Effect of deck cracking on prestress

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- This paper explores how the time of deck placement, deck concrete strength, differential shrinkage, and other variables affect deck cracking and prestress loss or gain for prestressed concrete girders with a composite concrete deck.
- Finite element models were created to simulate three lengths of composite prestressed concrete girders with varying strength, shrinkage, and time parameters.
- Analysis of the results shows that deck cracking will occur, but approximately 50% of the prestress gain due to differential shrinkage will be retained after the deck cracks.

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As soon as a prestressing force is applied to a concrete member, loss of that prestressing force begins to occur. The method used for calculating prestress losses in the first edition of the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*,[1] was modeled on the 17th edition of the AASHTO *Standard Specifications for Highway Bridges*[2] and considered losses due to elastic shortening, relaxation of prestressing strands, and creep and shrinkage in the concrete. While the effect of elastic shortening was calculated from mechanics, a simple formula was used to estimate the relaxation, creep, and shrinkage losses. For composite structures, the effects of adding a deck were not considered. These effects include the creep and shrinkage of the girder between the time the girder is fabricated and the time the deck is placed, the dead load of the deck when it is placed, and creep and shrinkage effects in the deck itself.

Based on the recommendations of the National Cooperative Highway Research Program (NCHRP) report 496,[3] a new method, called the refined method, was adopted by AASHTO for calculating time-dependent prestress losses.[4] The method divides the prestress losses into two phases: a phase from the initial fabrication of the girder to the time of deck placement and a phase after the deck is placed. Unlike the simple method, the refined method recognizes the effect of placing the deck on the girder and predicts a gain in the prestressing force due to differential deck shrinkage in the composite section. When a concrete slab is placed on an older girder, there is differential shrinkage between the two concrete sections. Shrinkage of the deck concrete is restrained by the girder, which has the effect of inducing compressive stress at the top of the girder and tensile stress at the bottom of the slab. The compressive stress at the top of the girder results in the decambering of the girder causing tension in the bottom of the girder and a gain in the prestressing force.

The refined method does not consider the possibility of cracking in the deck slab. The girder has a restraining effect on the slab when it starts to shrink, which causes tensile stresses in the slab. When these stresses exceed the tensile resistance of the slab, the deck slab cracks and the induced stress in the girder is reduced. This results in a loss of some of the prestressing force gain. Because of this, some state departments of transportation do not include prestressing force gain due to differential shrinkage in the prestressing force loss calculation. Some other state departments of transportation believe that not all of the gain is lost after cracking and allow for some percentage, often 50%, of the gain to be included in the prestress loss calculation. This paper uses finite element analysis to explore the effect of deck cracking on the prestressing force.

Objective of the study

This study examines the effect of adding a composite concrete deck to a prestressed concrete girder and the subsequent effect of cracking of that deck on the loss of prestressing force. Specifically, it examines the effect of deck cracking on prestressing force gain due to differential shrinkage of the deck with respect to the girder. The losses and gains of prestressing force in the girder depend on the strength, modulus of elasticity, creep characteristics, and shrinkage characteristics of the concrete. The values of these properties are highly variable, and any one of a number of different assumptions could be made. Thus, the purpose of this study is to show general trends and effects of deck cracking on the final value of the prestressing force.

Analytical model

Table 1 presents the simulation matrix for the finite element analyses. Three girder span lengths were modeled. One deck shrinkage coefficient close to the girder's shrinkage coefficient and one larger deck shrinkage coefficient were chosen. This was done to simulate low and high differential shrinkage. The deck concrete strength was kept as a variable because a deck with a higher concrete strength will have a higher tensile resistance to cracking. Using these variables, simulations were done in two broad categories: one where the cracking in the deck was most likely (due to a lower deck concrete strength and a high differential shrinkage) and the other where deck cracking was less likely (due to a higher deck concrete strength and a low differential shrinkage). These categories provide bounds to the solutions. Initially, the girder age at the time of deck placement was chosen as 90 days. If very little or no cracking was observed in the finite element model, the girder age at the time of deck placement was increased until cracking occurred. Later, to determine the effect on deck cracking of girder age at the time of deck placement, simulations were performed for various girder ages at the time of deck placement between 1 and 180 days for both of the previously mentioned categories.

The deck creep coefficient was initially taken as 1.35, which is a low value. A few models were run with a creep coefficient of 2.0, but the results were almost identical to the results for the lower creep coefficient. Because deck creep coefficient made little difference to the results, the results shown here are for the creep coefficient of 1.35.

Two other submodels were created along with the main model: one in which the cracking in the deck was prevented by providing the deck with a very high tensile strength and another in which there is no creep, shrinkage, or cracking in the deck. These two models bound the solutions. The model with a high deck tensile strength shows the maximum prestressing

Table 1. Simulation matrix for the finite element analyses

Girder length, ft	85	95	120
AASHTO girder type	Type III I-girder	BT-63 girder	BT-63 girder
Deck concrete compressive strength, ksi	4	4	4
Girder age when the deck is cast, days	1, 15, 30, 45, 60, 75, 90, 120, 150, and 180	1, 15, 30, 45, 60, 75, 90, 120, 150, and 180	1, 15, 30, 45, 60, 75, 90, 120, 150, and 180
Deck shrinkage coefficient	0.0008 and 0.001	0.0008 and 0.001	0.0008 and 0.001
Girder concrete compressive strength, ksi	10	10	10
Girder shrinkage coefficient	0.0007	0.0007	0.0007
Girder creep coefficient	1.80	1.80	1.80
Deck creep coefficient	1.35 and 2.0	1.35 and 2.0	1.35 and 2.0

Note: AASHTO = American Association of State Highway and Transportation Officials. 1 ft = 0.3048 m; 1 ksi = 6.895 MPa.

force gain that could be achieved if the deck never cracks; the model with no deck shrinkage shows the prestress loss if there is no gain due to differential shrinkage.

