DURABILITY ENHANCEMENT THROUGH THE USE OF INTEGRALLY-CAST WEARING SURFACES FOR PRECAST SEGMENTAL CONCRETE BRIDGES

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ABSTRACT

Long-term penetration of chlorides from de-icing agents or aggressive natural environments can accelerate corrosion and cause serious damage to deck reinforcement. Thus, the minimization of cracking within any protective overlay layer is important to the long-term durability of the deck. One method to prevent overlay cracking is the application of precompression, especially in conjunction with the post-tensioning of the rest of the structure. The details of structural analyses on two different precast segmental bridges are presented here in an effort to quantify and compare the state of longitudinal stress in two different types of deck overlays. The first, a conventional overlay applied as a secondary operation after erection is completed, does not act structurally and does not benefit from the post-tensioning of the bridge's tendons. The second overlay is cast integrally with the bridge segments and precompressed along with the structure. The results of this study found significant differences in the states of stress between the two types of overlays even when considering all time-dependent effects due to creep and shrinkage. The analyses also indicate that future removal and replacement of the integral wearing surface increases the total compressive stress in the bridge, particularly in the deck. The results imply that an overlay integrally cast and post-tensioned with the cross-section can enhance the durability of the bridge deck.

Keywords: durability, overlay, segmental, precast, span-by-span, balanced-cantilever, post-tension, integral.

INTRODUCTION

Sacrificial overlays applied to increase durability of bridge decks are widely used throughout the industry. Long-term penetration of chlorides from de-icing agents or aggressive natural environments can accelerate corrosion and cause serious damage to deck reinforcement. The migration of these deleterious materials is exacerbated by any pre-existing cracks or other damage to the deck overlay. Thus, minimizing cracking within the sacrificial overlay layer is important to the long-term durability of the deck.

Segmental concrete bridges are designed to minimize cracking in their deck surfaces through the use of post-tensioning. Bridges of this type present an opportunity to further enhance durability through the use of an overlay cast integral with the deck. This increase in durability of the integral overlay itself is achieved because it is precompressed along with the rest of the cross-section during post-tensioning, minimizing cracking and thus the potential for direct penetration of chlorides.

RECENT INDUSTRY DEVELOPMENTS

Beginning in 1992 routine inspections of several precast segmental bridges in the I-595 / I-75 interchange in Broward County, Florida found that water was regularly leaking through the segment joints. These bridges were constructed from 1986 to 1989 using the balanced-cantilever erection technique and featured joints sealed with epoxy at the time of segment joining[1]. After investigation of this problem, it was determined that the lack of a watertight seal at the segment joints resulted from a combination of problems including the "improper application of epoxy, overly aggressive cleaning of the match-cast faces by sand or high pressure water blasting, and imperfect duct seals…during casting[2]."

As a result of these problems the AASHTO T10 committee proposed Ballot Item 23, which recommends the use of an applied overlay placed as a secondary operation for all segmental bridges. It further recommends against the use of monolithic overlays cast integrally with the bridge cross-section. In doing so, the background for this Ballot Item references two primary concerns:

- Chloride intrusion at the segment joints
- The "complicate(d)…state of stress in the bridge at the time of 'overlay replacement'"

Chloride Intrusion of Epoxy Joints

Recent research and industry experience indicate that properly constructed epoxy joints in segmental bridges provide an effective barrier to prevent intrusion of chlorides into the deck. Accelerated corrosion tests were performed at the University of Texas at Austin in the late 1990's on a variety of specimens with various methods of construction. Application of epoxy, type of tendon duct, level of precompression at the joint, and grout admixtures were varied in an attempt predict the long-term performance of segmental bridge joints. The authors noted that the performance of specimens with epoxy joints was excellent in resisting corrosion of embedded items located in the vicinity of the joints. Over the four year accelerated corrosion period, only one of the 24 specimens built with epoxy joints showed any signs of corrosion activity. Even then, autopsy results for that specimen showed that the corrosion was minor and could not be attributed to the penetration of chlorides at the joint[3].

Florida's experience with the epoxy joint performance of the I-595 / I-75 interchange has not been repeated. To date in the United States there have been no other reported instances of corrosion of internal tendons in segmental bridges built with epoxy joints[4]. Thus, it appears reasonable to assume that focusing efforts to increase the quality of workmanship and inspection practices should further serve to prevent these isolated cases.

State of Stress During Overlay Replacement

The primary purpose of this paper is to present an attempt to quantify the state of longitudinal stress in two types of precast segmental bridges with different types of overlays. It is the authors' hope that this will clear up any confusion regarding the state of stress in a segmental bridge before, during, and after the removal and replacement of an overlay cast integral with the cross-section. The analyses presented herein were performed to compare stresses in integral and applied overlays during the lifetime of the structure and to determine the effects of the removal of the integral overlay and its subsequent replacement with an applied overlay.

ANALYSIS TECHNIQUES

The construction of two different types of segmental bridges was analyzed for this study. The first, and simpler, model represents the span-by-span method of construction. This method typically involves the use of a temporary support truss on which all segments in a span are placed and aligned. After the longitudinal tendons in the span have been stressed, the new span can support its own weight and the truss is moved to the next adjacent span to begin the process again. Structural continuity of a unit of several spans is achieved because the tendon profiles overlap across diaphragms located at each pier.

The balanced-cantilever method of segmental erection was modeled for the second analysis. At each pier location, a pier table with a diaphragm is erected for transfer of loads to the substructure. From this central segment, segments are erected on either side as matching pairs, creating two cantilevers of equal length. This process is repeated at each pier location. When the cantilevers from adjacent piers meet at approximately mid-span a cast-in-place closure segment is constructed. Longitudinal tendons running across the closure are stressed to provide structural continuity. With this method, locked-in construction stresses are relatively large and are highly dependent on the sequence of erection.

The effects of live loads on the state of stress in each structure were not investigated. For segmental bridges, live load effects are relatively small compared to dead loads, post-tensioning, and time-dependent stress redistributions. Application of live loads would be the same for each overlay model, and thus would provide little additional insight for a comparison of the state of stress in the bridges with the different types of overlays.

COMPUTER PROGRAM

The computer program BC was used to model the segmental bridges for this study. BC is a two-dimensional analysis program that can model the construction stresses stage-by-stage throughout the erection process. With this program, segments are "erected" and tendons are "stressed" in the computer as they would be during actual construction. Thus, the built-in stresses due to the erection steps are included in these analyses. Time dependent effects such as creep, shrinkage, and tendon relaxation are also tracked, and their effects on the state of stress at any time during the service life of the modeled structure can be quantified.

