A Crack Is Not a Crack: Torsional Cracking

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This article, which is the sixth article in this series on cracking, focuses on torsional effects and how additive stresses imposed by torsional effects can influence structural behavior. Torsional effects are typically observed in combination with the effects of other loads, and the interpretation of the observed cracking in bridges can sometimes be a challenging task. By providing a sufficiently in-depth discussion on combined load effects in the presence of torsional effects, this article aims to help engineers perform structural evaluation on bridges that show signs of torsional distress. To the extent necessary, we will consult the structural design provisions for combined effects of bending, shear, torsion, and axial loads published in the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*.[1] In doing so, we will revisit my LRFD article published in the Spring 2025 issue of *ASPIRE*®.

Combined Loading Effects and Cracking

To facilitate our discussion on torsion, I will use a series of loading scenarios rooted in field issues I have encountered over the past 25 years. To that end, let us focus our attention on the straddle bent shown in **Fig. 1**. As can be observed in this figure, the north ledge supports more load than the south ledge. This loading configuration results in the cap beam being subjected to torsion, in addition to other loading effects (shear and bending).

Next, let us consider five loading scenarios that could go along with this unbalanced load configuration. **Figure 2** illustrates cracking based on the first loading scenario (scenario A), in which we do not see any diagonal cracking on the south face but we do see a diagonal crack on the north face of the cap beam. This type of cracking may result from the additive nature of shear stresses on the north face of the cap, which is illustrated in **Fig. 3**. Conversely, the shear stresses created by the torsional effects and shear effects oppose each other on the south face. In this specific case, it is possible to conclude that the net diagonal tensile stress resulting from the superposition of loading effects is not large enough to result in cracking on the south face.

This condition may be one where the torsional effects are not considered significant. According to Article 5.7.2.1-3 and associated commentary of the AASHTO LRFD specifications, if the factored torsional moment is less than 25% of the factored pure torsional cracking moment, torsional effects can be deemed negligible. More specifically, AASHTO LRFD specifications include the following requirements:

Torsional effects shall be investigated where:

$$T_u > 0.25\phi T_{cr} \qquad (5.7.2.1\text{-}3)$$

- *For solid shapes:*

$$T_{cr} = 0.126K\lambda\sqrt{f'_c}\frac{A_{cp}^2}{p_c} \qquad (5.7.2.1\text{-}4)$$

- *For hollow shapes:*

$$T_{cr} = 0.126K\lambda\sqrt{f'_c}\,2A_o b_e \qquad (5.7.2.1\text{-}5)$$

in which:

$$K = \sqrt{1+\frac{f_{pc}}{0.126\lambda\sqrt{f'_c}}} \le 2.0 \qquad (5.7.2.1\text{-}6)$$

Figure 1. Straddle bent configuration used for the five loading scenarios presented in subsequent figures. Figure: Dr. Oguzhan Bayrak.

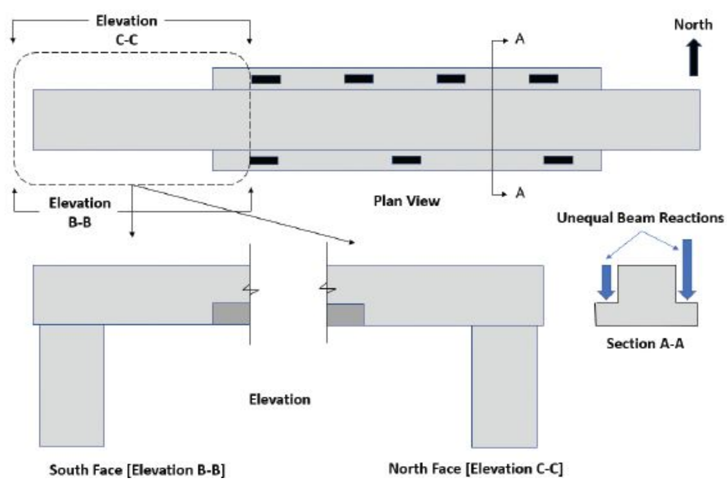
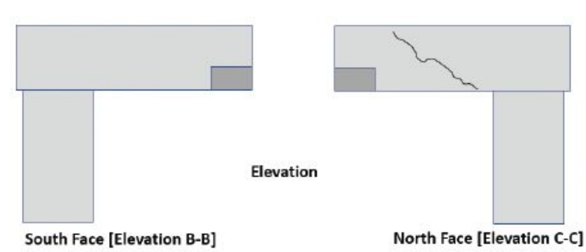


Figure 2. Cracking resulting from loading scenario A. Figure: Dr. Oguzhan Bayrak.