The concrete deck was 96 in. (2440 mm) wide, 8 in. (200 mm) thick, and had two layers of no. 5 (16M) reinforcing bars spaced at 10 in. (250 mm) center to center in both directions. The 85 ft (25.9 m) long girder was prestressed with twenty 0.6 in. (15 mm) diameter prestressing strands, and the 95 and 120 ft (29.0 and 36.6 m) long girders were prestressed with twenty-four 0.6 in. diameter prestressing strands.

Reinforcing steel was modeled as an elastic–perfectly plastic material. The damaged plasticity model for concrete in a finite element analysis software package was used. Solid eight-node brick elements were used for the girder and deck elements, and two-node truss elements were used for the prestressing strands and reinforcing bars. The first step in the analysis applied the pretensioning force to the strands. The girder elements were then activated and prestress was transferred to the girder. The girder was then allowed to undergo creep and shrinkage for the period of time to reach the desired girder age at deck placement. The dead load of the deck was applied to the girder, and the model of the deck was activated. Note that the deck elements had to be placed on the girder at the beginning of the simulation; however, they had no weight and an extremely low modulus of elasticity. This allowed the deck elements to camber up with the girder and ensure that they were placed properly. After activation, the deck was allowed to undergo creep and shrinkage until the end of the desired simulation period.

The software package does not have a built-in creep and shrinkage model, so Fortran subroutines were used. ACI 209R-92[5] equations were used to model creep and shrinkage effects in both the girder and the deck. Relaxation of the prestressing strands was not modeled; however, this effect is very small when using low relaxation strands (approximately 1%) and will not significantly affect the outcome.

The Fortran subroutines were originally written by Kasera, who performed some preliminary analysis on the Type III I-girders.[6,7]

Results

The results of the finite element analysis are shown in the figures as described in this section. The term *girder age* refers to the girder age at the time of deck placement. The results are subdivided into two categories:

- category 1: deck cracking most likely (low deck concrete strength and high differential shrinkage); deck concrete compressive strength = 4 ksi (28 MPa); deck shrinkage coefficient = 0.001; girder age = 90 days
- category 2: deck cracking least likely (high deck concrete strength and low differential shrinkage); deck concrete compressive strength = 5 ksi (34 MPa); deck shrinkage coefficient = 0.0008; girder age = 90 days

Figure 1 shows the camber of the 95 ft (29.0 m) girder at midspan for three cases in each category. In the first case, the deck is permitted to crack. For the second case, the deck shrinkage coefficient is set to zero to show what happens if there is no differential shrinkage. Because the equations in the AASHTO LRFD specifications assume that the deck does not crack, the third case has the deck tensile strength set to a very high value to prevent any cracking in the deck.

In both categories, the girder cambers upward until the deck is placed at 90 days. The weight of the deck then causes an immediate decambering of the girder. When the deck does not shrink, the system begins to camber upward due to continued creep and shrinkage of the girder. If the deck is permitted to shrink but prevented from cracking, the entire system continues to decamber due to differential shrinkage. For the case where the deck shrinks and is allowed to crack, the decam-

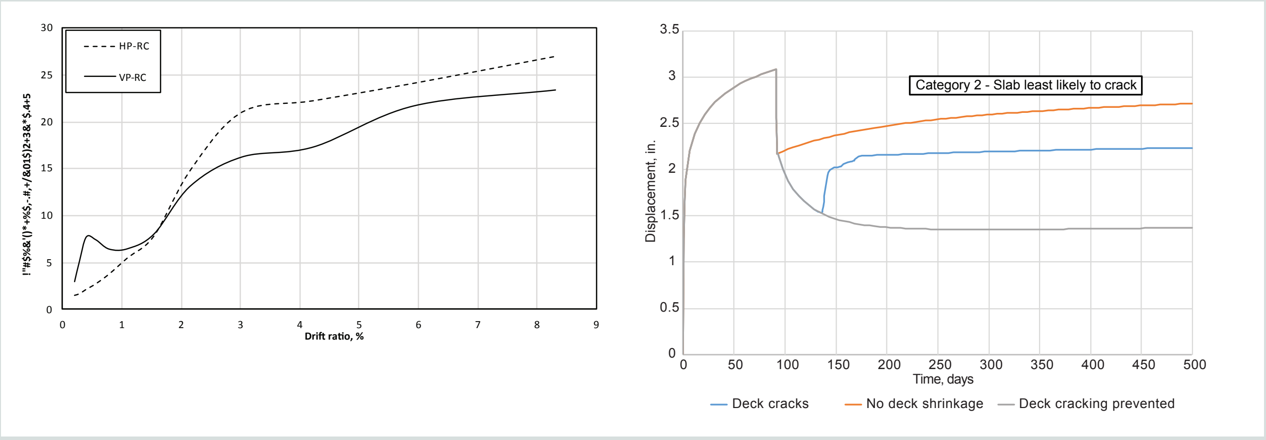

Figure 1. Camber at midspan of 95 ft girder top flange with deck placement at a girder age of 90 days in category 1 and 2. Note: 1 in. = 25.4 mm.; 1 ft = 0.305 m.