BRIDGE MODELING

Span-By-Span Models

The span-by-span construction models consist of a four-span continuous unit with typical span lengths of 150 feet (46 m) as shown in Figure 1. The superstructure cross-section is a single-cell precast segmental trapezoidal box girder with a nominal constant depth of 8'-6" (2.6 m) and approximate deck width of 57 feet (17.4 m) (see Figure 2). Longitudinal post-tensioning is provided by four pairs of 27~0.6" (15.24 mm) diameter strand tendons in each span.

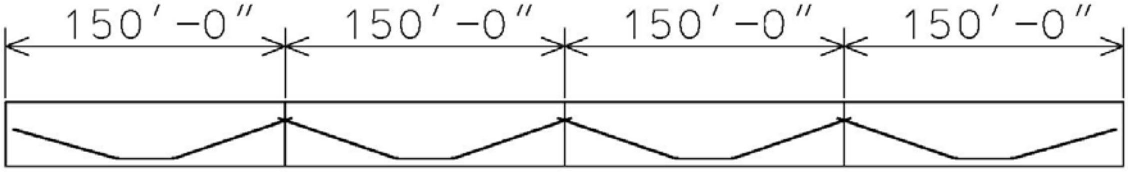

Fig. 1 Span Layout for the Span-By-Span Computer Models

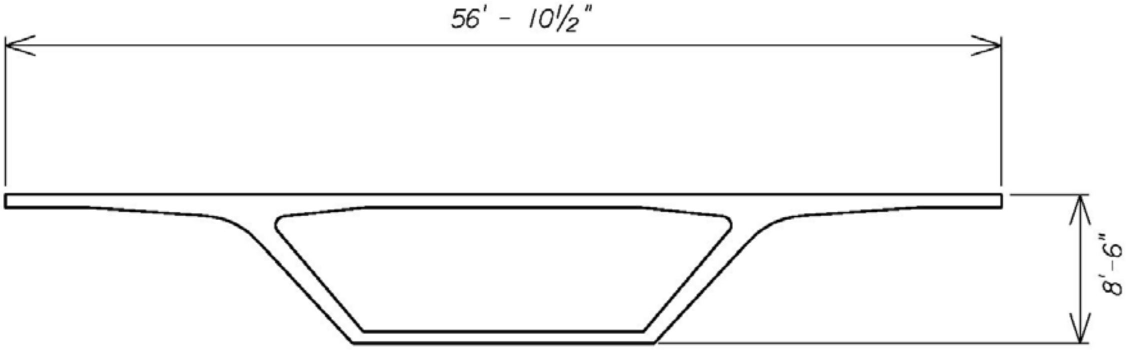

Fig. 2 Nominal Cross-Section for the Span-By-Span Computer Models

Balanced-Cantilever Models

As shown in Figure 3, the computer model for the balanced-cantilever construction method consists of a three span unit with lengths of 196’ – 316’ – 196’ (60 m – 96 m – 60 m). The nominal superstructure depths vary from 16’-0” (5.08 m) at the piers to a minimum of 7’-6” (2.34 m) at mid-span and in the end spans (see Figure 4). Two 19~0.6” (15.24 mm) diameter top slab cantilever tendons are provided for each segment. 19~0.6” (15.24 mm) diameter external draped tendons and 12~0.6” (15.24 mm) diameter bottom slab internal tendons provide capacity for live loads and structural continuity across the closure joints.

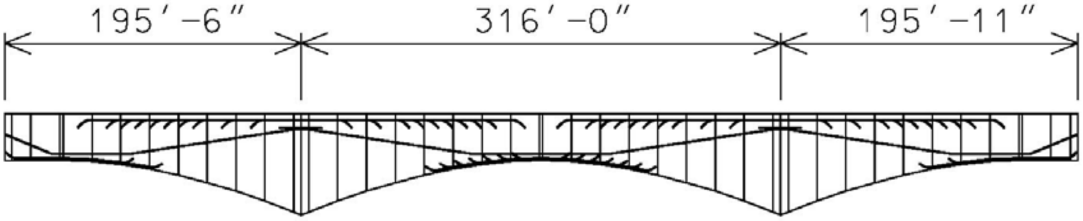

Fig. 3 Span Layout for the Balanced-Cantilever Computer Models

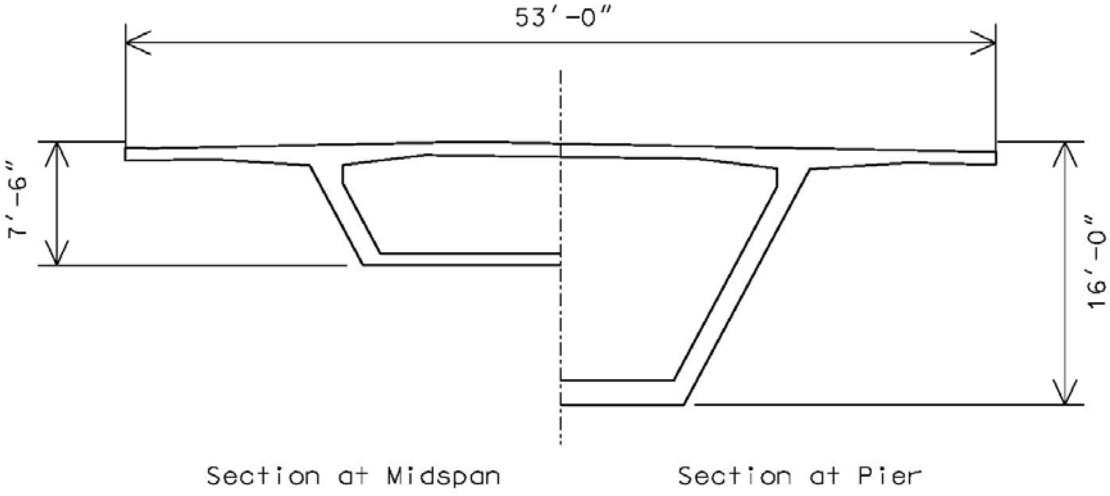

Fig. 4 Nominal Cross-Sections for the Balanced-Cantilever Computer Models at midspan and the pier.

