A Crack Is Not a Crack: Bridge Deck Cracking

by Dr. Oguzhan Bayrak, University of Texas at Austin

Bridge deck cracking has been a problem for bridge owners for decades, and it continues to be a significant maintenance challenge. Deck replacement efforts are a significant expense for most bridge owners during the service lives of bridges. This article discusses key issues that affect bridge deck performance and is intended to demystify the art and science behind deck design and construction. Concrete bridge deck cracking can be influenced by the structural design of decks and the associated reinforcing bar detailing; deck behavior at service and ultimate limit states; the interplay between reinforcing bar details; concrete mixture design; and volume changes that the deck concrete experiences. These influences will be discussed in this article in an effort to tackle the variety of topics affecting bridge decks. Within that context, let us first focus our attention on the most common bridges and deck types. In the vast majority of cases, decks are made from reinforced concrete and supported on beams. To understand the root causes of cracking for this type of bridge deck, let us start with the design process and then discuss concrete mixture proportions, construction, curing, and maintenance processes.

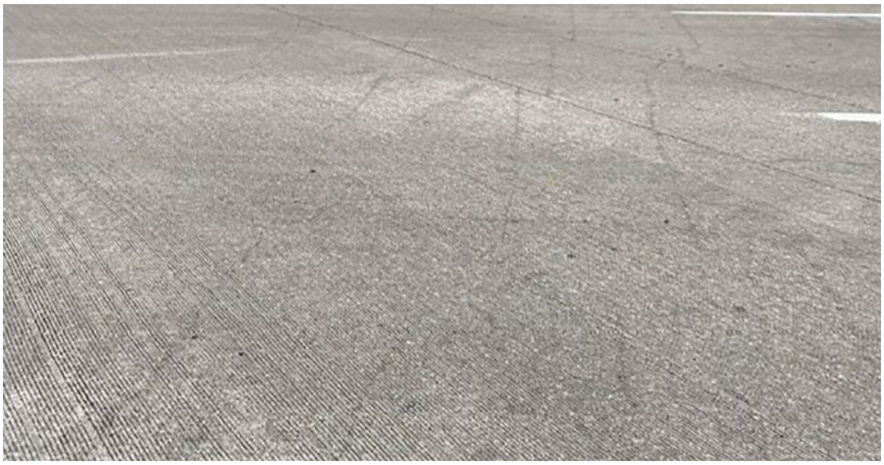
Design of Bridge Decks

Section 9 of the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[1] is devoted to decks and deck systems. It provides guidance on empirical deck design techniques as well as deck design methods that approach the analysis of deck behavior and the design process in a more refined manner. When bridge owners have their own bridge design manuals, those manuals often reference this section of the AASHTO LRFD specifications but include some variations that reflect the local jurisdiction's preferences. Those preferences tend to be rooted in decades of observations of deck performance in the owner's region. For example, requirements for concrete cover to the top layer of reinforcement in the deck will vary depending on the exposure conditions and, in some cases, the use of corrosion-resistant reinforcement.

Lane loads and truck loads applied on the decks are primarily distributed to the supporting beams in the transverse direction relative to the direction of traffic. In this context, we can envision a design strip that runs perpendicular to the beam lines in a typical, traditional deck design method. This design strip has the greatest level of flexural stiffness, attracting the great majority of the design loads. The percentage of the reinforcement in this "primary" direction is typically greater than that in the longitudinal direction. As the spacing of the beams that support the deck increases, so do the bending moments created by the permanent and transient loads. With increasing bending moments, the need to use larger quantities of transverse deck reinforcement increases. How deck reinforcement is detailed relates to how service loads are carried and, ultimately, to the additive effects of service load–induced stresses to those stemming from restrained shrinkage effects (to be discussed in later sections of this article). In some jurisdictions, the quantity of transverse reinforcement in each deck design is varied accordingly. In other jurisdictions, given the high volume of construction and standardized girder spacings and superstructure geometries, the quantity of transverse reinforcement is kept constant to simplify both the design process and the inspection process during construction.

