Evaluation of Shear Strength Design Methodologies for Slender Shear-Critical RC Beams

Zuanfeng Pan¹ and Bing Li²

Abstract: This paper seeks to examine the concrete contribution to shear strength and determine the inclination of the compressive strut within the variable truss model for slender RC shear-critical beams with stirrups. Using the modified compression field theory in place of the conventional statistical regression of experimental data, the expression for the concrete contribution to shear strength was derived, and the inclination of compressive struts was determined. A simplified explicit expression for shear strength was then provided, with which shear strength can be calculated without extensive iterative computations. This method was then verified using the available experimental data of 209 RC rectangular beams with stirrups and compared with the current methods from the American Concrete Institute and the Canadian Standards Association. The theoretical results are shown to be consistent with the experimentally observed behavior of shear-critical RC beams. DOI: 10.1061/(ASCE)ST.1943-541X.0000634. © 2013 American Society of Civil Engineers.

CE Database subject headings: Shear strength; Struts; Compression; Concrete beams; Design.

Author keywords: Shear strength; Concrete contribution to shear; Inclination of strut; Modified compression field theory; Evaluation.

Introduction

Although the flexural behavior of RC beams is generally well understood, the explanation of shear mechanisms is relatively inadequate. Over the last century, many researchers have managed to develop semiempirical theories based on extensive experimental data [ASCE-American Concrete Institute (ACI) Committee 426 1973; ASCE-ACI Committee 445 1998]. Representative models include the limit equilibrium theory, the truss model, the strut and tie model, the plastic theory, and the shear friction theory. However, given the complexity of shear failure mechanisms, none of these theories can offer a complete explanation, and as such, there has been no unanimously accepted theory. Recent years have seen renewed efforts to develop a theoretical model that is verified by experimental data.

Many truss analogy models such as the traditional 45° truss model, constant or variable angle truss model, and modified compression field theory (MCFT) (Vecchio and Collins 1986) are widely used as the basis of most shear design methodologies for RC beams. The general methods in LRFD-04 (AASHTO 2004) and Canadian Standard-04 [Canadian Standards Association (CSA) 2004] are both based on MCFT. Using the method in AASHTO LRFD-04, for beams with stirrups, the two factors, \( \beta \) and \( \theta \), need to be looked up in the data charts. On the other hand, in CSA-04, it is necessary to determine the longitudinal strain at the middepth of the member using extensive iterative computations and a rough gauge of its initial value. The proposed approach in this paper is based on MCFT, rendering it unnecessary for iterative calculations or reference to data tables. The results of the proposed approach are verified using the experimental data of 209 RC beams with stirrups and compared with the results obtained through the methods mentioned in ACI 318R-08 (ACI 2008) and CSA-04 (CSA 2004).

Shear Strength for Slender Shear-Critical RC Beams

It is worthwhile to note that for beams with a small \( \lambda \) or deep beams, the hypothesis that plane sections remain plane is not satisfied, and parts of the shear are directly transmitted to the supports by arch action. If the sectional shear design method is used, the results may be conservative without consideration of arch action. For RC beams with stirrups, when \( \lambda \geq 2.5 \), the arch action could be considered small (ASCE-ACI Committee 445 1998). In this paper, the present approach for shear strength based on MCFT is aimed mainly at the slender beams, which means \( \lambda \) of the beam is \( \geq 2.5 \), because the most practical RC beams are slender, with \( \lambda \) ranging from approximately 2.5 to 6 (Kassian 1990; Li and Tran 2008, 2012).

Formulas for shear strength in many codes for RC beams take into account the contribution of concrete \( V_c \), and the contribution of stirrups \( V_s \). The MCFT has made an attempt to simplify the transmitting mechanism of concrete using average stresses, average strains, and local variations (Collins and Mithell 1991). In the theory, the cracked concrete beam must be capable of resisting the effects of the shear, or the beam will fail before the breakdown of the aggregate interlock mechanism, to develop the capacity of a rough and interlocked crack interface for shear transfer. Derived by Collins and Mithell (1991), the contribution of concrete to shear is

\[
V_c = \min \left[ \begin{array}{c} 0.18 \sqrt{\rho bd_r} \\ \frac{24\varepsilon_1}{(a + 16) \left( \sin \theta + \cos \theta \frac{\cot \theta}{s_x} \right)} \\ 0.33\sigma_1 \sigma_2 b d_r \sqrt{2\gamma \cos \theta} \frac{1}{1 + \sqrt{500\varepsilon_1}} \end{array} \right]
\]

From Eq. (1), it can be seen that there are two unknowns needed to calculate shear strength: crack angle \( \theta \) and principal tensile strain \( \varepsilon_1 \).

1Lecturer, School of Civil Engineering, Tongji Univ., Shanghai 200092, China.

2Associate Professor and Director of Natural Hazards Research Centre (NHRC), Nanyang Technological Univ., Singapore 639798 (corresponding author). E-mail: cbl@ntu.edu.sg

Note. This manuscript was submitted on July 25, 2011; approved on July 20, 2012; published online on August 10, 2012. Discussion period open until September 1, 2013; separate discussions must be submitted for individual papers. This technical note is part of the Journal of Structural Engineering, Vol. 139, No. 4, April 1, 2013. ©ASCE, ISSN 0733-9445/2013/4-619–622/$25.00.