Proposals for New One-Way Shear Equations for the 318 Building Code

An introduction to six proposals covered in this issue of *CI*

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The basic one-way shear equations in the ACI 318 Building Code have been unchanged since 1963,[1] except for some changes in the minimum shear reinforcement requirements and the addition of part of the prestressed equations that occurred in 1971.[2] Over the past two decades, there have been significant changes in shear design provisions in other codes of practice, such as the Eurocode 2,[3] the Canadian Standards (CSA A23.3, 2004),[4] the U.S. bridge design specifications,[5] and the *fib* Model Code.[6] New approaches such as methods based on the depth of compression zone, the amount of longitudinal reinforcement, the level of axial strain, and fracture mechanics have also been developed. Most of these approaches consider a size effect for members without transverse reinforcement.

Members of ACI Subcommittee 318-E, Section and Member Strength, and Joint ACI-ASCE Committees 445, Shear and Torsion, and 446, Fracture Mechanics of Concrete, devoted significant efforts over the last two decades to investigate the effectiveness and safety of the current one-way shear design equations in the ACI 318 Code. Immediately after the ACI 318-14 code cycle,[7] these committees challenged the researcher-and-practitioner community to present proposals for new, safer, and more effective one-way shear design methods for possible incorporation into the 2019 edition of the ACI 318 Code. This article explains the need and process put in place to investigate the existing design equations and develop a new approach for one-way shear design.

This article is followed by six papers describing design approaches proposed by researchers from the international community. These proposals were presented at the Hot Topic session during The ACI Concrete Convention and Exposition–Spring 2016, in Milwaukee, WI. These proposals are being used by ACI Subcommittee 318-E to develop change proposals for the one-way shear equations for the ACI 318-19 Code.

History of Design Provisions

In accordance with ACI 318-14 Code, the calculation of the one-way shear capacity of a member is based on the sum of the contribution of the shear reinforcement V_s, the concrete V_c, and the vertical component of prestressing steel V_p. The contribution of shear reinforcement is based on a 45-degree truss model.[8] The concrete contribution to shear resistance was added more than a century ago, when test results illustrated that the strength values calculated by a 45-degree truss model were overly conservative.[9] Originally, V_c was taken to be a fraction of the concrete compressive strength multiplied by the width and depth of the beam. This was changed in ACI 318-63 to be the estimated diagonal cracking strength as recommended in the Joint ACI-ASCE Committee 326 report, "Shear and Diagonal Tension."[10] In this approach, V_c was made proportional to the square root of the cylinder compressive strength. The effects of bending moment, axial load, and amount of longitudinal tension reinforcement on V_c were also considered through additional equations. More expressions were introduced over time to establish limits and minimum requirements. As a result of this evolution, the ACI 318-14 Code comprises over 17 equations for calculation of one-way shear capacity (refer to Table 1).

There is no mechanistic model to justify that the diagonal cracking capacity has any correlation with the concrete shear contribution at ultimate, and so this method is empirically justified by beam shear tests. The V_c contribution at ultimate is generally considered to be from a combination of aggregate interlock, shear in the compression zone, dowel action, and

Table 1:

Summary of one-way shear design provisions in ACI 318-14 (not all limits and requirements shown)

ACI 318-14	Simplified method	Detailed method
V_n	$V_n = V_c + V_s$ $V_u \le \phi(V_c + 8\sqrt{f_c'}b_w d)$	
RC, V_c	$V_c = 2\lambda\sqrt{f_c'}b_w d$	Lesser of: $V_c = \left[1.9\lambda\sqrt{f_c'} + 2500\rho_w \frac{V_u d}{M_u}\right]b_w d$ $V_c = \left[1.9\lambda\sqrt{f_c'} + 2500\rho_w\right]b_w d$ $V_c = 3.5\lambda\sqrt{f_c'}b_w d$
V_c with axial load N_u	Axial compression: $V_c = 2\left[1 + \frac{N_u}{2000A_g}\right]\lambda\sqrt{f_c'}b_w d$ Axial tension: $V_c = 2\left[1 + \frac{N_u}{500A_g}\right]\lambda\sqrt{f_c'}b_w d$	Axial compression (lesser of): $V_c = \left[1.9\lambda\sqrt{f_c'} + 2500\rho_w \frac{V_u d}{M_u - N_u\frac{(4h-d)}{8}}\right]b_w d$ $V_c = 3.5\lambda\sqrt{f_c'}b_w d\sqrt{1 + \frac{N_u}{500A_g}}$
PC, V_c	Lesser of (a), (b), and (c), but > (d): $V_c = \left[0.6\lambda\sqrt{f_c'} + 700\frac{V_u d_p}{M_u}\right]b_w d$ (a) $V_c = \left[0.6\lambda\sqrt{f_c'} + 700\right]b_w d$ (b) $V_c = 5\lambda\sqrt{f_c'}b_w d$ (c) $V_c = 2\lambda\sqrt{f_c'}b_w d$ (d)	Lesser of V_{ci} and V_{cw}: $V_{ci} = 0.6\lambda\sqrt{f_c'}b_w d_p + V_d + \frac{V_i M_{cre}}{M_{max}}$ or $1.7\lambda\sqrt{f_c'}b_w d$ (use largest) $V_{cw} = (3.5\lambda\sqrt{f_c'} + 0.3f_{pc})b_w d_p + V_p$
V_s	$V_s = \frac{A_v f_{yt} d}{s}$	

residual tensile stresses across cracks; the first two of these are expected to provide the great majority of the resistance.[11]

There are several potential shortcomings to the ACI 318-14 shear design provisions, including:

- V_c is proportional to beam depth and thereby does not consider a size effect;
- V_c is the same for members with and without shear reinforcement;
- V_c at ultimate is taken as the diagonal cracking strength, and this is not model-based;
- The effect of axial compression on V_c is considered differently for compression due to applied load and compression due to prestressing;
- The effect of axial tension in reducing V_c may be too great;
- The angle of diagonal compression is fixed at 45 degrees, regardless of the axial load and amount of reinforcement;
- A low limit is placed on V_c to avoid diagonal compression failure, rather than considering it directly;
- There are discontinuities in the requirements for the minimum amount and maximum spacing of shear reinforcement;
- There are many relationships for V_c, each developed for specific conditions;
- V_c has been validated for members subjected to shear by tests in which V_s is based on the 45-degree truss model;
- Several influencing factors are not directly considered, including the effects of distributed longitudinal reinforcement, flanges, crack roughness, crack widths, state of straining, depth of the compression zone, and axial stiffness of reinforcement; and
- Although the provisions have been developed based on observations of beams tested in laboratories, the provisions do not accurately estimate the shear strengths of those beams, and those beams do not well represent members used in constructed projects.

Establishment of Beam Shear Databases

Over the last 15 years, Joint ACI-ASCE Committee 445 began establishing databases of slender beam (shear-span to depth [a/d] > 2.4) test results. This brought together database development efforts by researchers in the United States, Germany, and Canada. Some years after the efforts began, a formal partnership for these efforts was established between ACI and the German Committee for Reinforced Concrete (DAfStb). More recently, ACI and DAfStb have been working to link their database efforts with similar efforts in the International Federation for Structural Concrete (*fib*) community. For the purposes of comparing different shear design provisions, four different evaluation databases were created. Only test results that passed certain criteria (for example, beams that met minimum size limits, had specified material properties, and did not fail in flexure) were used. The contents and number of tests in these four databases (refer to References 12 and 13) are as follows:

- Nonprestressed members with shear reinforcement (784 beam tests);
- Nonprestressed members without shear reinforcement (170 tests);
- Prestressed members without shear reinforcement (214 tests); and
- Prestressed members with shear reinforcement (117 tests).

Although the databases have been tremendously useful, it must be recognized that they cannot serve as the ultimate way of judging the accuracy of any proposed design provisions, due to bias and limitations in the datasets and measured values.

Steps to Advancing ACI 318 Provisions

Joint ACI-ASCE Committee 445 and ACI Subcommittee 318-E continually examine the safety and effectiveness of the ACI 318 Code shear design provisions. For several years, these committees have discussed the impact of the size effect in shear, as well as advancements in understanding the impact of longitudinal strains and amount of longitudinal reinforcement. In 2014, these committees collaborated to invite proposals from the research and design community for new shear design provisions. The committees challenged researchers and practitioners to present proposals for new, safer, and more reliable one-way shear design methods for possible incorporation into the ACI 318-19 code cycle. A total of 10 proposals were submitted. The total was reduced to six after some groups found ways to merge their suggestions. These proposals were first evaluated against the existing experimental shear database (explained herein) and then implemented in a comprehensive design example database that included slabs, beams, and columns, all with and without prestressing. The six one-way shear proposals that were submitted to ACI Subcommittee 318-E for further investigation and consideration are listed as follows. These are further described and detailed in the following six articles included in this issue of *Concrete International*:

- "Updating the ACI Shear Design Provisions" by Evan C. Bentz and Michael P. Collins;
- "One-Way Shear Design Method Based on a Multi-Action Model; A compromise between simplicity and accuracy" by Antoni Cladera, Antonio Marí, Jesús-Miguel Bairán, Eva Oller, and Carlos Ribas;
- "A Unified Approach to Shear Design" by Robert J. Frosch, Qiang Yu, Gianluca Cusatis, and Zdeněk P. Bažant;
- "Shear Strength of Prestressed and Nonprestressed Concrete Beams" by Yi-An Li, Thomas T. C. Hsu, and Shyh-Jiann Hwang;
- "Unified Shear Design Method of Concrete Beams Based on Compression Zone Failure Mechanism" by Hong-Gun Park and Kyoung-Kyu Choi; and
- "Proposal for ACI 318 Shear Design" by Karl-Heinz Reineck.

Concluding Remarks

Both the "simplified method" and "detailed method" of the existing one-way shear provisions do not account for size effect and/or conditions with low percentages of longitudinal reinforcement. In ACI 318-14, a large number of equations are used to calculate the concrete contribution to shear strength, and many of these are considered complex. Additionally, prestressed and nonprestressed members with axial load are currently treated separately; this leads to inconsistency. As described previously, six design approaches were submitted to ACI Subcommittee 318-E for further investigation and consideration. The details of these approaches are included in separate papers that follow this article. ACI Subcommittee 318-E performed a thorough and comprehensive evaluation of the proposed approaches, considering the issues described herein.

As a result of this collective effort of the international research community and members of ACI Subcommittee 318-E and Joint ACI-ASCE Committee 445, a potential design approach is under consideration and is currently being balloted within ACI Subcommittee 318-E as well as ACI Committee 318. The proposed change proposal provides a simplified process for calculating shear capacity and it improves the accuracy of the equations when compared to the beam shear database. The results of this effort could result in changes in the one-way shear equations within the ACI 318 Code to be released in 2019.

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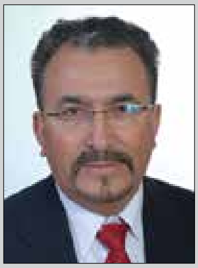
Selected for reader interest by the editors.



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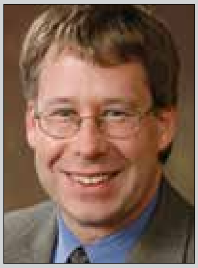

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