where:

T_u = *applied factored torsional moment (kip-in.)*

ϕ = *resistance factor [for torsion], specified in Article 5.5.4.2*

T_{cr} = *torsional cracking moment (kip-in.)*

λ = *concrete density modification factor, as specified in Article 5.4.2.8*

f'_c = *compressive strength of concrete for use in design (ksi)*

A_{cp} = *area enclosed by outside perimeter of concrete cross-section (in.^{2})*

p_c = *length of outside perimeter of the concrete section (in.)*

A_o = *area enclosed by the shear flow path, including any area of holes therein (in.^{2})*

b_e = *effective width of the shear flow path taken as the minimum thickness of the exterior webs or flanges comprising the closed box section (in.).* b_e *shall be adjusted to account for the presence of ducts.*

f_{pc} = *unfactored compressive stress in concrete after prestress losses have occurred either at the centroid of the cross-section resisting transient loads or at the junction of the web and flange where the centroid lies in the flange (ksi)*

The value of b_e*, defined above, shall not exceed* A_{cp}/p_c *unless a more refined analysis is utilized to determine a larger value.*

The effects of any openings or ducts in members shall be considered. K *shall not be taken greater than 1.0 for any section where the stress in the extreme tension fiber, calculated on the basis of gross section properties, due to factored load and effective prestress force exceed* $0.19\lambda\sqrt{f'_c}$ *in tension.*

When calculating K *for a section subject to factored axial force,* N_u*,* f_{pc} *shall be replaced with* $f_{pc} - N_u/A_g$. N_u *shall be taken as a positive value when the axial force is tensile and as a negative value when it is compressive.*

However, Article 5.7.2.1-3 references a design scenario, as opposed to a structural evaluation scenario, which is what is being discussed here. For structural evaluation, torsional effects shall be investigated. As shown in Fig. 3, seemingly negligible torsional effects may be sufficient to result in diagonal cracking on one face of the cap due to the additive nature of torsional and shear stresses on that face.

Figure 3. Stresses from shear and torsion are additive. On the north face of the cap the stresses are in the same direction, increasing the overall magnitude. On the south face, the shear stresses created by the torsional effects and shear effects oppose each other, thereby reducing the total magnitude. Figure: Dr. Oguzhan Bayrak.

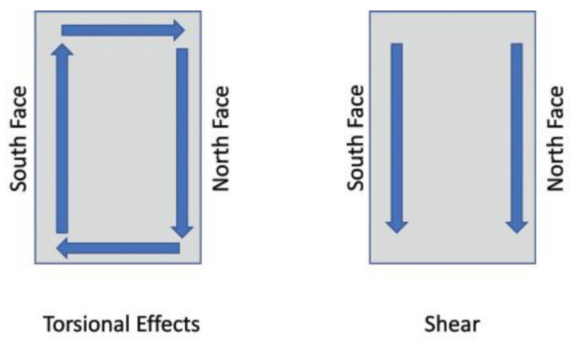


Figure 4 shows the cracking that results from our second loading scenario (scenario B). In Fig. 4, there is diagonal cracking on both faces of the cap. More specifically, on the north face of the cap, we see a diagonal crack in the typical shear cracking orientation. On the south face of the cap, we also see a diagonal crack; however, the inclination of this crack is in the reverse direction (that is, in the opposite direction to typical shear cracks). This type of cracking implies that torsional effects are significant, and their effects on the cap overshadow the effects from shear stresses. That is to say, in reference to Fig. 3, the torsional effects are large enough to overcome the shear effects on the south face and increase the diagonal tension to a stress level sufficient to cause cracking in the "reverse shear" direction on that face. Therefore, the cracks seen on north and south faces may complete a helical pattern of cracking that wraps around the entire cap. Such cracks would approximately follow the helical diagonal strut formation pattern (**Fig. 5**).

Figure 5 is constructed for a pure torsion case, and as such, the cracking angles in our example would differ due to combined loading present on the cap. With that stated, the stress flow shown in Fig. 5 helps us gain a complete understanding of how diagonal cracks that helically wrap around the element can occur. The strut-and-tie modeling (STM) approach offers a powerful tool in visualizing the stress fields and flow of forces through structural members from their point of application to the foundations. The torsional model shown in Fig. 5 is a good example for this truss analogy. However, to examine even earlier examples of the STM construct, we must go back to the pioneering work conducted by Ritter and Mörsch in the late 19th and early 20th centuries.[2,3]

Figure 4. Cracking resulting from loading scenario B. Figure: Dr. Oguzhan Bayrak.

