Crack-Control Reinforcement: Strength and Serviceability Implications

by Dr. Oguzhan Bayrak, University of Texas at Austin

This article discusses the role of crack-control reinforcement, modeling of that reinforcement, both implicitly and explicitly, and background information on the crack-control reinforcement requirements of the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*.[1]

Behavioral Difference between B-Regions and D-Regions

The behavioral difference between B-regions (beam or Bernoulli regions) and D-regions (disturbed or discontinuity regions) as defined in the AASHTO LRFD specifications can be understood by looking at the behavior of a typical beam.[2] The shear span *a* of a beam is the distance between the applied load and the reaction; the depth *d* is the effective depth of the member, or the distance from the extreme compression fiber to the centroid of the tension steel. Article 5.8.2.1 of the AASHTO LRFD specifications recommends that strut-and-tie modeling (STM) should be considered for members with $a/d < 2$ (that is, a low shear span-to-depth ratio). **Figure 1** shows results of a beam test that was conducted to compare the behavior observed in a short shear span ($a/d = 1.2$ on the left-hand side of the beam) and a long shear span ($a/d = 2.5$) on the right-hand side of the beam). At low loads ($P = 300$ kip), the strains measured in the lowermost layer of flexural tension reinforcement follow a strain pattern that closely mimics the moment diagram for this beam under a single concentrated applied load *P*. The strain profiles along the beam shown in Fig. 1 indicate that, with increasing loads and after substantial cracking of the beam (which occurred at a load of about 1000 kip), the behavior in the short shear span is quite different from that of the longer shear span. When the applied load exceeds 1500 kip, the strain in the flexural tension reinforcement is nearly uniform for the span with $a/d = 1.2$. This strain profile signals the formation of a direct strut associated with a truss-like behavior that has a constant tie force along the shear span. In direct contrast to the observed behavior in the short shear span, the right-hand side of the beam ($a/d = 2.5$) more closely follows Bernoulli-type behavior, in which plane sections remain plane and the strain response can be reasonably predicted using the moment diagram for this beam. Birrcher et al.[2] concluded that at ultimate load for long shear spans considered in their study (with $a/d = 2.5$), nearly two-thirds of the applied load was transferred into the support by internal shears and moments (Bernoulli beam response) and a third of the load was transferred directly into the support by a strut. In recognition of this behavior, the AASHTO LRFD specifications recommend differentiating B-regions from D-regions and using strut-and-tie modeling (STM) provisions to design the D-regions.

