A Crack Is Not a Crack: Restrained Shrinkage Cracking

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Shrinkage and shrinkage-related cracking are the focus of this article, the second in a series about cracking in reinforced and prestressed concrete structures. (See the Summer 2024 issue of *ASPIRE*® for the first article.) Broadly speaking, shrinkage can be defined as the volume changes that concrete experiences as a result of early-stage chemical reactions (autogenous shrinkage) or as concrete loses moisture over time (drying shrinkage). While drying shrinkage is the most significant shrinkage mechanism in the conventional concrete used in bridge construction, autogenous shrinkage has been observed to be a more significant contributor to overall concrete shrinkage in emerging materials such as ultra-high-performance concrete. Let us focus our attention on drying shrinkage, as this type of shrinkage is the most common form of shrinkage in bridge construction.

As concrete loses moisture, its volume decreases. Left unrestrained, the volume changes that concrete experiences would not result in any cracking. Internal restraint provided by reinforcement, if present, or external restraint provided by the remaining portions of the structure can result in cracking. To better understand these phenomena, let us focus on several examples.

Example 1—Wall Pier–to–Foundation Connection

Figure 1 depicts the connection region of a wall pier to the supporting foundation. When foundation concrete is placed, dowels are typically left to connect the reinforcing bars from the foundation to the wall pier. When the concrete for the wall pier is placed, the foundation concrete can be several weeks or several months old. The second-stage concrete (that is, the concrete placed in the wall pier) will not be "free" to change its dimension in the *x* direction.

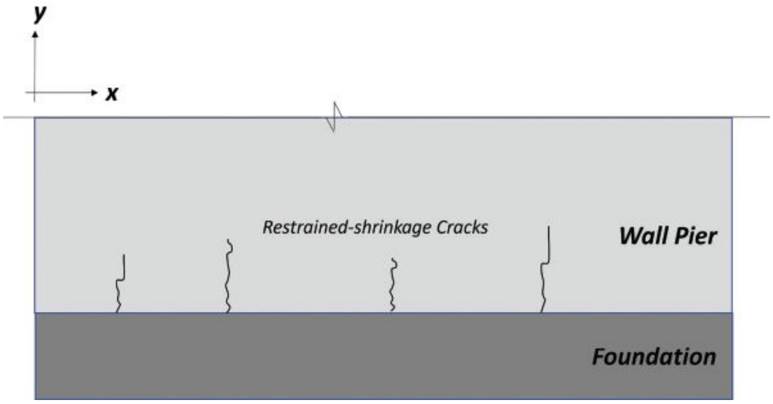

Figure 1. Possible cracking at a wall pier–to–foundation connection. All Figures: University of Texas at Austin.

To better understand the mechanics of the interaction between the wall pier and its foundation, let us use a force method of analysis, and accordingly, break the connection between the wall pier and its foundation and then apply a force to restore that boundary condition. Without that connection, the wall pier will be free to "slide" against the foundation and change its dimension in the *x* direction freely. To restore the boundary condition back to its original state, consistent with the actual support condition, we must apply a force in the *x* direction on the wall and stretch the wall while applying a colinear force on the foundation and compress the foundation. Compression acting on the foundation will be insignificant in relation to the typical compressive strength of concrete used in construction. Conversely, the tensile force required to restore the boundary condition must cause approximately 200 to 600 $\mu\varepsilon$ of tensile strain within the plane of the wall pier in the *x* direction. This level of strain, which is typical for conventional concrete mixtures, may be large enough to cause tensile cracks. If those cracks form, their orientation and overall appearance would resemble those of the vertical cracks in Fig. 1. Measuring the widths of the cracks and dividing them by the spacing of those cracks can help an engineer assess the average strains in the *x* direction. The value of those strains can be compared with the yield strain of the reinforcing bars crossing the restrained-shrinkage cracks in Fig. 1. For crack-control reinforcement to be effective, its strain must remain less than the yield point. Typical design specifications aim to limit that value to less than 60% to 75% of the yield strain by maintaining the stress in such reinforcement to less than 36 to 40 ksi.

