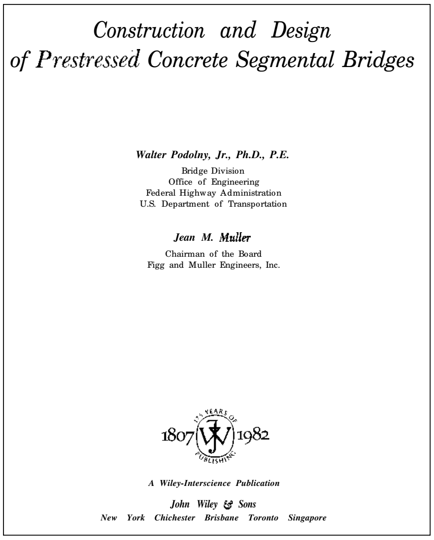
A History of Checks on Web Principal Tensile Stress in Bridge Design Specifications

by R. Kent Montgomery, GM2 Associates

All concrete bridges should be designed for the strength limit state, which controls the safety of the structure. Concrete bridges should also be designed to meet the service limit state, primarily to control cracking, which can have a direct impact on the durability of the structure. As a part of service limit state design, web principal tensile stresses must be kept below limiting stresses to help ensure that there is no shear cracking in the webs. Article 5.9.2.3.3 in the ninth edition of the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[1] limits the web principal tensile stress at the service limit state to $0.110\lambda\sqrt{f'_c}$ ksi for all post-tensioned superstructures of any concrete strength and for pretensioned girders with design strengths greater than 10 ksi. (The equations shown in this article are based on values of f'_c in ksi units.) While designing for web principal tension is currently included in design specifications, that was not always the case.

In the United States, limiting web principal tension was first used in the 1970s, for the design of concrete segmental bridges. At that time, AASHTO's *Standard Specifications for Highway Bridges*[2] was the design specification used for bridge design. The AASHTO standard specifications (including later editions) included only strength-based design provisions for web shear ($V_{ci}-V_{cw}$ method) and did not include provisions that limited web principal tensile stresses. However, limitation of web stresses for service loads was used for the design of most concrete segmental bridges and was, arguably, considered standard practice. Early segmental concrete designs used the guidance provided in *Construction and Design of Prestressed Concrete Segmental Bridges* (**Fig. 1**).[3] This book, which is no longer in print, provided guidance to limit the web shear stress to $0.05f'_c + 0.20\ f_x + 0.40\ f_y$, where f'_c is the concrete strength, f_x is the horizontal longitudinal compressive stress, and f_y is the vertical compressive stress. Most often, $f_y = 0$; however, some designs introduce vertical compression in the webs through the use of vertical post-tensioning (typically, post-tensioning bars). This simplified linear version of a web stress limitation facilitates computation and has been used in numerous designs. With the advent of computers for computations, designing to limit the actual principal tensile stress became the norm. No formal limits existed, but limits between $0.0948\sqrt{f'_c}$ and $0.1264\sqrt{f'_c}$ ksi were typically used.

AASHTO's *Guide Specifications for Design and Construction of Segmental Concrete Bridges*[4] was introduced in 1989. This publication included new shear design provisions using a truss model (segmental shear design method), which was discussed in a 1995 American Segmental Bridge Institute newsletter article about the previously adopted provisions.[5] The provisions in the first edition of the segmental bridge guide specifications used a conservative limit on the maximum nominal shear (force) capacity of $0.316\sqrt{f'_c} \times b_w \times d$. Based on industry input and a review of experimental results, the second edition (1999) of the AASHTO segmental bridge guide specifications increased this limit to $0.379\sqrt{f'_c} \times b_w \times d$. (The limits for combined shear and torsion are different than the limits for shear, but they seldom govern. For brevity, this article only discusses the limits for shear.) The provisions in the AASHTO segmental bridge guide specifications also specified the conservative approach of using 45-degree diagonal compressive struts, thereby avoiding the need to provide additional longitudinal reinforcement. The shear design provisions in the AASHTO segmental guide specifications were strength based, and there was no requirement to check web principal tensile stress for service loads; however, as previously mentioned, it was standard practice for the design of concrete segmental bridges to limit web principal tension.


Construction and Design of Prestressed Concrete Segmental Bridges

Walter Podolny, Jr., Ph.D., P.E.
Bridge Division
Office of Engineering
Federal Highway Administration
U.S. Department of Transportation

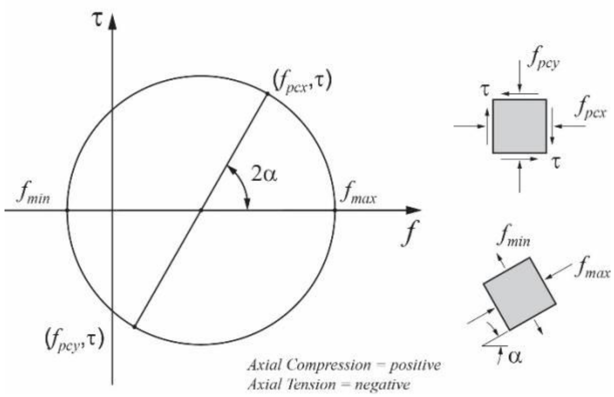
Jean M. Muller
Chairman of the Board
Figg and Muller Engineers, Inc.