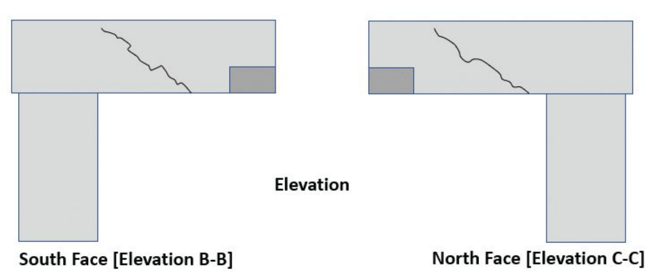
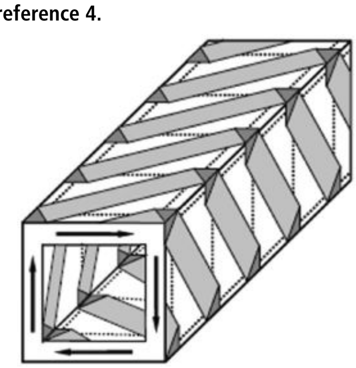


Figure 5. Formation of diagonal struts under torsional loads. Figure: Adapted from reference 4.



I would be remiss if I did not mention that the seemingly similar-looking cracking patterns shown in **Fig. 6** signal yet a different loading scenario (scenario C). The diagonal cracking seen in Fig. 6, which is the same on both faces, is attributable to the splitting of the diagonal strut that forms between the inside corner of a knee joint and the outside corner that redirects the tension field on the top side of a cap to the back face of a column. While such cracking can also be important in column-to-cap connections designed to accommodate bending-moment transfer, such diagonal cracks are not to be confused with the other diagonal cracking patterns discussed in this article. After all, not all diagonal cracks are created equal—a crack is not a crack.

The Additive Effects of Torsion on Cracking

Let us now focus our attention on a new cracking pattern resulting from a new loading scenario (scenario D) (**Fig. 7**). In this case, we see the formation of diagonal cracks on the north face, and these cracks have consistent direction with shear cracking. We also see the "reverse shear cracking" direction on the south face. At first glance, this cracking appears consistent with the second loading case we discussed previously. It is true that due to the reverse direction of diagonal cracks, significant torsional effects are at play. We also see that the cracks appear steeper (that is, the inclination from the horizontal axis is greater than 45 degrees), which may be a telltale sign of axial tension that has developed in the cap beam due to restraint provided by the two columns in the straddle cap. In the situation where the cap beam experiences drying shrinkage, the restraint provided by the columns may result in significant tensile forces in the cap. In this combined loading and structural restraint scenario, we expect the inclinations of the cracks to be steeper than those shown in Fig. 4, as shown in Fig. 7. Overall, the axial tension will impose additional demand on the longitudinal reinforcement, increase the widths of the diagonal cracks, and serve to reduce the ability of the cracked concrete to transmit shear stresses across the diagonal cracks.

Figure 6. Cracking in cap-to-column connection due to strut splitting (loading scenario C). Figure: Dr. Oguzhan Bayrak.

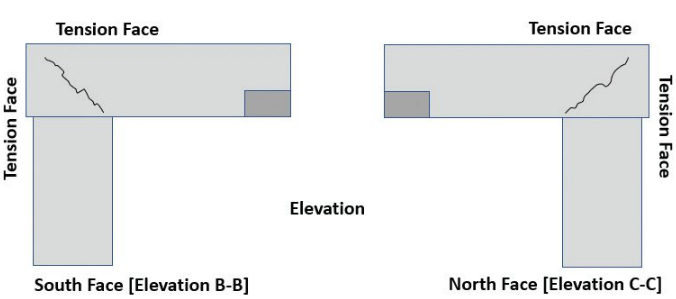
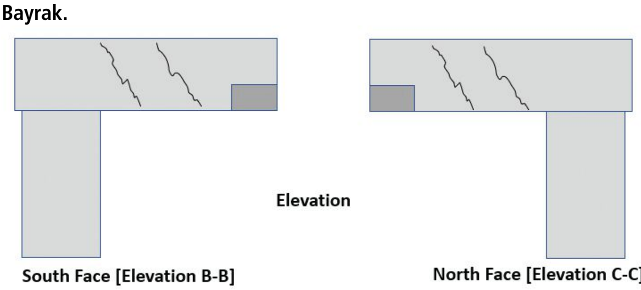


Figure 7. Cracking resulting from loading scenario D. Figure: Dr. Oguzhan Bayrak.