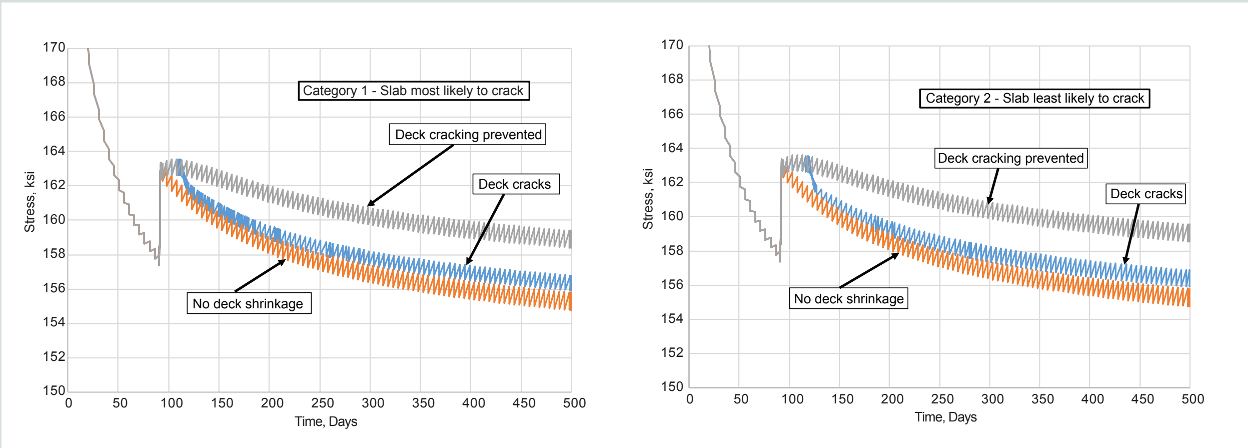

Figure 2. Prestress in strands over time at midspan for 95 ft girder, considering and ignoring cracking in the slab. Note: 1 ft = 0.305 m; 1 ksi = 6.895 MPa.

bering continues until the deck cracks. At this point, there is an increase in camber that occurs over a few days and then a gradual increase in camber over time. Note that the camber never reaches the value it would obtain if there were no shrinkage in the deck, indicating that the deck shrinkage provides some restraint after cracking. The differences between categories 1 (cracking likely) and 2 (cracking less likely) are that the category 2 deck cracks at a later age and the effect of cracking on the camber is more gradual.

Figure 2 compares the prestressing force over time for category 1 (cracking more likely) and category 2 (cracking less likely) for the cases where the deck cracks, where the deck does not shrink, and where the deck is prevented from cracking. All cases are for the 95 ft (29.0 m) girder at midspan. The case where cracking is prevented has the highest prestressing force at the end of the 500-day simulation period because the prestress gain due to differential shrinkage is retained. The no shrinkage case has the lowest value of prestressing force because there is no gain due to differential shrinkage between the girder and the deck slab. Until the deck cracks, the "deck cracking prevented" and the "deck cracks" cases have curves that overlap. After the deck cracks, there is a decrease in the prestressing force for the case where the deck cracks, but the prestressing force remains greater than that of the no shrinkage case. This indicates that after the deck cracks, the deck still provides some restraint and approximately 60% of the prestressing force gain due to differential shrinkage is retained.

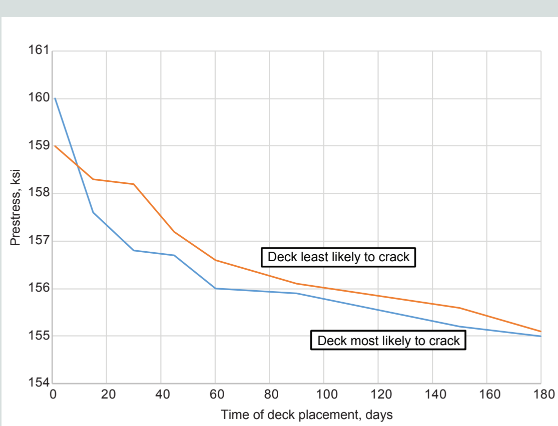

Figure 3. Variation of prestressing force at 500 days with girder age at time of deck placement for 95 ft girder. Note: 1 ft. = 0.3048 m; 1 ksi = 6.895 MPa.

Figure 3 shows how prestressing force varies (at the end of the 500-day simulation) depending on the girder age at the time the deck is placed for the 95 ft (29.0 m) girder. In both category 1 (cracking most likely) and category 2 (cracking least likely), the plot has a descending trend, indicating that as the girder age at the time of deck placement increases, the final value of prestressing force decreases.