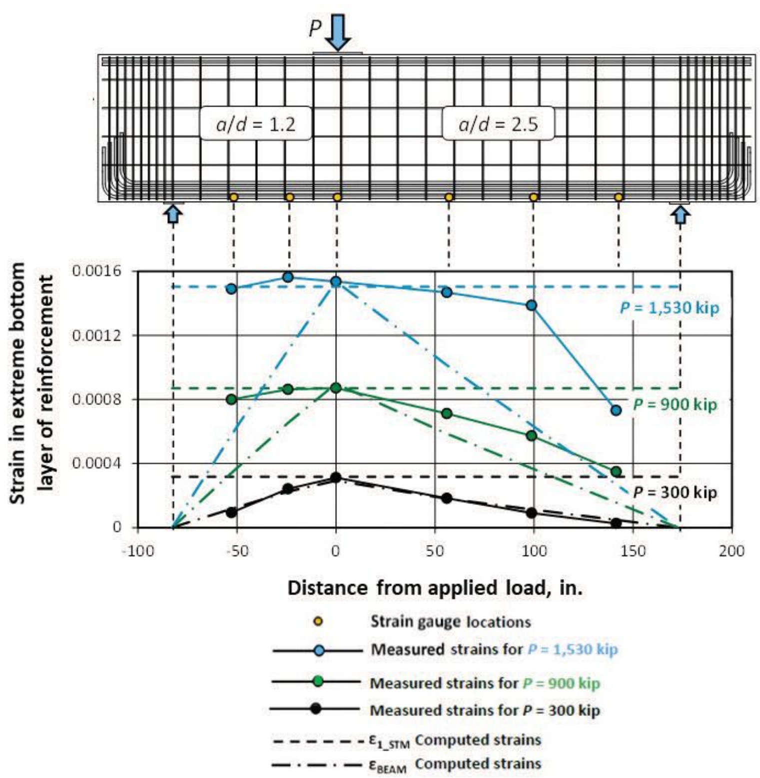

Figure 1. Test results for a specimen with short and long shear span–to–depth (*a*/*d*) ratios demonstrate the performance differences between B- and D-regions. Note: Strain gauge locations are shown in top figure. Solid lines with dots indicate measured strain response. *a* = the distance between the applied load and the reaction; *d* = the effective depth of the member; *P* = applied load; ε_{1_STM} = calculated strain using strut-and-tie model; ε_{BEAM} = calculated strain using beam model. Figure: Dr. Oguzhan Bayrak, adapted from Fig. 5.42 in Birrcher et al.[2]

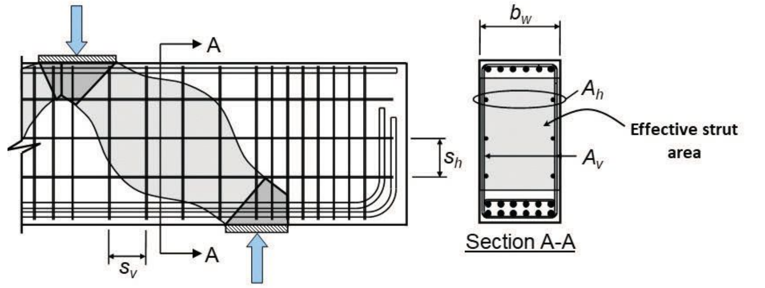

Figure 2. Compression spread and distribution of crack-control reinforcement in a diagonal strut. Note: A_h = total area of horizontal crack-control reinforcement within spacing s_h; A_v = total area of vertical crack-control reinforcement within spacing s_v; b_w = web width; s_h = spacing of horizontal crack-control reinforcement; sv = spacing of vertical crack control reinforcement. Figure: Dr. Oguzhan Bayrak, adapted from Fig. 3.8 in Birrcher et al.[2]

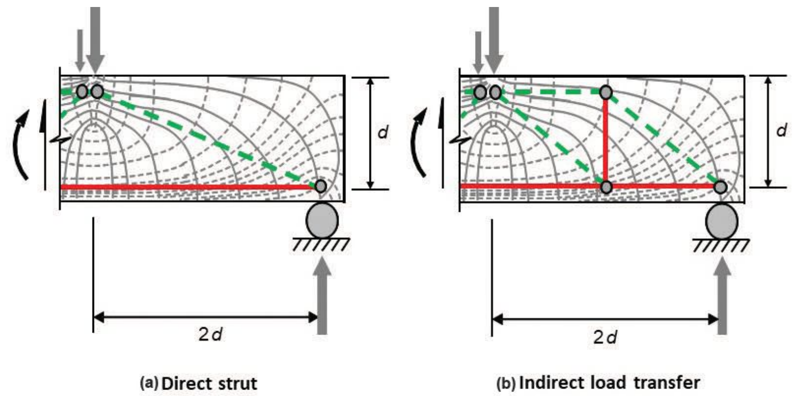

Figure 3. Comparison of models showing transfer of applied load to support by (a) direct strut and (b) indirect load transfer with a vertical tie. Figure: Dr. Oguzhan Bayrak, adapted from Fig. 2.5 in Birrcher et al.[2]

