

# Longitudinal Reinforcement: Understanding the Demands Imposed on It and Its Capacity as Presented in the *AASHTO LRFD Bridge Design Specifications*

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Over the decades, bridge design specifications have evolved to reflect findings from research and development efforts. The first edition of the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*, published in 1994,<sup>1</sup> based shear design on modified compression field theory (MCFT) which was a significant change in bridge design and load rating practices. Since then, the AASHTO LRFD specifications have been updated several times, and the 11th edition<sup>2</sup> will be published soon.

This article reviews the load effects as well as the resistance provided by the longitudinal reinforcement as presented in the AASHTO LRFD specifications. Article 5.7.3 is devoted to sectional design. To set the stage for our discussion, let us consider Commentary C5.7.3.3, in which the traditional shear design is explained:

*The traditional approach to proportioning transverse reinforcement involves the determination of the required stirrup spacing at discrete sections along the member. The stirrups are then detailed such that this spacing is not exceeded over a length of the beam extending from the design section to the next design section out into the span. In such an approach, the shear demand and resistance provided is as shown in Figure C5.7.3.3-1.*

*In situations where a significant amount of the load is applied below the mid-depth of the member, such as inverted T-beam pier caps, and the section model is used to design for shear, it is more appropriate to use the traditional approach to the design of transverse reinforcement shown in Figure C5.7.3.3-1.*

*For typical cases where the applied load acts at or above the mid-depth of the member, it is practical to take the traditional approach as shown in Figure C5.7.3.3-1 or a more liberal yet conservative approach as shown in Figure C5.7.3.3-2 which has the effect of extending the required stirrup spacing for a distance of  $0.5d_v \cot \theta$  toward the bearing.*

where

- $d_v$  = effective shear depth, as determined in Article 5.7.2.8 (in.)
- $\theta$  = angle of inclination of diagonal compressive stresses, as determined in Article 5.7.3.4 (degrees)

Figures C5.7.3.3-1 and C5.7.3.3-2 are reproduced herein as **Fig. 1** and **2**, respectively. They clearly demonstrate that by adjusting the detailing (for example, the number of stirrup legs) and the spacing of the stirrups, we can provide shear resistance that is consistent with the shear demand. The number of sections where we change the stirrup detailing can also be controlled by the changes in flexural element geometry. A designer or load rater must identify critical sections along the length of the component when evaluating spliced girder and segmental bridges. Points where the beam depth, web width, or flange thickness vary along the span are common for this type of construction.

Article 5.7.3.5 addresses the demands imposed on the longitudinal reinforcement by a variety of different load effects. Equation (5.7.3.5-1) shows the capacity of flexural tension reinforcement as well as the demands imposed on that reinforcement as follows:

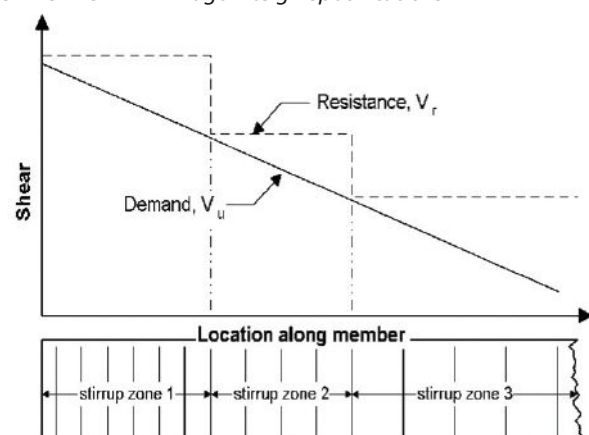
$$A_{ps}f_{ps} + A_s f_y \geq \frac{|M_u|}{d_v \phi_f} + 0.5 \frac{N_u}{\phi_c} + \left( \left| \frac{V_u}{\phi_v} - V_p \right| - 0.5V_s \right) \cot \theta$$