1807 1982

A Wiley-Interscience Publication
John Wiley & Sons
New York Chichester Brisbane Toronto Singapore

Figure 1. Early segmental concrete designs used the guidance provided in *Construction and Design of Prestressed Concrete Segmental Bridges*,[3] which included limiting web shear stress.

The first edition of the AASHTO LRFD specifications was published in 1994. This specification introduced new shear provisions based on modified compression field theory (MCFT) as the primary shear design method. Early editions also included the $V_{ci}-V_{cw}$ method given in the AASHTO standard specifications as an alternative legacy method for shear design. The previously mentioned segmental concrete shear design method was added as an alternative legacy method in the



$$f_{\min} = \frac{1}{2}\left(\left(f_{pcx} + f_{pcy}\right) - \sqrt{\left(f_{pcx} + f_{pcy}\right)^2 + \left(2\tau\right)^2}\right)$$

$$f_{\max} = \frac{1}{2}\left(\left(f_{pcx} + f_{pcy}\right) + \sqrt{\left(f_{pcx} + f_{pcy}\right)^2 + \left(2\tau\right)^2}\right)$$

Figure 2. Mohr's circle analysis for determining principal stresses. Source: Article C5.9.2.3.3-2 of the *AASHTO LRFD Bridge Design Specifications*.[1]

2005 interim revisions to the AASHTO LRFD specifications. All of these methods are strength limit state methods, and no service limit state design provisions were included in early editions of the AASHTO LRFD specifications. The MCFT shear design method offered a potentially more economical design through a reduction in required web thickness. That is because the method uses a limit on the maximum nominal shear capacity of $0.25f'_c \times b_v \times d_v$, whereas the limit for the segmental method is $0.379\sqrt{f'_c} \times b_w \times d$. For a given web thickness, representative calculations have shown that the maximum nominal shear capacity allowed by the MCFT method is on the order of 33% larger than that allowed by the segmental method.

In the early 2000s, a few recently constructed concrete segmental bridges experienced noticeable web cracking. With the previous conservative limit on maximum nominal shear capacity, concrete segmental bridges seldom experienced web cracking. It was thought that the observed web cracking was, at least in part, due to thinner webs allowed by the MCFT method. (It should be noted that bridges properly designed for shear using the MCFT method have adequate strength and safety, and the cracking experienced was only a serviceability concern.) To address these concerns, the AASHTO T-10 Technical Committee for Concrete Design balloted two items in 2004 related to shear design in segmental concrete bridges. The first item was to add a service limit state check for principal tension in the webs of segmental bridges, with a tensile stress limit of $0.110\sqrt{f'_c}$ ksi (for normalweight concrete) to minimize the possibility of web cracking. Note that principal stresses can be calculated from closed-form equations derived from a Mohr's circle analysis (**Fig. 2**). The second item was to add the segmental shear design method to the AASHTO LRFD specifications as an alternative strength-based legacy method. These changes, primarily the web principal tensile stress limit, appear to have solved the observed web-cracking issues.

In 2013, the T-10 committee reorganized Section 5, Concrete Structures, of the AASHTO LRFD specifications to improve organization, clarity, and consistency among the articles. While undertaking this reorganization, the committee recognized that including a web principal tensile stress limit for all types of concrete bridges had value, as any concrete web could potentially crack at the service limit state. Therefore, the committee decided to add provisions limiting the web principal tensile stress to $0.110\lambda\sqrt{f'_c}$ ksi for all concrete post-tensioned bridges and pretensioned girders with concrete design strengths greater than 10 ksi. Pretensioned girders with lower concrete strengths were excluded to limit the calculational burden for girders that have a proven track record with respect to web shear cracking. However, as designers push current limits with ever deeper girders and thinner webs, it is perhaps advisable to check web principal tension for new pretensioned girder sections for which there are no historical performance data. The reorganized Section 5, including the web principal tensile-stress check for most concrete bridges, was incorporated in the eighth edition AASHTO LRFD specifications (2017).

Good concrete bridge design practice should include shear design for both the strength and service limit states. Limiting web principal tension at the service limit state and designing the web reinforcement for the strength limit state is analogous to limiting flexural concrete stresses at the service limit state and providing adequate flexural strength. Both must be performed to ensure a structure that has not only adequate strength and safety but also enhanced durability. Although it took time to develop design specifications that consistently include service limit state design provisions for shear, the AASHTO LRFD specifications now include design provisions for both the strength and service limit states.

References

1. American Association of State Highway and Transportation Officials (AASHTO). 2020. *AASHTO LRFD Bridge Design Specifications.* 9th ed. Washington, DC: AASHTO.
2. AASHTO. 2002. *Standard Specifications for Highway Bridges*. 17th ed. Washington, DC: AASHTO.
3. Podolny, W., and J. M. Muller. 1982. *Construction and Design of Prestressed Concrete Segmental Bridges*. New York, NY: Wiley.
4. AASHTO. 1999. *Guide Specifications for Design and Construction of Segmental Concrete Bridges.* 2nd ed. Washington, DC: AASHTO.
5. Ramirez, J. 1995. "Shear and Torsion Design Provisions for Segmental Concrete Bridges." *ASBI Newsletter*. Austin, TX: American Segmental Bridge Institute.

EDITOR'S NOTE

The modification factor for lightweight concrete λ was first included in the AASHTO LRFD specifications with the 2005 interim revisions. Therefore, the factor is included with the stress limits in this article only when referring to specifications after 2005.