The descending trend is expected because although the effect of differential shrinkage on the prestressing force is greater for decks placed on older girders, the possibility of deck cracking also increases with the increase in differential shrinkage. After the deck cracks, some of the prestress gain due to deck shrinkage is lost. The more cracking, the more of the gain that is lost, and this is seen in the difference between the two curves.

Figure 4 shows the effect of placing the deck at different girder ages for the 95 ft (29.0 m) girder in category 1, where cracking is most likely. At 90 days, approximately 60% of the total shrinkage of the girder will have occurred so there will be a large amount of differential shrinkage between the girder and the deck. Younger girders have only experienced a small amount of shrinkage when the deck is placed, so there is less differential shrinkage. As shown in Fig. 4, all of the decks crack, but the slabs placed on older girders crack in a shorter

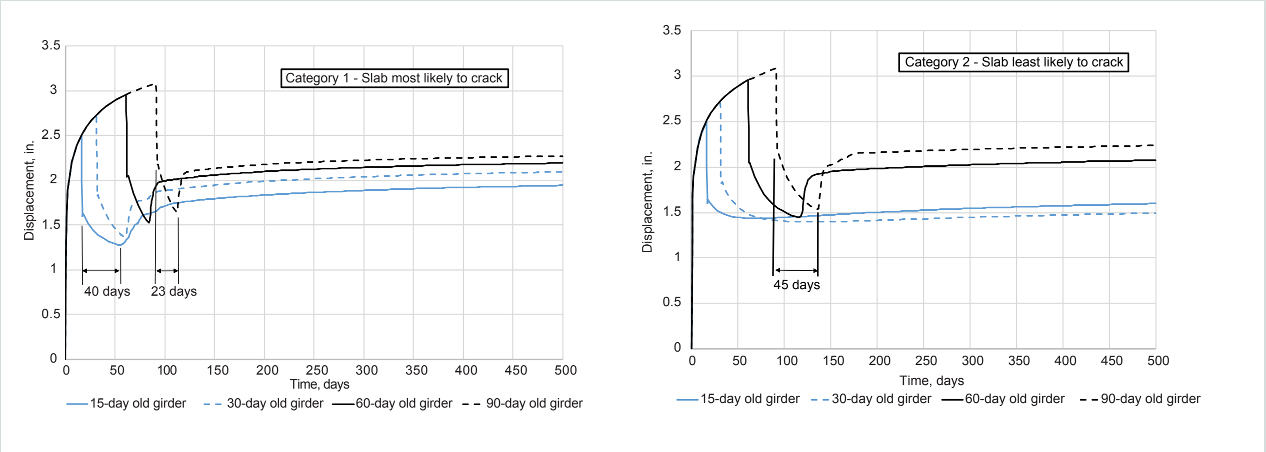

Figure 4. Comparison of camber and prestress at midspan for 95 ft girder when slabs added at different ages in category 1 and 2. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

period of time after deck placement. Figure 4 (right) shows category 2, where cracking is less likely. Here, when the slab is placed at a girder age of 15 days, there is no cracking. The plot does not show any cracking when the slab is placed at 30 days, but the finite element analysis result showed some cracking in the slab near the end of the girder. Slabs placed on 60- and 90-day-old girders crack, and the results are similar to the category 1 results but the cracking occurs at later times.

Figure 5 shows the deck cracking patterns for categories 1 and 2 for decks placed at different girder ages on the 95 ft (29.0 m) girder. The crack pattern is at the end of the 500-day simulation period. In category 1, with low deck concrete strength and high differential shrinkage (deck cracking most likely), the deck cracks even when it is cast on a 1-day-old girder; however, the cracks are limited to areas near the end of the girder This does not have an appreciable effect on the system. It tends to behave as an uncracked system, and prestressing gains due to differential shrinkage are retained. The cracks are more distributed for decks placed at a girder age of 15 days and later, and the cracking now affects the system behavior, causing some of the gain in prestressing force due to differ-