The deck reinforcement that is placed in the longitudinal direction is intended to control the widths of transverse cracks, if and when they form. In this sense, the design requirements are typically rooted in the crack-control reinforcement requirements. My first article in this series provides the technical basis for the crack-control requirements by providing the first principles–based explanation of the cracking phenomenon and the stresses that develop in reinforcing bars crossing those cracks (see the Summer 2024 issue of *ASPIRE*®). Spacing, bar size, and clear cover requirements all influence the efficacy of the crack-control reinforcement, as well as the widths of any cracks that may form.

Deck cracking is a complex topic. Transverse cracking of the decks is a phenomenon that has been observed in many bridges and in many jurisdictions. All Photos: Dr. Oguzhan Bayrak.



The deck reinforcement details ultimately influence the widths and lengths of the cracks that form under combined effects of restrained concrete shrinkage, as well as the quantity of cracks formed. While the primary reinforcement details are rooted in flexural design considerations, flexural effects rarely control the failure of decks (ultimate conditions). That is to say, findings from numerous bridge deck testing projects have led to the conclusion that punching shear is the most common failure mode observed in bridge decks loaded to ultimate in laboratory conditions. The primary variables that influence the strength of the punching shear cone that forms around patch-loaded areas (that is, a 10 × 20 in. truck tire area on the deck) include the deck thickness (commonly 8 to 9 in.), the percentage of transverse and longitudinal reinforcement, and the compressive strength of concrete (as a surrogate indicator for the tensile strength of concrete). The typical failure loads observed in testing are between 5 and 7.5 times the design truck or tandem loads of the AASHTO LRFD specifications. This type of safety margin over the design loads is very high. In fact, if we were to increase the live loads acting on a bridge 5 to 7.5 times, we would run into strength issues in our girder designs as well as in many aspects of bridge substructure designs. Such great levels of reserve capacities are unusual. Because we do not expect to see these types of loads on our bridges, we do not typically design for safety margins of that magnitude.

As an aside, the design of the overhang portion of the decks is typically governed by the loads transferred to the decks by the bridge rails under a vehicle- or truck-impact loading scenario; these loads deserve their own separate design considerations. All aspects of the aforementioned design and structural-behavior items point to the fact that loading and the need to safely support the HL-93 loads constitute only one aspect of deck design. The service performance of the decks and additional considerations that influence the service performance are at least as important, if not more important, as the structural aspect of deck design. Simply stated, we need to consider deck design, durability, and performance in a holistic manner. This type of comprehensive evaluation is particularly important in identifying the root cause of the deck cracks that form during the service life of a bridge deck.


An example of longitudinal cracking in a concrete bridge deck.

The design of complex bridges and post-tensioned decks involves additional considerations. With that said, and broadly speaking, the compressive stresses applied by the post-tensioning systems to the deck concrete are beneficial as a means to extend the service lives of bridge decks. National Bridge Inventory data and additional surveys conducted by the American Segmental Bridge Institute serve as testaments to the superior deck performance observed in post-tensioned bridges.[2,3]

Concrete Mixture Proportions

The quality of the concrete greatly influences bridge deck performance and can help control deck cracking. The leading cause of deck cracking is the volume changes experienced by the deck when it is restrained by the primary load-carrying elements that support the deck. (For in-depth discussion of restrained shrinkage cracking, see my second article in this series, in the Fall 2024 issue of *ASPIRE*.) To reduce shrinkage strains, it is important when designing the concrete mixture proportions to reduce the paste content for a given volume of aggregates. Well-graded aggregates help us achieve this goal and create optimal concrete mixtures. A good gradation of the aggregates helps minimize the volume that must be filled with a cementitious paste, thereby reducing the shrinkage potential.

We must do whatever we can do to minimize all forms of shrinkage (autogenous, drying, and plastic). To that end, an effective strategy may be to reduce the water content and carefully use admixtures to improve workability. When applying this strategy, we must give due consideration to all effects of those admixtures to avoid unintended consequences and adverse effects.