Given that typical Grade 60 reinforcing steel would yield at 2000 to 2100 $\mu\varepsilon$, crack-control reinforcement would be quite effective to control the widths of the restrained-shrinkage cracks. In such a case, the structural implications of restrained-shrinkage cracks would be insignificant on their own. While their presence must be considered within the context of all structural load cases, such cracks are usually fairly benign. The durability of the structural wall should also be addressed, particularly if the wall pier is situated in an environmentally challenging location that involves exposure to seawater or the presence of chlorides that may challenge the durability of the reinforcement within the wall. In such cases, if the crack widths exceed approximately 0.006 to 0.008 in., some owners may require filling and/or sealing the cracks through epoxy injection. The natural question that follows this discussion is, What can be done to mitigate such crack formation? The use of well-graded, high-quality aggregates in fresh concrete in which the paste content is minimized typically helps reduce the shrinkage potential of concrete. Some owners and their contractors use shrinkage-reducing admixtures and overall reduction of water content as additional measures. These solutions should be viewed as means and methods to minimize such cracking rather than as ways to eliminate the formation of such cracks. The use of smaller-diameter bars that are better distributed along the exposed concrete surfaces is more effective for crack control than using larger-diameter bars that are spaced farther apart.

Example 2—Bridge Decks

Bridge deck cracking was the subject of several recent research studies and continues to be a point of interest in the bridge community. Regardless of the deck construction type (prestressed concrete stay-in-place, partial-depth deck panels or full-depth cast-in-place concrete decks) and superstructure type, deck cracking has been observed in many applications. While restrained shrinkage is not the sole source of deck cracking, it has been a significant contributor. In typical decks supported by prestressed concrete or steel girders, in-plane deck movements are restrained by the girders and the diaphragms (if present). Longitudinal restraint provided by beams supporting the deck leads to transverse deck cracking, and transverse restraint provided by the superstructure and its elements—such as intermediate and end diaphragms—can result in longitudinal cracks. While the level of longitudinal restraint is common for all superstructure types, the level of transverse restraint varies depending on the use of cross braces, diaphragms, and so forth. As a result, transverse deck cracks are more common than longitudinal cracks. In this context, we must also recall that the length of a bridge span is typically greater than its width, and cumulative shrinkage strains are therefore expected to be greater in the longitudinal direction (that is, the direction of traffic) than in the transverse direction.

The American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[1] recognizes the interaction between decks and superstructure beams and offers guidance on computing the gain in effective prestress in pretensioned girders due to deck shrinkage.

When combined with load effects and thermal effects, restrained deck shrinkage is likely to cause cracking in bridge decks. Such cracking can be minimized by tightly controlling the concrete mixtures used, the curing regimens to which the decks are subjected, and concrete placement temperatures (for example, placement of deck concrete at night in hot climates). While owners are aware of local environmental conditions during deck placements and take measures to minimize cracking to improve the service life of their bridge decks, complete elimination of deck cracking is usually not possible. Deck reinforcement quantities and details are tailored to mitigate the effects of deck cracks. Many states consider using special reinforcement, such as nonmetallic or stainless steel reinforcement, to mitigate the corrosion potential of reinforcement in challenging environmental exposure conditions. Some owners have also developed solutions that use fiber-reinforced concrete to allow for better distribution of cracks. General observations of the overall deck performance in segmentally constructed concrete bridges in which deck cracking is minimized to a higher degree by keeping deck concrete in compression transversely and longitudinally serve as a testament to the beneficial effects of prestressed concrete decks.