OVERLAY MODELING

Applied Overlay

For the purposes of this study, the term "applied overlay" refers to a wearing surface constructed as a secondary operation after erection of the bridge segments is completed. For the computer models, a 2-inch (50 mm) thick applied concrete overlay was assumed with a density of 150 lb/ft^3 (2400 kg/m^3). This type of overlay is assumed to not act structurally with the rest of the cross-section, and is applied as an additional dead load to the superstructure (see Figure 5). For the applied overlay models, the nominal cross-sectional properties are not affected by the presence of the overlay concrete. Removal and replacement of an applied overlay is modeled as a removal of the applied dead load and replacement with an equivalent dead load.

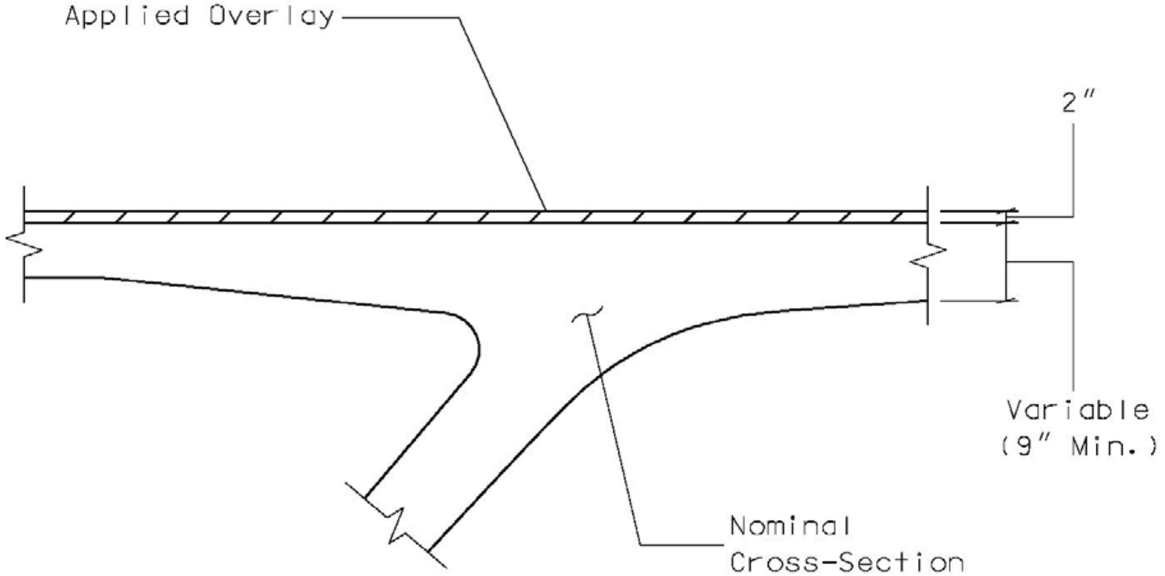

Fig. 5 Applied Overlay

Integral Overlay

Unlike an overlay applied as a secondary construction operation after segment erection, the integral overlay is cast with each segment prior to erection. Thus the integral overlay affects the cross-sectional properties and acts with the structure during post-tensioning. For this study, the integral overlay is assumed to increase the deck thickness of the nominal cross section by 2 inches (50 mm) across the full roadway width (see Figure 6).

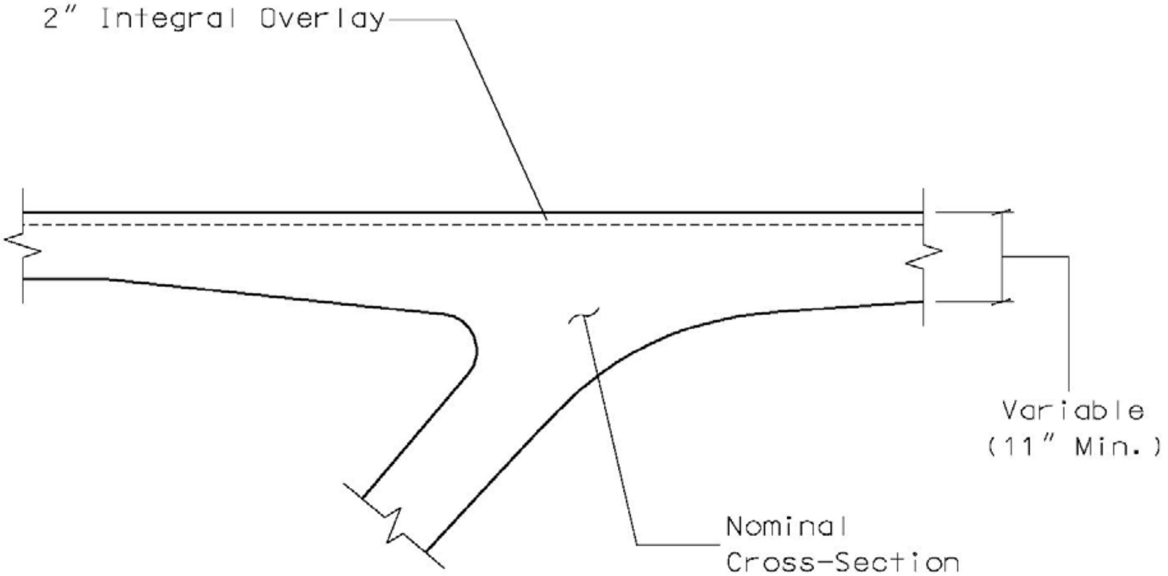

Fig. 6 Integral Overlay

Because an integral overlay affects the cross-sectional properties of the bridge, its "removal" cannot be simulated in the computer model by applying an opposite dead load of the same magnitude as the overlay weight. The change in cross-sectional properties that occurs during removal of the overlay must be accounted for in the analysis. To achieve this, the integral overlay computer models uses "offset segments" to represent the overlay concrete (see Figure 7).

Using this technique, the integral overlay cross-sectional properties are modeled separately from the nominal cross-section. The bridge and overlay segments are connected by rigid links with full shear transfer capability. This technique allows the overlay segments to be removed from the model, leaving the nominal cross-section behind. Application of an applied overlay after removal of the integral overlay is then simply a matter of applying the appropriate distributed dead load to the model. The construction history and time-dependent effects are applied to the overlay segments concurrently with the bridge segments.

To verify the results of the offset segment method used to model the integral overlay, "baseline" computer models were created with cross-sectional properties that included the integral overlay concrete. Section properties for the baseline models reflected the increase in cross-sectional area and moment of inertia due to the presence of the overlay. Like the offset segment models, the baseline models were run through all construction phases and to the assumed end of time-dependent effects. The states of longitudinal stress for the baseline and offset segment models were virtually identical (within approximately 1.5%), thus verifying that the offset segment models were behaving as expected (see also Table 1).