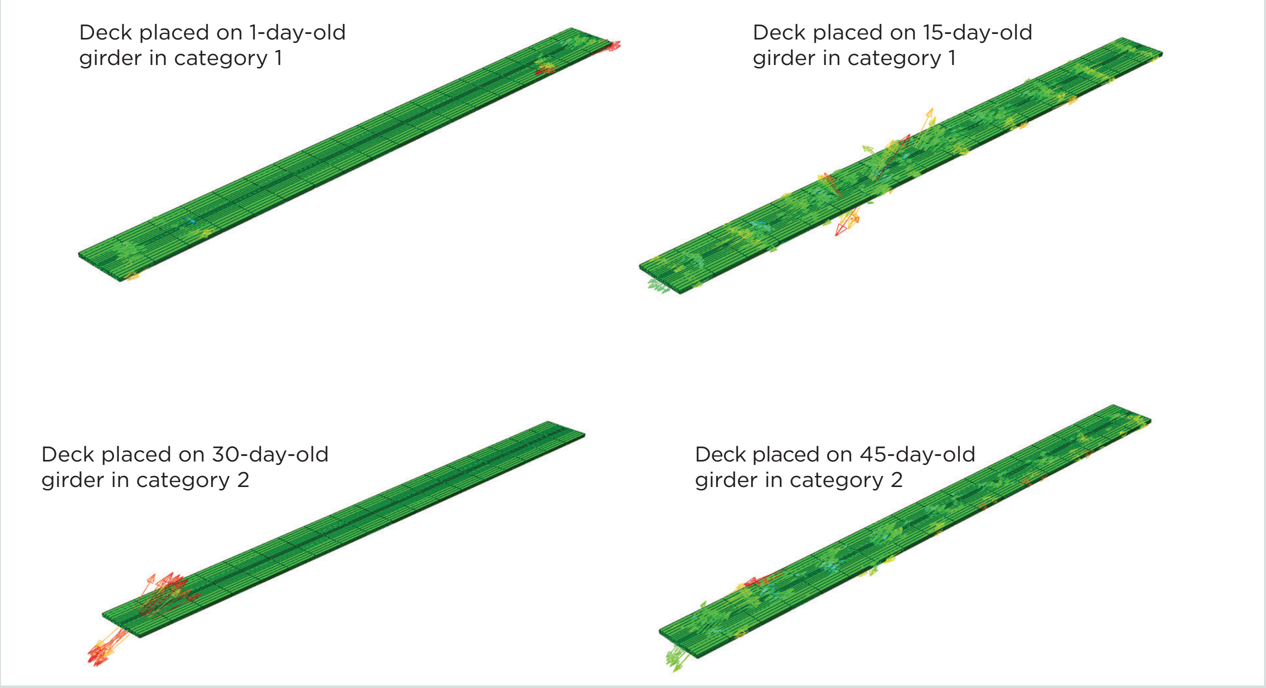

Figure 5. Deck cracking patterns for 95 ft (29.0 m) girder.

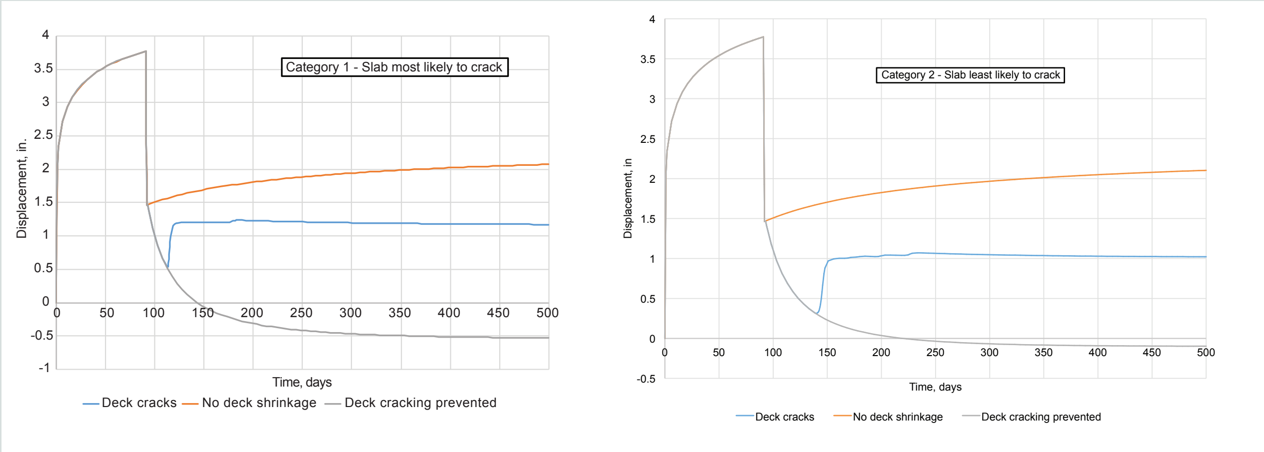

Figure 6. Camber at midspan of 120 ft girder top flange, considering and ignoring cracking. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

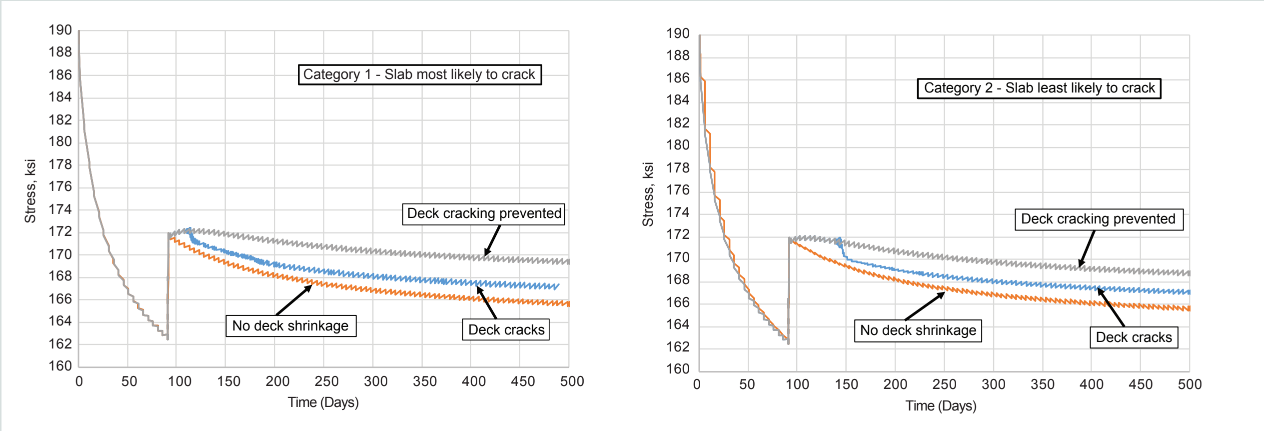

Figure 7. Prestress over time at midspan for 120 ft girder, considering and ignoring cracking in the slab. Note: 1 ft = 0.305 m. 1 ksi = 6.895 MPa.