Example 3—Pretensioned Concrete I-Beams

Pretensioned concrete beams offer a significant cost advantage over some alternatives, and their superior field performance with respect to durability renders them a top-tier option for many typical bridge spans. In the context of restrained-shrinkage cracking, let us direct our attention to the beam fabrication process. While the cracking discussed within this context is uncommon, there have been cases in which such cracking was noted during beam fabrication. With that preamble, let us focus on 5- to 6-ft-deep pretensioned concrete girders (**Fig. 2**).

Typical production cycles for such beams last less than 24 hours, but in some cases, prestress transfer takes place on the third or fourth day to accommodate weekends or other production cycle–related constraints. If curing conditions, concrete mixture proportions, and prestress transfer time create a condition that allows sufficient concrete shrinkage to take place, steel forms restrain the movement of the top flange closer to the bottom flange (vertical direction in Fig. 2). In such cases, horizontal cracks that form between the web-to-top-flange or web-to-bottom-flange transition zones may be visible. Because the pretensioned girders are prestressed longitudinally and not in the vertical direction (Fig. 2), the widths of such cracks are controlled by the mild steel (shear) reinforcement that is commonly present in the vertical direction, and the presence of such

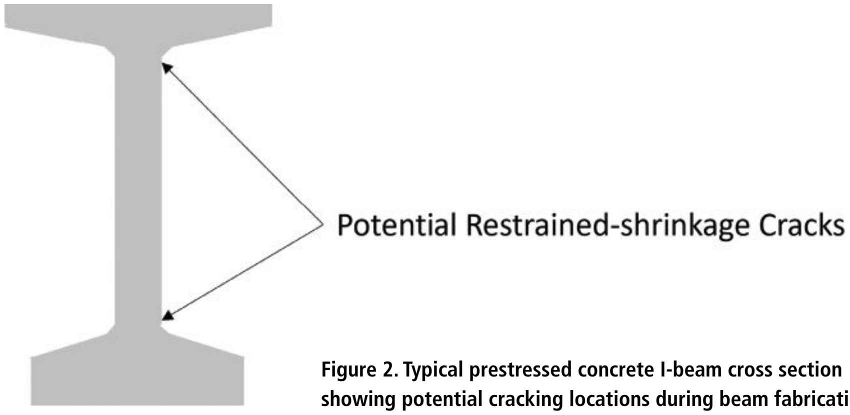

Figure 2. Typical prestressed concrete I-beam cross section showing potential cracking locations during beam fabrication.

hairline cracks does not adversely affect structural performance. Such cracks can also occur in regions where beams are fabricated in hot-weather conditions, and similar cracks are viewed as "thermal cracking." Thermal movements of the formwork material relative to thermal movements experienced by curing concrete further exacerbate this condition.

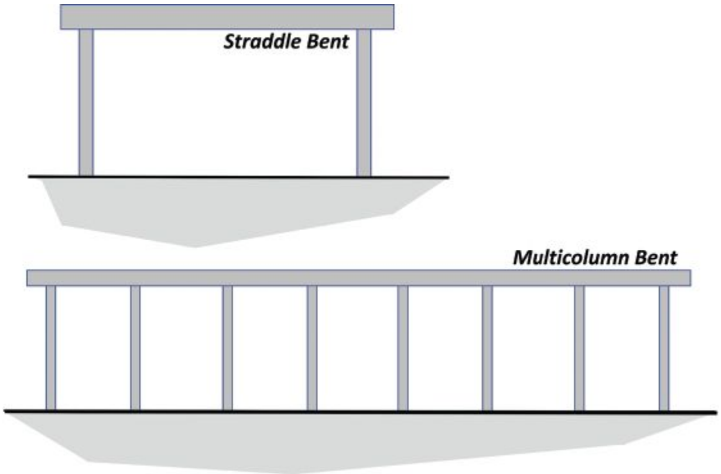

Figure 3. Examples of a straddle bent and a multicolumn bent.