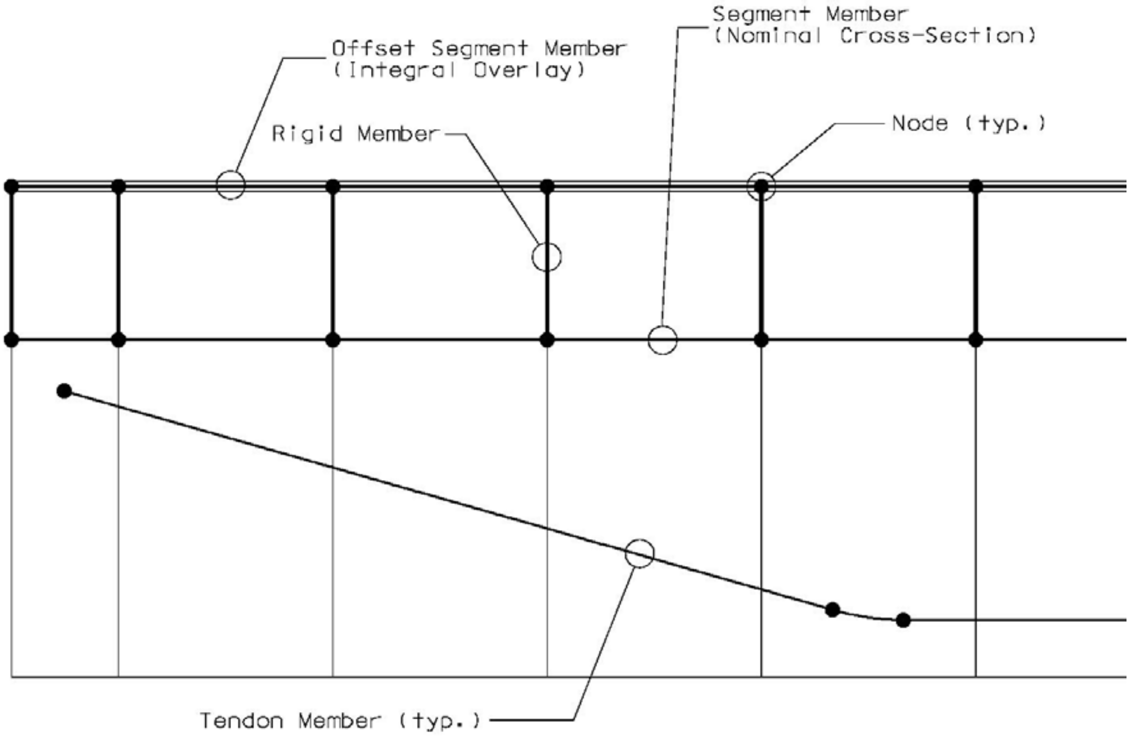

Fig. 7 Modeling of Integral Overlay Using Offset Segments

Consistency Between Models

The increase in dead load beyond that of the nominal cross-section due to each type of overlay is equal: the applied overlay models contained the overlay weight as an applied load, while the weight of the integral overlay was contained within the cross-section. To provide complete consistency between the overlay models, the location of the post-tensioning tendons for each structure type is exactly the same with respect to the bottom of the structure. The distance from the top deck to centerline of the tendons is 2 inches (50 mm) greater for the integral overlay models.

The consistency in total applied dead load and layout of post-tensioning allows a direct comparison of results between the models with the different overlay types. Table 1 shows the general construction steps taken in each computer model.

Table 1 General Construction Stages for the Computer Models

Day	Construction Stage	Computer Modeling Actions		
		Applied Overlay Model	Integral Overlay Models	
			Offset Segments	Baseline
1	Begin Segment Erection	Begin Erection	Begin Erection	Begin Erection
200	End Segment Erection	End Erection	End Erection*	End Erection*
200	Install Applied Overlay	Add Distributed Dead Load	N/A	N/A
4000	Complete All Time-Dependent Effects	End Time-Dependent Effects	End Time-Dependent Effects *	End Time-Dependent Effects *
4000	Remove Overlay	Remove Distributed Dead Load	Remove Offset Segments	N/A
4000	Install New Applied Overlay	Add Distributed Dead Load	Add Distributed Dead Load	N/A

* Verification check between the baseline and offset segment models for the integral overlay cases.

RESULTS

SPAN-BY-SPAN MODELS

State of Overlay Axial Stress

Figure 8 illustrates the comparison of the axial stresses in each type of overlay including the effects of all time-dependent losses.

The integral overlay exhibits a substantial and predictable state of compressive stress. Because the integral overlay acts as a part of the cross-section during erection and post-tensioning, the compressive stress varies from –46 ksf to –89 ksf (-2.2 to –4.3 MPa) along the length of the four-span unit. The average compression in the integral overlay is –76 ksf (-3.6 MPa).

Prediction of the state of stress in the applied overlay is more complicated. For this study, it was assumed that the overlay was placed in one continuous operation and that the overlay concrete cured uniformly along the length of the four-span unit. Two curves are used in an attempt to bracket the behavior of the applied overlay.

The lowerbound curve shown in Figure 8 assumes that the applied overlay experiences the same stresses that the top of the structural section sees from the time it is applied until all time dependant losses have occurred. This curve represents the lower end of the possible range of stresses in the applied overlay because no allowance for shrinkage of the overlay itself was made. Assuming no restrained shrinkage stresses, the applied overlay exhibits a small level of tensile stress along most of the length of the structure. The tensile stresses averaged approximately +5 ksf (+0.24 MPa) and peaked at up to +12 ksf (+0.57 MPa) over the piers.

The upperbound curve adds the estimated restrained shrinkage stress in the overlay concrete to the lowerbound curve. Based on the relative shrinkage strain between the structural cross-section and the overlay using the approach outlined by CEB-FIP, a strain of 0.00016 was applied to estimate this stress[5]. Using this estimate, the upperbound curve averages approximately +107 ksf (+5.1 MPa) of tensile stress and peaks at approximately +114 ksf (+5.5 MPa). However, it is unlikely that the applied overlay would ever see that value of stress: the Modulus of Rupture is approximately +84 ksf (+4.0 MPa). Thus, the Modulus of Rupture would become the new upperbound for defining the state of tensile stress in the applied overlay.