AASHTO LRFD Eq. (5.7.3.5-1)

where

- $\phi_f, \phi_v, \phi_c$  = factors taken from Article 5.5.4.2 as appropriate for moment, shear, and axial resistance
- $V_s$  = shear resistance (kip) provided by transverse reinforcement at the section under investigation as given by AASHTO LRFD Eq. (5.7.3.3-4), except  $V_s$  shall not be taken as greater than  $V_u/\phi_v$  in Eq. (5.7.3.5-1) and (5.7.3.5-2)

Figure 1. Traditional shear design. Source: Figure C5.7.3.3 -1 from the *AASHTO LRFD Bridge Design Specifications*.<sup>2</sup>



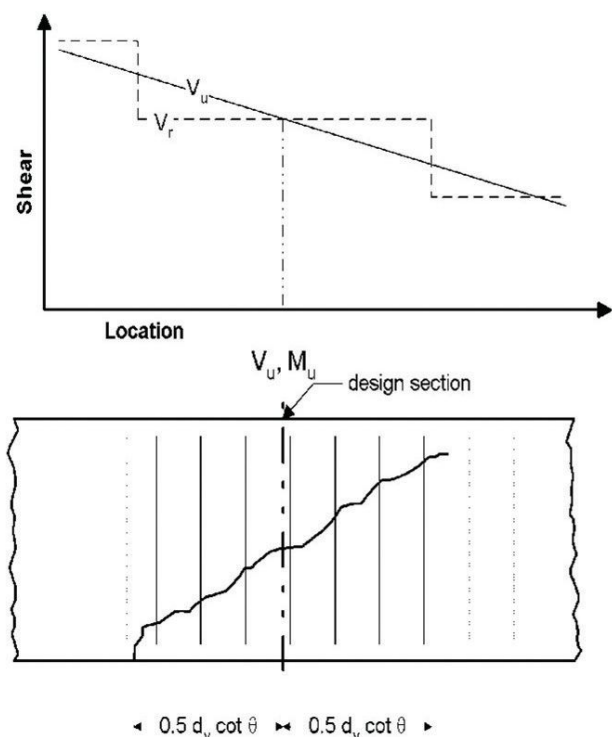


Figure 2. Simplified design section for loads applied at or above the middepth of the member. Source: Figure C5.7.3.3-2 from the AASHTO LRFD Bridge Design Specifications.<sup>2</sup>

It is important for the designer (or a load rater) to recognize that the left-hand side (that is, the capacity side) of the expression may be governed by the available development length of the reinforcing bars and prestressing strands. Additionally, the presence or absence of debonded strands will also influence the capacity. To better understand the demands imposed on the longitudinal reinforcement (the right-hand side) of Eq. (5.7.3.5-1), let us consider the commentary for Article 5.7.3.5:

*Shear causes tension in the longitudinal reinforcement. For a given shear, this tension becomes larger as  $\theta$  becomes smaller and as  $V_c$  becomes larger. The tension in the longitudinal reinforcement caused by the shear force can be visualized from a free-body diagram such as that shown in Figure C5.7.3.5-1. Taking moments about the compression force  $C$  in Figure C5.7.3.5-1, assuming that the aggregate interlock force on the crack, which contributes to  $V_c$ , has a negligible moment about the compression force  $C$ , and neglecting the small difference in location of  $V_u$  and  $V_p$  leads to the requirement for the tension force in the longitudinal reinforcement caused by shear.*

Figure C5.7.3.5-1 is reproduced herein as **Fig. 3**. As explained in the commentary, moment, shear, and axial load will all influence the force in the tension tie. In cases in which torsional forces act on the element, those forces will also introduce additional demands and should be accounted for by using the provisions included in Article 5.7.3.6.3. Importantly, Article 5.7.3.5 states that “at each section the tensile capacity of the longitudinal reinforcement on the flexural tension side of the member shall be proportioned to satisfy” Eq. (5.7.3.5-1). The mandatory nature of the specification language is