Example 4—Axially Restrained Bent Caps

The straddle bent and multicolumn bent shown in Fig. 3 are constructed in a sequence similar to that discussed in Example 1. Once the foundations are in place, the columns are constructed; finally, the bent caps are placed and connections are made to the columns.

Let us focus on the straddle bent first. Assume the columns shown for the straddle bent in **Fig. 3** are 40 ft apart. If we assume that the shrinkage-related deformations along the length of the bent amount to a shrinkage strain of 500 $\mu\varepsilon$ in an unrestrained condition, that amount of strain over the length of the cap would result in a 0.25-in. deformation. That is, if the cap were not connected to one of the columns, that end of the cap would tend to move inward by 0.25 in. as it slip-slides against the column. To restore the boundary condition back to its original state, we must apply a tensile force on the cap as we apply a shear force at the tip of the column. To allow us to restore that boundary condition, the lateral tip deflection of the column and axial deformation of the cap should total 0.25 in. Doing so may introduce a substantial amount of force both on the columns and the cap, depending on the stiffness of the columns. Should the tensile stress introduced to the cap exceed the tensile strength of concrete, we would see restrained-shrinkage cracking in the cap. If the design intent is to keep the cap in its elastic, crack-free state, the design must account for this force. Naturally, this axial tension must be considered in calculating the shear strength of the cap as axial tension would reduce the concrete contribution to shear strength to some extent. Further, the column designs must accommodate the shear force that will be introduced at their connection point to the cap due to restraint-related action-reaction. If restrained-shrinkage cracking is allowed and crack-control reinforcement is provided to mitigate the adverse effects of such cracking, the force generated through restrained shrinkage at the cap-to-column connection will reduce to the point of being insignificant in most cases. Designers often employ this solution.

Going one step further, let us consider the multicolumn bent. Due to the increased length of the cap and additional restraint provided by columns, the tensile force accumulation in the cap can be significant enough to result in restrained-shrinkage cracking, and prevention of such cracking will prove to be quite challenging. Once these restrained-shrinkage cracks form, the relief provided by cracking would result in a substantial force reduction between the columns and the cap. Thus, from the standpoint of reduced forces due to cracking, this outcome is a positive one. Once again, these cracks are crossed by reinforcement and therefore their widths do not go uncontrolled. The presence of reinforcement crossing those cracks would serve to control the widths of those cracks.

What Does the AASHTO LRFD Specifications Say?

Article 5.4.2.3 of the AASHTO LRFD specifications clearly acknowledges the fact that creep and shrinkage are highly variable. The commentary to Article 5.4.2.3.1 states the following:

> ***Creep and shrinkage of concrete are variable properties that depend on a number of factors, some of which may not be known at the time of design.***
>
> ***Without specific physical tests or prior experience with the materials, the use of the empirical methods referenced in these specifications cannot be expected to yield results with errors less than ±50 percent.***

Within the context given in that commentary, Article 5.4.2.3.3 of the AASHTO LRFD specifications presents a method that can be used to estimate shrinkage strains. The method is used in commercially available software packages as well as software developed by bridge owners for use in their respective states.

Finally, and importantly, Article 5.10.6 of the AASHTO LRFD specifications discusses shrinkage and temperature reinforcement to help designers detail reinforcement to control the widths of the cracks that result from restrained shrinkage and temperature effects.

Conclusion

Elimination of restrained-shrinkage cracking in all bridge parts and components is not practical. Common practices to manage such cracking include using a concrete mixture that is purposefully calibrated to minimize cracks, and providing crack-control reinforcement to mitigate the adverse effects of restrained-shrinkage cracking.

The examples presented in this article are not intended to be an exhaustive list of possible cases encountered in bridge construction. They were selected as sufficiently diverse cases to facilitate the discussion of restrained-shrinkage cracking in bridge applications.

Reference

1. American Association of State Highway and Transportation Officials (AASHTO). 2020. *AASHTO LRFD Bridge Design Specifications*. 9th ed. Washington, DC: AASHTO.

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