The type of coarse aggregate greatly influences the modulus of elasticity of concrete. The strongest and stiffest aggregates may not be the most effective to reduce deck cracking. The use of more-compliant aggregates (that is, aggregates with a lower modulus of elasticity) such as crushed limestone has been found to effectively reduce deck cracking. Because stiff aggregates will concentrate the deformations in the cement paste that binds the aggregates, it stands to reason that the use of stiff aggregates will challenge the paste/matrix to a greater extent and may lead to conditions that are conducive to early deck cracking.

Concrete mixtures with low coefficients of thermal expansion typically perform better than those that have higher coefficients of thermal expansion. The quantification of thermal expansion properties of concretes made with locally available aggregates, primarily coarse aggregates, can be burdensome; however, in some cases, testing may be necessary to identify these properties when developing best practices. After the placement of fresh concrete, heat is generated during the hydration process. Sometimes, the hydrating cement in concrete heats up too much (perhaps due to the environment in which concrete is placed, the type of cement that is used in the concrete mixture, and insulation provided during its curing). In such cases, as the concrete cools down, the restraint provided by the primary load-carrying system may lead to thermal cracking of the decks. Thermal strains experienced by the deck during early stages of its life (construction) and over the long run will be minimized if concrete mixtures are designed to have lower coefficients of thermal expansion.

Formwork

In addition to its primary function of shaping the deck concrete to a desired geometry, formwork plays an important role in maintaining or dissipating the heat that builds up during the hydration process. The use of wooden forms is the traditional option available to contractors for forming concrete. In many jurisdictions, common alternatives to wooden forms include permanent metal deck forms (PMDFs) and stay-in-place, partial-depth precast, pretensioned concrete deck panels. Whereas wooden forms and PMDFs can be used to construct full-depth cast-in-place (CIP) concrete decks, the use of partial-depth, pretensioned concrete deck panels can reduce the volume of CIP concrete considerably. The reduction may be 40% to 60%, depending on the deck thickness (commonly 8 to 9 in.) and panel thickness (commonly 3.5 to 4.5 in.).

The use of partial-depth deck panels as it relates to deck cracking deserves additional discussion. These panels are fabricated to industry standards in precast concrete plants and shipped to construction sites. There are guidelines and specifications for their production, storage, and shipping. (See the FHWA article in the Winter 2024 issue of *ASPIRE* for discussion of current practices for partial-depth precast concrete deck panels.) When considering deck cracking and overall deck performance, the age of the pretensioned concrete deck panels is important. Based on the considerable experience of the states that use these deck panels, it is recommended to allow time for creep and shrinkage to take place within the pretensioned panels before the panels are shipped to the jobsite and CIP concrete is placed. After the volume changes experienced by the partial-depth deck panels have stabilized, they can be transported and properly installed on the beams. At this point, the panels provide a safe construction environment for the installation of the top mat reinforcement and eventually CIP concrete placement. In the past, there were cases in which "green" panels were shipped to jobsites immediately after prestress transfer at the fabrication plant (that is, within the first few days after panel fabrication) and installed on the bridge beams. The use of such "green" panels led to the formation of longitudinal cracks that follow the beam lines on a bridge deck. The lessons learned from such practices have led to specifications that indicate the minimum age that deck panels must reach before they are shipped.

To establish ideal bonding between the panels and the CIP concrete, it is important to wet the precast concrete panels to saturated surface-dry condition before concrete placement. Additionally, it is necessary to provide sufficient room for the CIP concrete to flow underneath the panel edges so that the panels are evenly and firmly supported on the top flanges of the beams.

The experiences of states that employ this technology indicate that when state-of-the-art production, shipping, storage, and installation guidelines are followed, the incidence and severity of deck cracking are comparable to what is observed in full-depth CIP concrete decks. In other words, the use of partial-depth pretensioned concrete deck panels does not worsen deck cracking or compromise long-term deck performance. Therefore, decision-makers can focus on other issues such as structural performance, worker safety, project timelines, and project costs, where the use of partial-depth deck panels can offer significant benefits.