As I discussed in my LRFD article in the Spring 2025 issue of *ASPIRE*, torsion increases the demand on shear reinforcement. Torsion also increases the demand on longitudinal reinforcement. For a quick overview, let us direct our attention to Eq. 5.7.3.6.3-1 of the AASHTO LRFD specifications, which addresses the longitudinal reinforcement required in solid sections:

$$A_{ps}f_{ps} + A_s f_y \geq \left| \frac{|M_u|}{\phi d_v} + \frac{0.5N_u}{\phi} + \cos\theta \sqrt{\left(\left|\frac{V_u}{\phi} - V_p\right| - 0.5V_s\right)^2 + \left(\frac{0.45 p_h T_u}{2A_o \phi}\right)^2} \right|$$

This equation shows that bending moment, axial force, shear force, and torsion all impose additive demands on the longitudinal reinforcement. If we greatly increased the axial tensile force until it overshadows all other effects, the observed cracking would be nearly vertical. The cracking shown in Fig. 7 reflects a case in which all contributing factors (load effects as well as the structural restraint) are contributing to the observed cracking in a more "balanced" manner. That is to say, restrained shrinkage effects and the tensile stresses that result from those effects influence the orientation of the torsional cracks. The formation of multiple cracks in Fig. 7 indicates that the cap is being challenged to a great extent with respect to its structural capacity.

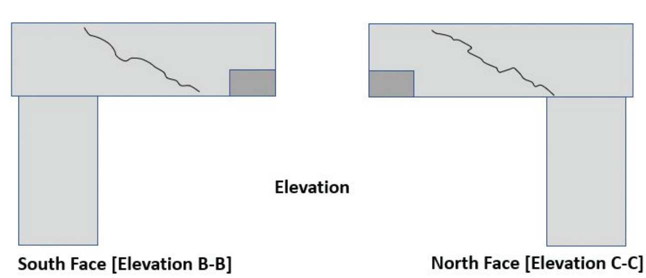
Figure 8 illustrates the cracking pattern that results from our fifth and final loading scenario (scenario E). This cracking pattern somewhat resembles those shown in Fig. 4 and 7. The one notable difference we see in this case relates to the "flatter" inclination of the diagonal cracks. That is to say, the orientation of the cracks with respect to the horizontal seems to be less than 45 degrees. This flatter cracking is in contrast to that shown in Fig. 7, where axial tension was present due to restraint effects. The flatter diagonal crack patterns in the cap beam seen in Fig. 8 suggest that axial compression is a factor. For example, the presence of post-tensioning force, in addition to shear, bending moment, and torsion, can lead to the flatter, diagonal cracking inclinations shown in Fig. 8.

Concluding Remarks

Considering the crack patterns and probable loading scenarios presented in this article, it is appropriate to review a few points we can take away from this discussion:

- Combined loading conditions may create complex stress states that require us to give consideration to boundary conditions that may or may not generate forces in the structural elements that are being investigated. The straddle bent considered in this article includes structural connections between the column and

Figure 8. Cracking resulting from loading scenario E. Figure: Dr. Oguzhan Bayrak.



cap. In the 25 years I have spent researching and investigating concrete bridges, I have also encountered cases in which inverted tee beams are supported on bearing pads placed on columns. Such support conditions will allow rotations at support points, and the stresses, cracks, and deformations will be quite different than the examples in this article. In short, the support/boundary conditions matter. They influence the forces that may develop in structural components. Finally, and importantly, in such circumstances, the rotations need to be considered in the bearing design process.

- The interaction among various loads and the resulting principal tensile stress influences the cracking of a reinforced or prestressed concrete component. That is to say, consideration of torsional effects in isolation can be misleading unless those effects dominate the overall structural response. Holistic consideration of all loads and their effects is necessary to reach correct conclusions.
- Diagonal cracking observed in a bent cap may not be indicative of reduced capacity of that structural component. The examples considered in this article focus on cracking that may occur in service conditions. The AASHTO LRFD specifications for strength limit state are based on the ability of cracked concrete to transmit shear stresses. In older bridge designs that were based on approaches developed in the 1940s, 1950s, and 1960s, the formation of initial diagonal cracking was interpreted as a clear indication of the "strength" or "structural capacity" of a member. This interpretation led to conservative design approaches that worked well within the bridge design and construction community. Over the years, particularly since the adoption of the modified compression field theory, more-refined designs and interpretations of structural behavior have become possible. With that serving as a backdrop, we should be careful about setting aside initial formation of diagonal cracks from the exploitation of the full structural capacity by the loads.

In summary, a holistic view of structural behavior will give due consideration to loading effects, boundary conditions, and, most importantly, the first principles of structural engineering. The examples we considered in this article are not intended to be comprehensive or exhaustive. They were selected to facilitate the discussion that is rooted in the first principles that include safety, stability, and serviceability.

References

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