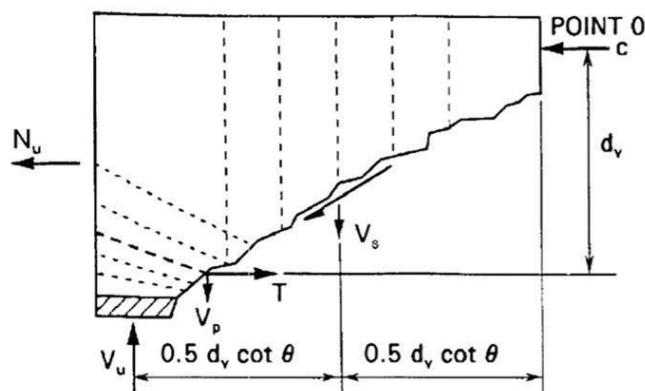


Figure 3. Forces assumed in resistance model caused by moment and shear. Source: Figure C5.7.3.5-1 from the AASHTO LRFD Bridge Design Specifications.<sup>2</sup>

significant. It is also important that Eq. (5.7.3.5-1) is *not* limited to the ends of simply supported beams. However, it is true that beam ends become particularly important. To that end, Article 5.7.3.5 states the following:

*At the inside edge of the bearing area of simple end supports to the section of critical shear, the longitudinal reinforcement on the flexural tension side of the member shall satisfy:*

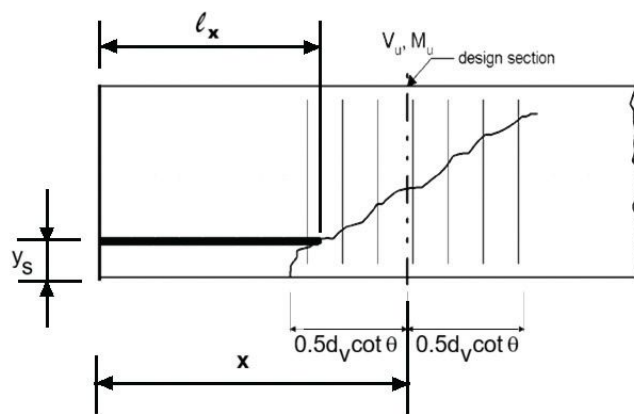
$$A_s f_y + A_{ps} f_{ps} \geq \left( \frac{V_u}{\phi_v} - 0.5 V_s - V_p \right) \cot \theta$$

[AASHTO LRFD Eq. (5.7.3.5-2)]

Equation (5.7.3.5-2) is a simplified version of Equation (5.7.3.5-1) where the bending moment and axial loads are equal to zero at the simply supported ends of a beam. In other words, Eq. (5.7.3.5-1) is a more general expression that covers all locations, including the beam ends with due recognition given to boundary conditions.

There are many design examples that illustrate the calculation of strength of and demands on the longitudinal steel at the face of support, but few examples demonstrate how to evaluate the strength of and demands on the longitudinal steel at an arbitrary section. **Figure 4** is a

Figure 4. Embedment of longitudinal steel for a design section located at a distance  $x$  from the end of a beam.