Deck Concrete Placement

The sequence of deck concrete placement can be important for longer-span bridges and, in particular, for continuous spans. Based primarily on their past experiences and structural analysis of these statically indeterminate systems, owners often define the placement sequence for simple and continuous spans with the ultimate objective of minimizing, if not eliminating, the tensile stresses caused by the deck weight—in addition to consideration of stability of the incomplete structure, beam deflections, and stresses experienced by the beams during construction. To minimize transverse deck cracking, it is important to detail construction joints and expansion joints correctly and select appropriate locations for them. If the deck has a cross slope or a significant elevation change between the two ends of a span, the deck geometry must also be taken into account when sequencing concrete placement. Starting at low points and "climbing up" during concrete placement will usually improve results and minimize deck cracking.

To minimize deck cracking, maximize the service lives of decks, and reduce maintenance expenditures, it is important to develop good practices for placing concrete in hot or cold weather and to take into account environmental exposure conditions at the jobsite. For example, in Texas, when decks are placed during summer months, the work may occur at night to take advantage of cooler nighttime temperatures. The ambient air temperature, the temperature of the fresh concrete at placement, the type of deck-forming system (wooden forms, PMDFs, concrete partial-depth deck panels), and the use of blankets, burlap, plastic sheets, or other materials that affect concrete moisture will all contribute to whether the heat of hydration dissipates or is trapped; these variables all affect the maximum concrete temperatures reached during curing. In addition, in windy conditions, fresh concrete dries faster during placement and curing. If we think about the massive exposed area of concrete in relation to the volume of deck concrete, we can better appreciate how quickly loss of moisture can occur in windy conditions. Rapid drying of such expansive concrete surfaces is detrimental for both short- and long-term deck performance because it will lead to significant increases in deck cracking and improper or deficient hydration of cement. Precipitation during concrete placement and curing will also affect the deck concrete's quality and curing temperatures, thereby impacting the durability of the deck.

Curing of Decks

Methods to keep concrete moist or wet during its early ages include the use of moisture barriers (for example, plastic sheets) or moisture retainers (for example, burlap and plastic sheets), wetting of the curing concrete (for example, by spraying), and the application of curing compounds and liquid membranes. The attention paid to all relevant details during the curing process promotes a favorable hydration environment for the concrete and minimizes shrinkage of concrete. That effort will pay dividends in minimizing cracking in decks and improving the quality of deck concrete.

Deck Maintenance

Like all things, bridge decks require routine maintenance. Installation of proper deck drains, grading the deck to eliminate ponding of water, and keeping the drains clean and functional are all important for deck durability and the safety of the traveling public. Vehicles traveling over bridges with clogged drains and ponding water may hydroplane, posing a safety concern. In addition, accumulated water and the contaminants it may contain can accelerate the degradation of decks. With regard to deck cracks and corrosion, it may make sense to routinely wash bridge decks, as is done in some northern states.

Conclusion

A crack-free deck seems to be a difficult, if not impossible, goal to achieve. Therefore, it is prudent to deploy effective strategies to minimize the number of deck cracks and limit the widths of those cracks when (not if) they form, and the designer and owner should understand the implications of deck cracking for the structure's integrity and service life. Undoubtedly, the presence of deck cracks can facilitate the delivery of contaminants such as chlorides from deicing salts to the deck reinforcement and accelerate the corrosion of the deck reinforcement. In regions where contamination from deicing salts is likely, corrosion-resistant reinforcement (metallic or nonmetallic) can be used to mitigate corrosion concerns and extend the service lives of bridge decks. In coastal regions, a greater concern than the corrosion of deck reinforcement may be corrosion of reinforcement in substructure components, which is a topic beyond the scope of this article. The implications of deck cracks can be quite different in different jurisdictions, depending on the environmental exposure conditions as well as the selected type of deck reinforcement.

Deck cracking is a complex topic. Transverse cracking of the decks is a phenomenon that has been observed in many bridges and in many jurisdictions. This type of cracking has been observed in full-depth CIP concrete decks as well as decks with precast, pretensioned concrete deck panels. Good concrete mixture designs, appropriate construction practices during concrete placement and curing, and ongoing deck maintenance are fundamental aspects of bridge deck stewardship that will extend the service lives of bridges. The different experiences of various jurisdictions translate into regional variations in best practices for deck design, construction, and maintenance. The good news is that the lessons learned by all bridge professionals contribute to better-performing decks with better details and longer service lives.

References

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