ential shrinkage to be lost. For category 2, where the deck has a high concrete strength and low differential shrinkage, there is no cracking when the deck is placed at an early girder age. Cracking first appears when the deck is placed on a 30-day-old girder, with widespread cracks beginning from a girder age of 45 days. This shows that both the absolute shrinkage potential of the deck and the differential shrinkage potential are important factors in determining when the deck will crack. The girder age at the time of deck placement affects the differential shrinkage between the deck and girder, and if the deck is placed on an older girder the differential shrinkage will likely cause cracking. However, if the deck's shrinkage potential is high, it will crack even when placed on a very young girder where there is less differential shrinkage potential.

The results shown in Fig. 1 through 5 are for a 95 ft (29.0 m) long bulb-tee girder. To see the effect of span, a 120 ft (36.6 m) long bulb-tee girder was also simulated (**Fig. 6** and **7**). The results for the 120 ft girder are similar to those for the 95 ft gird-

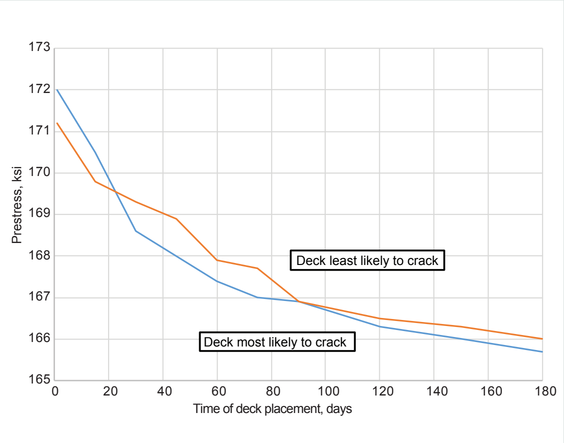

Figure 8. Variation of prestress at 500 days with girder age at time of deck placement for 120 ft girder. Note: 1 ft = 0.305 m; 1 ksi = 6.895 MPa.

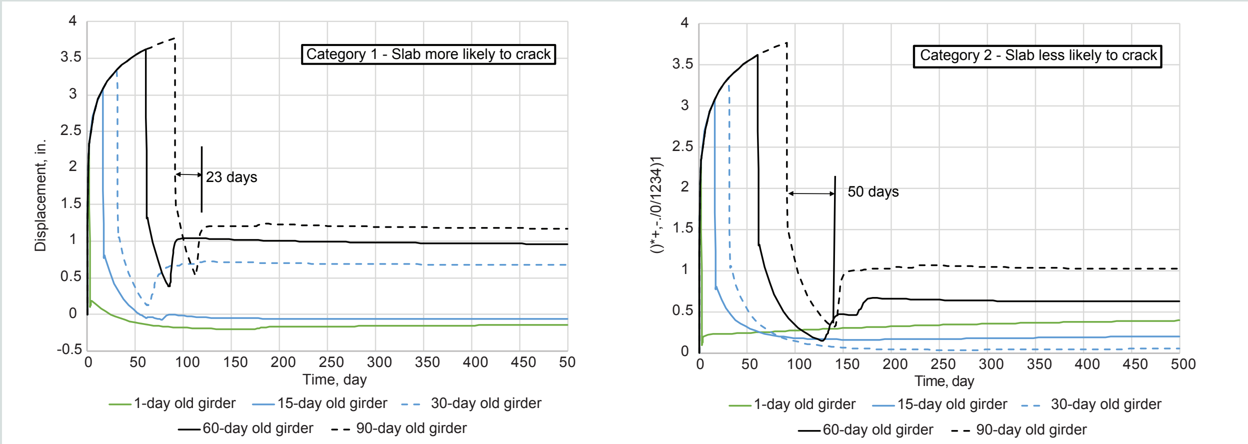

Figure 9. Deck cracking patterns for 120 ft girder when slab added at different ages for category 1 and 2. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

er. Figure 7 also shows that deck restraint after cracking allows about 50% of the gain in prestressing force to be retained.

Figure 8 shows the variation in the prestress (at the end of the 500-day simulation) with girder age at the time of deck placement for the 120 ft (36.6 m) girder. Overall, the results are similar to the trend observed in the 95 ft (29.0 m) girder. As with the 95 ft (29 m) girder, there is cracking in the deck even for decks placed when the girder is one day old; however as **Fig. 9** shows, it does not affect the girder behavior until distributed cracking starts to occur. Distributed cracking is seen when the deck is placed on a 30-day-old girder. For category 2, where deck cracking is less likely, there is no cracking seen when the deck is placed at a girder age of 30 days but distributed cracking is seen at an age of 60 days. Some additional analysis showed that cracking near the ends of the girder occurred when the slab was placed at a girder age of 45 days.