In all likelihood, an actual applied overlay would not reach the levels of tensile stress shown in the Figure 8. It would experience numerous cracks that would then release any significant tensile stress and compromise the effectiveness of the overlay concrete. The graph in Figure 8 illustrates the wide stress variations averaging 78 ksf (3.7 MPa) that are theoretically possible in the applied overlay.

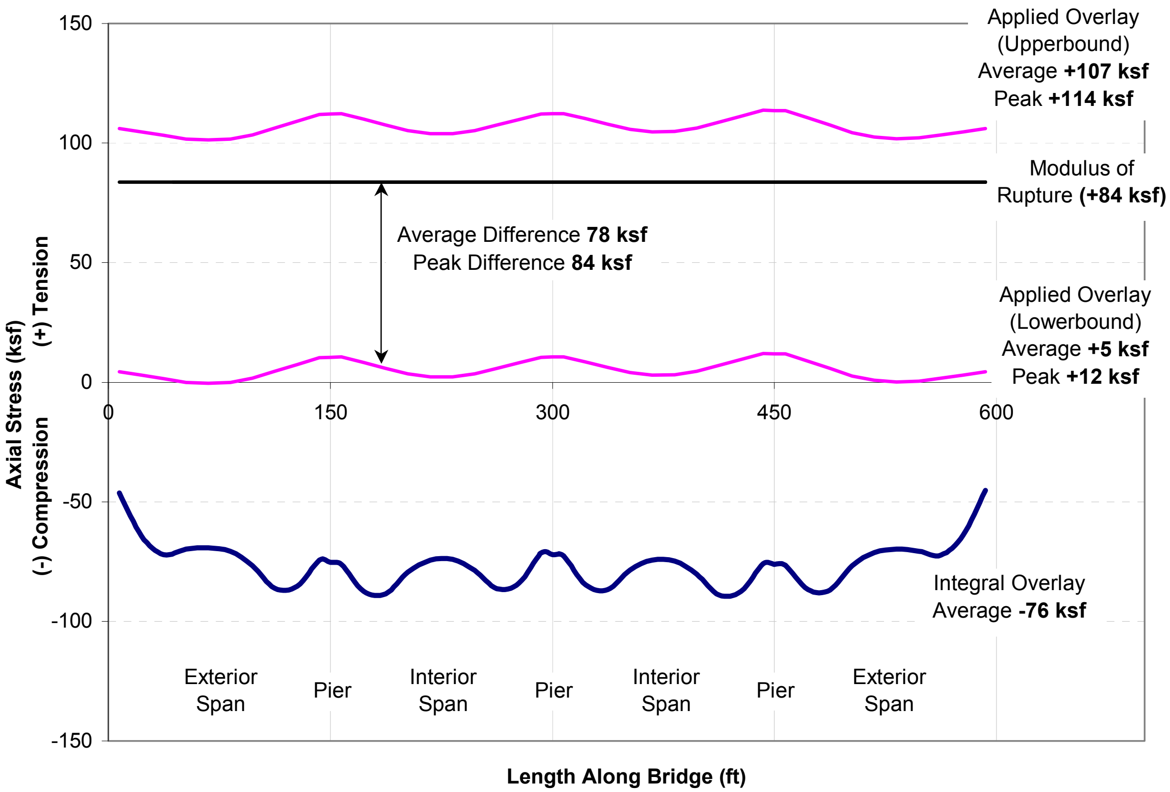

Fig 8 Span-By-Span Model: Overlay Axial Stresses Including All Losses (Creep, Shrinkage, PT Steel Relaxation)

Removal of the Integral Overlay and Replacement with an Applied Overlay

The axial stress changes in the top and bottom fibers of the structure due to removal of the 2" (50 mm) integral overlay are shown in Figure 9. When removal of the integral overlay is complete the post-tensioning stresses redistribute over a smaller cross-sectional area. This produces a net increase in compression that averages approximately –8 ksf (-0.38 MPa) along the length of the structure. The level of compressive stress in the top fibers of the section increases throughout the four-span unit.

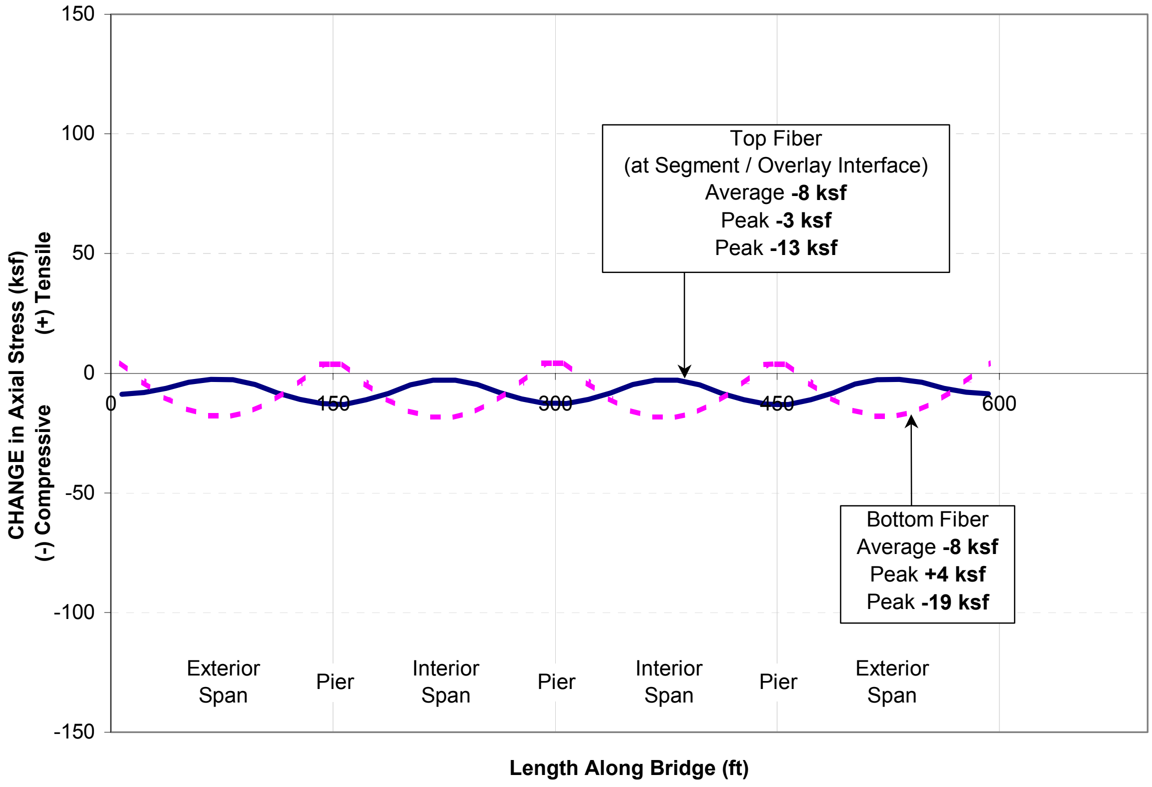

Fig 9 Span-By-Span Model: Change in Axial Stresses
Due to Removal of the Integral Overlay Concrete