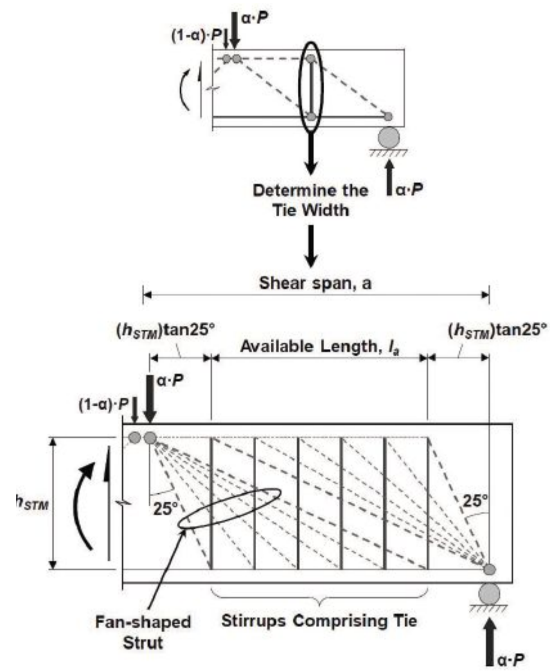

Figure 4. Example indicating available length in the shear span in which stirrups contribute to capacity of vertical tie. Figure: Adapted from Fig. C5.8.2.2-2 of the AASHTO LRFD specifications.[1]

Crack-Control Reinforcement

Although crack control reinforcement requirements vary for B-regions and D-regions, all elements (regardless of the region) designed using the STM design provisions must contain the appropriate amount of crack-control reinforcement specified in Article 5.8.2.6 of the AASHTO LRFD specifications, which requires the use of a minimum quantity of crack-control reinforcement. More specifically, Article 5.8.2.6 requires 0.3% reinforcement, defined as 0.003 times the effective area of the strut, which is provided in two orthogonal directions (horizontal and vertical in **Fig. 2**) as crack-control reinforcement. This reinforcement has two purposes related to strength and serviceability. Regarding strength, a grid of reinforcement is necessary to handle the transverse tension that results from the spread of compression in the diagonal strut (Fig. 2). Although the actual quantity of reinforcement needed to satisfy equilibrium of forces upon cracking of concrete is a function of material and geometric properties of the member, 0.3% reinforcement is typically sufficient to cover all cases encountered in bridge elements designed using STM. Regarding serviceability, Birrcher and colleagues[2] proved that use of reinforcement quantities that are less than 0.3% do not provide sufficient crack control. For example, in cases where 0.2% reinforcement was used as crack-control reinforcement, the width of the diagonal cracks exceeded 0.016 in. when they first formed and crack width increased with additional loading.

To model the spread of compression in a diagonal strut (Fig. 2), let us consider the direct and indirect load transfer mechanisms shown in **Fig. 3**. This figure shows that the direct load transfer mechanism (that is, a direct strut that forms between the load point and the near support) does not explicitly require the use of stirrups (Fig. 3a). However, the use of 0.3% reinforcement in each direction (not shown in the figure), in accordance with Article 5.8.2.6, accomplishes the goal of providing stirrups that act as shear reinforcement. Alternatively, if a two-panel truss is used (Fig. 3b), the vertical tie reinforcement can be explicitly evaluated and provided in the member. When using this approach, the available length, l_a, as defined in the right part of **Fig. 4**, should be used to identify those stirrups that will contribute to the capacity of the vertical tie. In other words, the tension resulting from the spread of compression in a strut can be explicitly modeled by using a vertical tie between the load and the support (Fig. 3b). Therefore, if a designer chooses to use the indirect load transfer model shown in Fig. 3b, the vertical reinforcement (stirrups) will partially or fully satisfy the crack-control requirements of Article 5.8.2.6 in the vertical direction. In contrast, the primary flexural reinforcement (top or bottom) shown outside of the effective strut area in Fig. 2 cannot be used to satisfy the crack-control reinforcement requirement in the horizontal direction because it does not contribute to controlling the width of cracks that may form due to the spread of compression in a strut.

References

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

2. Birrcher, D., R. Tuchscherer, M. Huizinga, O. Bayrak, S. Wood, and J. Jirsa. 2009. "Strength and Serviceability Design of Reinforced Concrete Deep Beams." Technical Report 0-5253-1. Austin: Center for Transportation Research, University of Texas at Austin.