To investigate shorter spans, an 85 ft (25.9 m) girder was modeled. **Figure 10** shows a comparison of the midspan camber versus time for the 85, 95, and 120 ft (25.9, 29, and 36.6 m) girders for both categories. Note that the longer the span, the shorter the time over which cracking occurs. The shorter the span, the less camber recovery that occurs.

Figure 11 shows the variation of prestress with girder age for the 85 ft (25.9 m) girder for categories 1 and 2. For the case where cracking is more likely, there is a descending trend similar to the 95 and 120 ft (29.0 and 36.6 m) girders. The cracking in the deck starts at a girder age at the time of deck placement of 15 days, but cracks are only at the end of the girder. The cracks are more distributed for a girder age of 30 days and greater.

The data for category 2 show a different trend. The curve is basically flat until the point where the deck is placed at 75 days, after which the curve descends. This is because no cracking occurs in this slab for cases where the slab is placed at an age of 45 days or less. For slabs placed between 45 and 75 days, the cracking is only at the ends so the system still basically behaves as uncracked. Distributed cracking does not occur until the deck is placed at an age of 120 days.

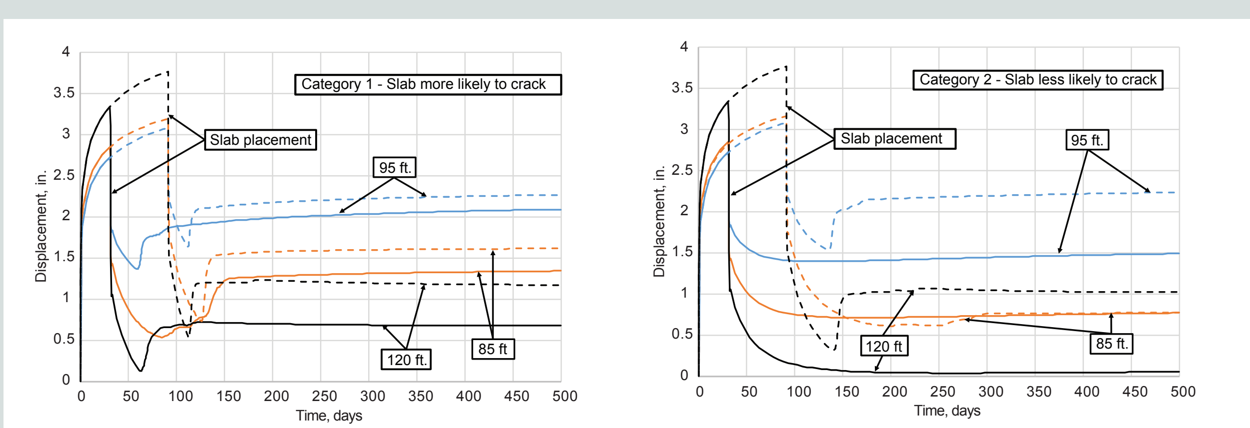

Figure 10. Deck cracking patterns for 85 ft girder in category 1 and 2 when slab added at girder ages of 30 to 90 days. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

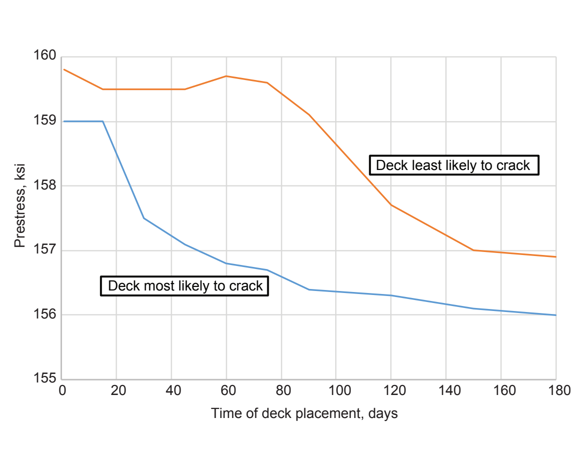

Figure 11. Variation of prestress at 500 days with girder age at time of deck placement of 85 ft girder in category 1. Note: 1 ft = 0.305 m; 1 ksi = 6.895 MPa.

Table 2 shows the greatest age at which the slab can be placed on the girder without any shrinkage cracking occurring. The table shows the greatest age of deck placement for any cracking to occur and the greatest age of deck placement at which distributed cracking occurs. Recall that shrinkage cracking does not affect the gain of prestressing force until the cracking becomes distributed.

Table 3 shows the time gap between the first occurrence of shrinkage cracking and the point at which further cracking no longer affects the system. At this second point, any deck restraint that will be lost due to cracking has completely occurred.

The data show that for shorter girders it is possible to place the slab when the girder is young and not have shrinkage cracking occur, even if there is a large potential for differential shrinkage. However, if there is a large shrinkage potential, the age at which the slab needs to be placed for cracking not to occur is so young as to be impractical for most real cases. For longer girders, cracking will occur under almost all circumstances if the differential shrinkage potential is high. For

Table 2. Girder age at deck placement and age where the deck starts to crack for categories 1 and 2

Girder length, ft	Greatest age at which slab can be placed on girder without any shrinkage cracking, days		Greatest age at which slab can be placed on girder without distributed shrinkage cracking, days	
	Cracking most likely	Cracking least likely	Cracking most likely	Cracking least likely
85	15	45	30	120
95	1	30	15	45
120	1	45	30	60

Note: 1 ft = 0.3048 m.

