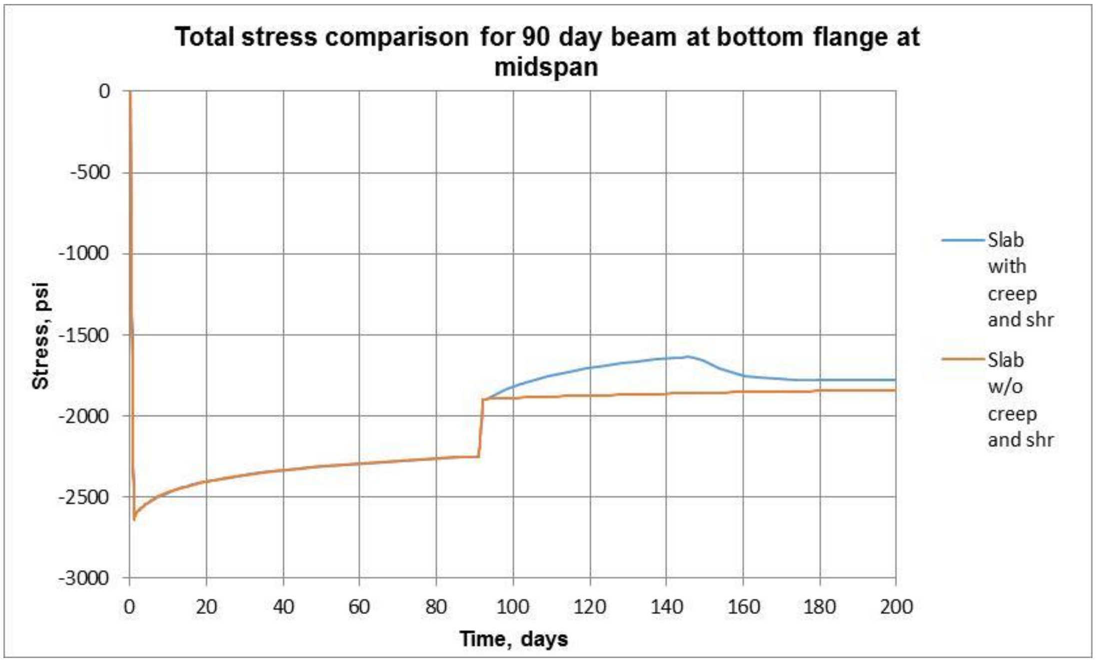

Figure 10 - Stress in the bottom flange at midspan for the case of placing the deck at 90 days

CONCLUSIONS

A series of finite element analyses was run to determine the effect of deck shrinkage and cracking on a composite, prestressed concrete bridge girder. Cases were studied where the deck was placed on the girder when the girder ages were 10, 30, 60 and 90 days. Based on this study, the following conclusions can be stated:

1) Prior to deck placement, the camber of a prestressed concrete girder will increase due to creep and shrinkage of the concrete. When a deck is placed on the beam, the slab itself restrains some of the growth in camber and shrinkage of the deck concrete will counteract this growth in camber. If the deck has a low shrinkage and/or if it is placed on the girder when the girder is young, the effect of the differential shrinkage will be small. However, there will still be some restraint from the deck and the change in camber over time will be small. If the deck has a large shrinkage and/or if the deck is placed when the girders is older, the effect of differential shrinkage will be pronounced and the girder may actually decamber. However, in these cases the deck is likely to crack. When the deck cracks, some, but not all, of the loss of camber is recovered. After the loss of camber is recovered, the long term change in camber tends to be small. For all but the 30 day case (which represents the most extreme differential shrinkage without cracking), the long term camber is not much different than the camber value just after the deck is placed. For the 30 day case, there is some net decambering, but it is small (<10%). The general trend of the long term camber of the girder is similar to that found in research performed at Washington State[6].

2) Then the deck is placed, differential shrinkage should cause the girder to decamber and add stress to the prestressing strands, resulting in a gain of prestressing force. The AASHTO LRFD Specifications allow the engineer to add this gain to the loss of prestressing force calculation. The analysis shows this gain does indeed occur as long as the deck does not crack. Once the deck cracks, some, but not all, of this gain is lost. The approach used by some states of allowing 50% of the prestressing gain to be counted seems to be reasonable for cases where the deck cracks.
3) The loss of prestressing force appears to be affected more by the occurrence of deck cracking than the time of deck placement. For the cases where the deck was placed when the girder was either 10 or 30 days old, the deck did not crack and net loss of prestressing force was virtually identical. For the cases where the deck was placed when the girder was either 60 or 90 days old, prior to deck cracking the net loss of prestressing force was virtually identical to the 10 and 30 day cases. However, after deck cracking the net loss of prestressing was virtually identical for the 60 and 90 day cases, but was more than for the 10 and 30 day cases.
4) Shrinkage and creep of the deck does cause an additional tensile stress to develop at the bottom of the girder. When added to the tensile stresses caused by applied loads, the allowable tensile stress may be exceeded. Deck cracking will relieve some, but not all of the stress and significant, but temporary, tensile stresses may occur before the deck cracks.

In this study, the deck placed when the girder was 30 days old did not crack but the deck placed when the girder was placed at 60 days did crack. The reader is cautioned against using these ages as some indication of when deck cracking will occur. The creep, shrinkage and tensile properties of concrete are extremely variable and different, but realistic, assumptions of these properties will alter the numerical results. Thus, the results should be treated qualitatively.

If the deck is placed when the girder is young, the effect of differential shrinkage will be minimal but this case rarely occurs in the field. If the deck is placed when the girder is old, the deck will likely crack and some of the effects of differential shrinkage will be relieved. There is a maximum girder age when the deck can be placed without cracking and when the effects of differential shrinkage will be most pronounced, but given the wide variation of concrete properties it is unlikely this could be calculated with any accuracy. Even if an accurate calculation was possible, it is unlikely the engineer could predict the day of deck placement.

It is recommended that the engineer assume the deck will crack. In these cases, the long term camber (not including temperature camber) will not be that much different than the value just after deck placement. The gain in prestressing stress due to deck shrinkage should be limited to 50% of the calculated value. The engineer should also consider the increase in tensile stress at the bottom of the girder due to shrinkage and creep effects and the possibility this additional stress could crack the girder.

Finally, it should be noted that the only variable considered here was the age at which the deck was placed. Other variables, such as deck width, differential stiffness between the deck and girder, amount of reinforcing in the deck (which would affect net shrinkage), girder end conditions (simple vs. fixed end) both in terms of bending restraint and axial restraint, variations in shrinkage and creep properties and temperature effects are also important. These are subjects for future work.

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