The change in the state of longitudinal stress in the span-by-span bridge due to removal of the integral overlay concrete and its replacement with an applied overlay of equal thickness is shown in Figure 10. The top slab stresses exhibit a higher level of compressive stress even after application of the applied overlay at all locations along the length of the structure. The increase in compressive stress averages approximately –8 ksf (-0.38 MPa). For the majority of the length of the structure, the bottom fibers also show a slight increase in compressive stress. A small decrease in compressive stress of approximately +4 ksf (+0.19 MPa) occurs at the outer portions of the end spans in the bottom fibers.

These results indicate that the redistribution of the post-tensioning forces across the smaller cross-sectional area of the segments without the integral overlay is the predominant effect during overlay removal and replacement. This shows that the act of removing and replacing an integral wearing surface with a new applied overlay effectively precompresses the bridge further, especially in the top fibers of the section.

Because an applied overlay does not act as a part of the section during post-tensioning (all tendons are typically stressed prior to application of an applied overlay), its removal and replacement causes little if any change in the state of longitudinal stress in the structure.

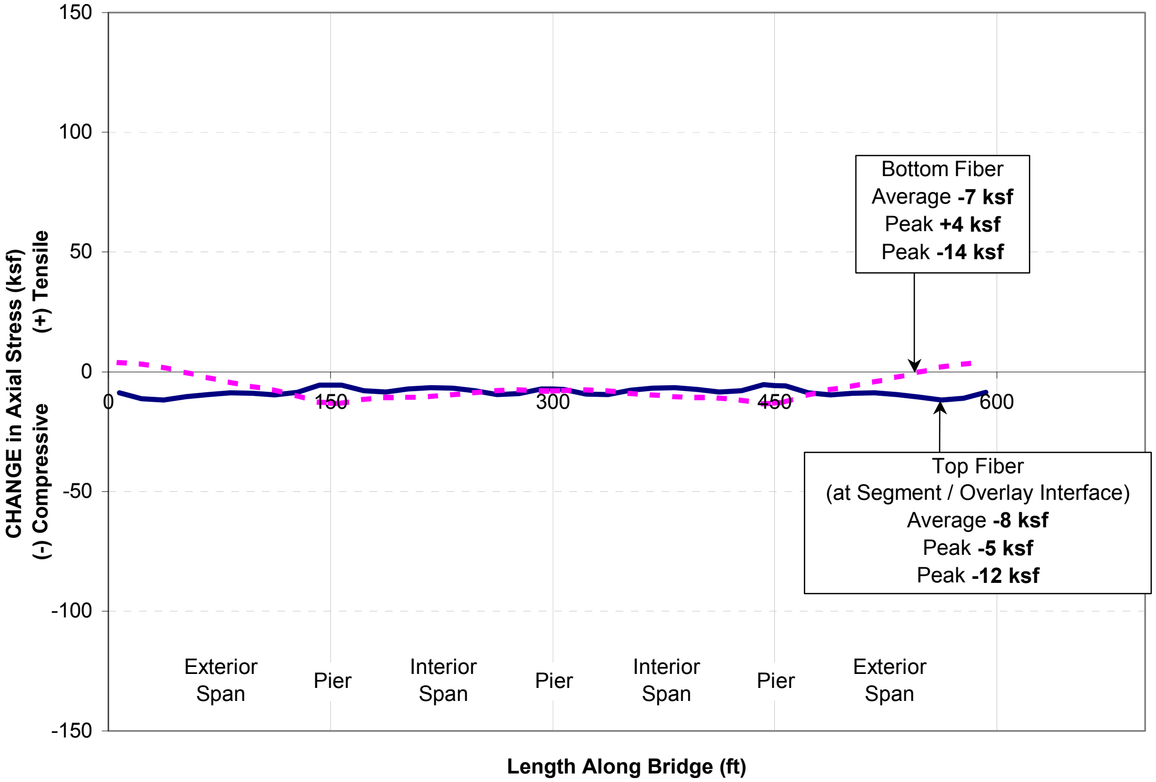

Fig 10 Span-By-Span Model: Change in Axial Stresses Due to Removal of the Integral Overlay and Replacement with an Applied Overlay

BALANCED-CANTILEVER MODELS

State of Overlay Axial Stress

Similar to the span-by-span model results discussed previously, a comparison of the axial stresses in the integral and applied overlays with all time-dependent losses for the balanced-cantilever models is shown in Figure 11.

The integral overlay, post-tensioned along with the bridge cross-section during erection, exhibits substantial and predictable compressive stresses. The average compression in the integral overlay is –103 ksf (-4.9 MPa).

The state of stress in the applied overlay is more complicated and varies more widely than the span-by-span model's results. The applied overlay lowerbound curve shown in Figure 11, which assumes that no restrained shrinkage stresses have occurred in the overlay concrete, exhibits a wide range of tensile and compressive stresses along the length of the three-span balanced-cantilever unit. The tensile stresses peak at approximately +29 ksf (+1.4 MPa) and the compressive stresses are as low as -20 ksf (-0.96 MPa) near midspan.

The upperbound curve adds the effects of the estimated shrinkage strain of 0.00016 to the lowerbound curve as done previously for the span-by-span models. The peak tensile stresses in the upperbound curve are as high as +131 ksf (+6.3 MPa), much higher than the Modulus of Rupture of approximately +84 ksf (+4.0 MPa). Because of this, the balanced-cantilever model's upperbound tensile stress envelope is probably defined by the Modulus of Rupture, indicating a high likelihood that cracking occurs in the applied overlay concrete.

Based on the results of the balanced-cantilever models shown in Figure 11, stress variations up to 103 ksf (4.9 MPa) are theoretically possible in the applied overlay. This makes the actual state of longitudinal stress in the applied overlay difficult to predict.