Table 3. Girder age at deck placement and time to deck cracking for categories 1 and 2

Girder length, ft	Approximate time between deck placement and cracking in deck			
	Cracking most likely		Cracking least likely	
	Girder age at time of deck placement, days	Time between deck placement and cracking, days	Girder age at time of deck placement, days	Time between deck placement and cracking, days
85	30	55	90	150
	60	47	90	150
	90	38	120	99
95	30	35	45	70
	60	25	60	55
	90	21	90	45
120	30	35	45	110
	60	28	60	69
	90	25	90	51

Note: 1 ft = 0.3048 m.

cases where the differential shrinkage potential is low, it is possible to place the slab on the girder at a realistic age (such as 60 days) and not have shrinkage cracking occur. This is more likely with shorter girders.

As was noted, actual concrete compressive strength, modulus of elasticity, creep, and shrinkage properties are extremely variable in concrete. It is almost impossible to accurately predict these properties during the design phase, so it is not likely that the engineer could use these simulations to predict the exact time of deck cracking. Rather, the results show that in most practical cases it is reasonable to assume that the deck will eventually crack and approximately 50% of the prestress gain due to differential shrinkage will be lost. This should be accounted for in the design phase.

Conclusion

The loss of prestress in girders with a composite concrete deck is affected by cracking in the deck, which in turn is affected by the time of deck placement. When the girder arrives at the construction site, it has a camber that is increasing due to creep and shrinkage. When the deck is placed on the girder, the deck weight and the shrinkage of deck concrete will decamber the girder.

- Due to the decambering of the girder, a net tension is produced at the bottom of the girder that adds stress to the prestressing strands and results in a gain in the prestressing force. The finite element analysis showed that there is a gain in the prestressing force due to deck shrinkage. However, this can be a temporary condition and some of the effect of differential shrinkage is lost if the deck cracks.

- In this project, by taking deck concrete strength and deck shrinkage as variables, simulations were done in two extreme categories where cracking in the deck was the most and the least likely to occur. In both categories the deck cracked. In most cases, the deck would start to crack from a girder age at the time of deck placement of 60 days and greater, regardless of the deck concrete strength or the deck's shrinkage coefficient. It is recommended that engineers assume that for any realistic time of deck placement, the deck will eventually crack.

- The AASHTO LRFD specifications assume, in the refined loss calculation, that differential shrinkage between the slab and girder results in a gain in prestressing force. However, the results show that in many cases, the slab will crack. When this cracking happens, some of the restraint of the deck is lost and some of the gain in prestressing force is lost. The system can tolerate some cracking before the restraint is lost, but restraint is lost if the cracking becomes widespread and distributed.

- The differential shrinkage potential is a combination of the absolute difference in the ultimate shrinkage potential of the deck and girder concrete and the age of the girder when the deck is placed. As expected, the older the girder when the deck is placed, the greater the cracking potential. If the absolute difference in ultimate shrinkage potential is small and the deck is strong enough, it is possible to place the deck on the girder in a reasonable amount of time (30 to 60 days) and not have cracking occur. In cases where the difference in shrinkage potential is high and/or the deck is made of a lower-strength concrete, deck cracking is likely to occur for any reasonable age of deck placement. For decks placed at the same girder age, it appears that cracking is more likely in longer girders.

- After the deck cracks, the restraining effect of the deck is not entirely lost and the deck continues to provide some restraint to the girder, thus all of the prestress gain due to differential shrinkage is lost after deck cracking. Although it varied in the simulation, on average 50% of the prestress gain was retained postcracking. Therefore, the approach followed by some state departments of transportation of accounting for 50% of the prestress gain due to differential shrinkage is supported by the results presented.

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Abstract

The American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications* have a refined method for the calculation of time-dependent losses in prestressing force. This method estimates a gain in the prestressing force due to differential shrinkage between the precast concrete girder and the cast-in-place deck; however, it does not consider the possibility of cracking in the deck. Some state departments of transportation believe that after the deck cracks, the gain in the prestressing force is lost, and they do not include it in the prestress loss calculations. Some other state departments of transportation believe that not all of the prestress gain is lost and allow some percentage of the gain to be retained. This study focuses on the effect of deck cracking on the long-term loss of prestressing force.

A finite element software model was used to simulate three different girder lengths with varying deck concrete strengths, differential shrinkage parameters, and girder ages at the time the deck was placed. When the girder age at the time of deck placement is more than 60 days, there is a high probability that the deck will crack, though a deck placed on a girder of any age may crack, depending on the properties of the deck and girder. When the deck cracks, some of the gain of prestressing force is lost, but the percentage lost depends on the extent of cracking in the deck. The older the girder is when the deck is placed, the greater the cracking. The cracked deck still provides some restraint, and even in cracked decks, nearly 50% of the prestress gain due to differential shrinkage was retained.

Keywords

AASHTO refined method, camber, cracking, differential shrinkage, prestressing force loss.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

Reader comments

Please address any reader comments to *PCI Journal* editor-in-chief Emily Lorenz at elorenz@pci.org or Precast/Prestressed Concrete Institute, c/o *PCI Journal*, 200 W. Adams St., Suite 2100, Chicago, IL 60606.