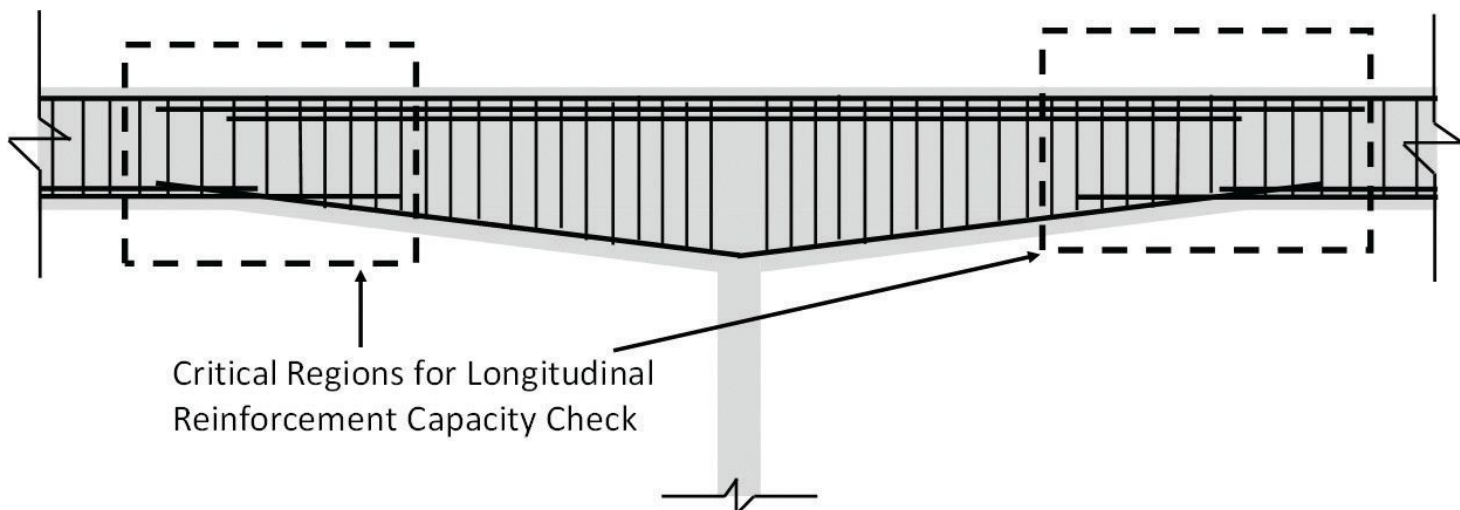


Figure 5. Possible locations where a longitudinal reinforcement check may control the capacity. Source: Based on the Jasper Bridge

version of Fig. C5.7.3.3-2 modified by the author. It shows that, for a given design section, the embedment length of the longitudinal steel must be evaluated at the point where the longitudinal steel crosses the crack. The embedment length is given as

$$\ell_x = x - (0.5d_v - y_s) \cot \theta$$

where

$\ell_x$  = embedment length of the longitudinal steel  
 $x$  = distance from the end of the beam to the design section  
 $y_s$  = distance from the bottom of the beam to the centroid of longitudinal steel

In this equation,  $d_v$  and  $\theta$  are as previously defined.

If there is only one or two layers of steel,  $\ell_x$  can be calculated based on the centroid of all the steel. However, if there are more than two layers of steel, it is advisable to find  $\ell_x$  for each individual layer.

**Figure 5** shows an example of details near a pier segment where flexural tension reinforcement terminations and the variable depth of the concrete section make it critical for a designer (or a load-rating engineer) to check the adequacy of longitudinal reinforcement with due consideration given to all load effects.<sup>3,4</sup>

It is important to recognize that Eq. (5.7.3.5-1) and (5.7.3.5-2) are intended for use with concurrent forces. In other words, bending moment, shear force, and axial force envelope diagrams may produce maximum values for a section, but those maxima do not concurrently exist. The use of values from envelope diagrams would be conservative. However, this level of conservatism may be, and in most cases will be, unnecessarily high.

The Federal Highway Administration's *Modified Compression Field Theory (MCFT) for Shear Load Rating—Pretensioned*

*Example* (FHWA-RC-24-0005)<sup>4</sup> provides a comprehensive discussion, with sample calculations, about how to use MCFT to calculate shear capacity and demonstrates how the longitudinal reinforcement check can be performed along the length of flexural members.

## Concluding Remarks

This article emphasizes the importance of the longitudinal reinforcement adequacy check in accordance with the AASHTO LRFD specifications. Bending moments, shear forces, axial loads, and torsional moments all influence the demands imposed on flexural reinforcement. The adequacy of longitudinal reinforcement should be checked with due consideration given to reinforcing bar or prestressing strand development. For existing bridges where the interaction between bending moments and shears were not explicitly considered in the original designs, this check may present a challenge. Nevertheless, it is important to take this interaction into account in our new designs as well as load ratings.

## References

1. American Association of State Highway and Transportation Officials (AASHTO). 1994. *AASHTO LRFD Bridge Design Specifications*. Washington, DC: AASHTO.
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