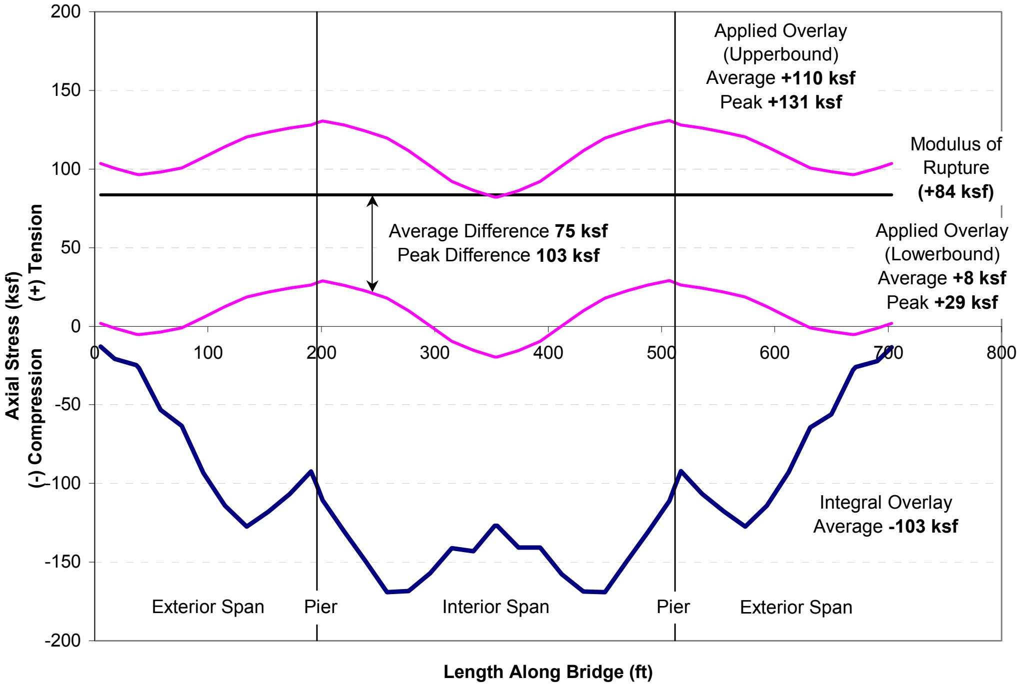

Fig 11 Balanced-Cantilever Model: Overlay Axial Stresses Including All Losses (Creep, Shrinkage, PT Steel Relaxation)

Removal of the Integral Overlay and Replacement with an Applied Overlay

The axial stress changes in the top and bottom fibers of the balanced-cantilever unit due to removal of the 2-inch (50 mm) integral overlay are shown in Figure 12. The top fibers undergo a slight decrease in compression of approximately +12 ksf (+0.57 MPa) at midspan. At the piers, the top slab compressive stresses increase by –28 ksf (-1.3 MPa). The bottom slab undergoes changes in axial stress similar in magnitude but opposite in sign to those in the top slab.

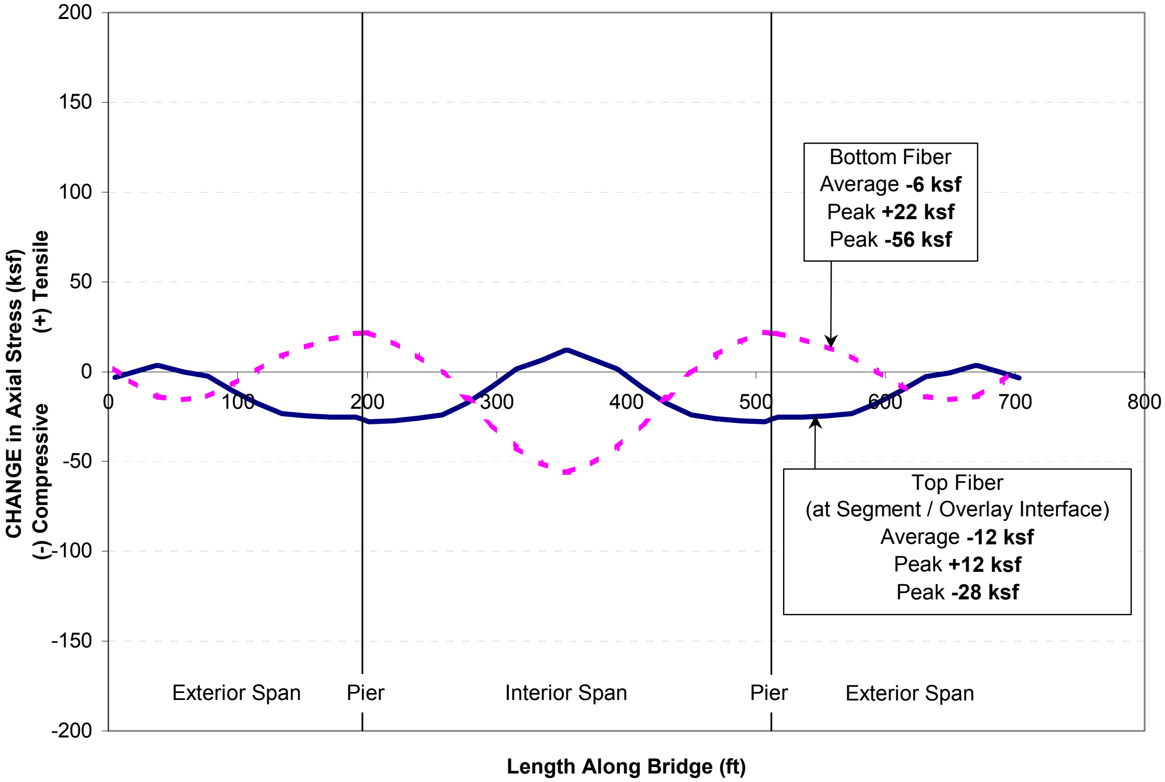

Fig 12 Balanced-Cantilever Model: Change in Axial Stresses
Due to Removal of the Integral Overlay Concrete

Removal and replacement of the integral overlay concrete in the balanced-cantilever model produces an increase in compressive stress in the top fibers along the entire length of the three-span unit. This additional compression averages approximately –10 ksf (-0.48 MPa). The effects in the bottom slab are similar with an average increase in compression of –9 ksf (-0.43 MPa). Small portions of the bottom slab show a slight decrease in compressive stress of +2 ksf (+0.10 MPa) at the extreme ends of the sidespans.

Like those of the span-by-span model, these stress changes indicate that removal and replacement of the integral wearing surface adds a small amount of compression to the top and bottom fibers of the section. These changes are small and evenly distributed along the length of the unit, and represent an unintended benefit to the bridge cross-section: additional precompression at a point in the future service life of the structure without the installation of additional post-tensioning tendons.

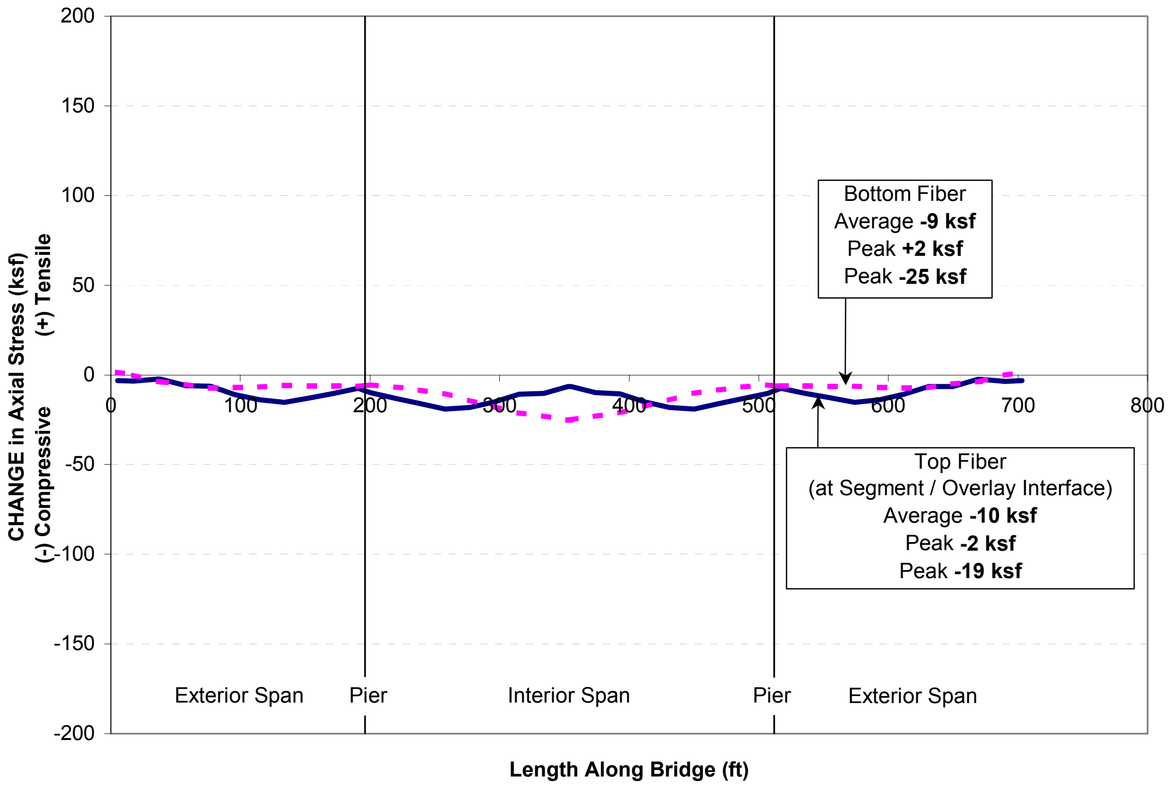

Fig 13 Balanced-Cantilever Model: Change in Axial Stresses Due to Removal of the Integral Overlay and Replacement with an Applied Overlay

IMPLICATIONS OF RESULTS

The results of these analyses hold several implications for the perceived and actual durability of the two types of overlays.

First, the computation of design stresses in an integral overlay is simple and accurate. This is due to the fact that the structural section remains under substantial compression at all times. With no cracking of the structural section stress calculations are simplified. Gross section properties may be used and redistribution of stresses is always occurring on a section under a constant state of compression.

Prediction of the actual state of stress in an applied overlay is difficult and highly dependent on factors unknown at the time of the design. The condition of the applied overlay concrete is affected by placement and curing methods, the mix design, and ambient weather conditions at the time of installation[6]. The lack of precompression in the applied overlay implies that the concrete is more sensitive to long-term stress changes. The redistribution of stresses due to creep and shrinkage increases the likelihood for crack development, reducing the effectiveness of the overlay as a bridge deck protective measure.

Future removal of the integral overlay concrete and replacement with a new applied overlay produces the unintended benefit of additional compression in the bridge deck's top fibers. This is due to the redistribution of the post-tensioning forces over a slightly smaller cross-section, which is the predominant effect. The small amount of additional compressive stress could further enhance the durability of a bridge deck.

CONCLUSIONS

Concerns regarding the long-term performance of segmental bridge overlays cast integrally with the bridge deck appear to be related primarily to isolated workmanship and inspection problems during the application of epoxy and erection of segments. Accelerated corrosion testing results support the general industry experience that segment joints with epoxy successfully perform their intended function as a sealant against intrusion of water and chlorides into the bridge deck.

The computation of the state of longitudinal stress in an integral overlay is simple and accurate. Along with the nominal bridge cross-section, this type of overlay enjoys the structural benefits of the applied post-tensioning. The integral overlay concrete is under a significant and consistent state of compressive stress throughout the service life of the material. This, in turn, further reduces cracking and enhances the effectiveness of the overlay as a protective barrier.

An overlay applied as a secondary operation receives no benefits from precompression. Furthermore, the long-term effects of creep and shrinkage in the structure apply tensile stresses to the applied overlay material. This situation is exacerbated by the potential for restrained shrinkage tensile stresses that are often enhanced by environmental conditions and construction methods that are outside the control of the designer. All of these factors combine to increase the likelihood of cracking of the overlay, reducing its effectiveness in protecting the bridge deck from water and chloride infiltration.

Concrete is a permeable material. Even with no cracking an integral overlay will eventually need to be replaced. The integral overlay "buys time" by delaying the need for an applied overlay. Future removal of the integral overlay concrete and replacement with a new applied overlay further benefits the bridge deck by producing a small amount of additional compressive stress in the deck's top fibers. Durability of the deck is potentially enhanced by this operation.

Integral wearing surfaces provide precast segmental bridge owners with another viable option for extending the life of their bridge decks.

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