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Recent Approaches to Shear Design of Structural Concrete

Reported by Joint ACI-ASCE Committee 445



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Recent Approaches to Shear Design of Structural Concrete

Reported by Joint ACI-ASCE Committee 445

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Truss model approaches and related theories for the design of reinforced concrete members to resist shear are presented. Realistic models for the design of deep beams, corbels, and other nonstandard structural members are illustrated. The background theories and the complementary nature of a number of different approaches for the shear design of structural concrete are discussed. These relatively new procedures provide a unified, intelligible, and safe design framework for proportioning structural concrete under combined load effects.

Keywords: beams (supports); concrete; design; detailing; failure; models; shear strength; structural concrete; strut and tie.

CONTENTS

Chapter 1—Introduction, p. 2

- 1.1—Scope and objectives
- 1.2—Historical development of shear design provisions
- 1.3—Overview of current ACI design procedures
- 1.4—Summary

Chapter 2—Compression field approaches, p. 5

- 2.1—Introduction
- 2.2—Compression field theory

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- 2.3—Stress-strain relationships for diagonally cracked concrete
- 2.4—Modified compression field theory
- 2.5—Rotating-angle softened-truss model
- 2.6—Design procedure based on modified compression field theory

Chapter 3—Truss approaches with concrete contribution, p. 17

- 3.1—Introduction
- 3.2—Overview of recent European codes
- 3.3—Modified sectional-truss model approach
- 3.4—Truss models with crack friction
- 3.5—Fixed-angle softened-truss models
- 3.6—Summary

Chapter 4—Members without transverse reinforcement, p. 25

- 4.1—Introduction
- 4.2—Empirical methods
- 4.3—Mechanisms of shear transfer
- 4.4—Models for members without transverse reinforcement
- 4.5—Important parameters influencing shear capacity
- 4.6—Conclusions

Chapter 5—Shear friction, p. 35

- 5.1—Introduction
- 5.2—Shear-friction hypothesis
- 5.3—Empirical developments

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- 5.4—Analytical developments
- 5.5—Code developments

Chapter 6—Design with strut-and-tie models, p. 37

- 6.1—Introduction
- 6.2—Design of B regions
- 6.3—Design of D regions

Chapter 7—Summary, p. 46

- 7.1—Introduction
- 7.2—Truss models
- 7.3—Members without transverse reinforcement
- 7.4—Additional work

Appendix A—ACI 318M-95 shear design approach for beams, p. 49

Appendix B—References, p. 50

CHAPTER 1—INTRODUCTION

1.1—Scope and objectives

Design procedures proposed for regulatory standards should be safe, correct in concept, simple to understand, and should not necessarily add to either design or construction costs. These procedures are most effective if they are based on relatively simple conceptual models rather than on complex empirical equations. This report introduces design engineers to some approaches for the shear design of one-way structural concrete members. Although the approaches explained in the subsequent chapters of this report are relatively new, some of them have reached a sufficiently mature state that they have been implemented in codes of practice. This report builds upon the landmark state-of-the-art report by the ASCE-ACI Committee 426 (1973), *The Shear Strength of Reinforced Concrete Members*, which reviewed the large body of experimental work on shear and gave the background to many of the current American Concrete Institute (ACI) shear design provisions. After reviewing the many different empirical equations for shear design, Committee 426 expressed in 1973 the hope that “the design regulations for shear strength can be integrated, simplified, and given a physical significance so that designers can approach unusual design problems in a rational manner.”

The purpose of this report is to answer that challenge and review some of the new design approaches that have evolved since 1973 (CEE 1978, 1982; Walraven 1987; IABSE 1991a,b; Roman 1993). Truss model approaches and related theories are discussed, and the common basis for these new approaches are highlighted. These new procedures provide a unified, rational, and safe design framework for structural concrete under combined actions, including the effects of axial load, bending, torsion, and prestressing.

Chapter 1 presents a brief historical background of the development of the shear design provisions and a summary of the current ACI design equations for beams. Chapter 2 discusses a sectional design procedure for structural-concrete one-way members using a compression field approach. Chapter 3 addresses several approaches incorpo-

rating the “concrete contribution.” It includes brief reviews of European Code EC2, Part 1 and the Comité Euro-International du Béton–Fédération International de la Précontrainte (CEB-FIP) Model Code, both based on strut-and-tie models. The behavior of members without or with low amounts of shear reinforcement is discussed in Chapter 4. An explanation of the concept of shear friction is presented in Chapter 5. Chapter 6 presents a design procedure using strut-and-tie models (STM), which can be used to design regions having a complex flow of stresses and may also be used to design entire members. Chapter 7 contains a summary of the report and suggestions for future work.

1.2—Historical development of shear design provisions

Most codes of practice use sectional methods for design of conventional beams under bending and shear. ACI Building Code 318M-95 assumes that flexure and shear can be handled separately for the worst combination of flexure and shear at a given section. The interaction between flexure and shear is addressed indirectly by detailing rules for flexural reinforcement cutoff points. In addition, specific checks on the level of concrete stress in the member are introduced to ensure sufficient ductile behavior and control of diagonal crack widths at service load levels.

In the early 1900s, truss models were used as conceptual tools in the analysis and design of reinforced concrete beams. Ritter (1899) postulated that after a reinforced concrete beam cracks due to diagonal tension stresses, it can be idealized as a parallel chord truss with compression diagonals inclined at 45° with respect to the longitudinal axis of the beam. Mörsch (1920, 1922) later introduced the use of truss models for torsion. These truss models neglected the contribution of the concrete in tension. Withey (1907, 1908) introduced Ritter’s truss model into the American literature and pointed out that this approach gave conservative results when compared with test evidence. Talbot (1909) confirmed this finding.

Historically, shear design in the United States has included a concrete contribution V_c to supplement the 45 degree sectional truss model to reflect test results in beams and slabs with little or no shear reinforcement and ensure economy in the practical design of such members. ACI Standard Specification No. 23 (1920) permitted an allowable shear stress of $0.025f'_c$, but not more than 0.41 MPa, for beams without web reinforcement, and with longitudinal reinforcement that did not have mechanical anchorage. If the longitudinal reinforcement was anchored with 180 degree hooks or with plates rigidly connected to the bars, the allowable shear stress was increased to $0.03f'_c$ or a maximum of 0.62 MPa (Fig. 1.1). Web reinforcement was designed by the equation

$$A_v F_v = V' s \sin \alpha / jd \quad (1-1)$$

where

- A_v = area of shear reinforcement within distance s ;
- F_v = allowable tensile stress in the shear reinforcement;
- jd = flexural lever arm;

- V' = total shear minus $0.02f'_c bjd$ (or $0.03f'_c bjd$ with special anchorage);
 b = width of the web;
 s = spacing of shear steel measured perpendicular to its direction; and
 α = angle of inclination of the web reinforcement with respect to the horizontal axis of the beam.

The limiting value for the allowable shear stresses at service loads was $0.06f'_c$ or a maximum of 1.24 MPa, or with anchorage of longitudinal steel $0.12f'_c$ or a maximum of 2.48 MPa. This shear stress was intended to prevent diagonal crushing failures of the web concrete before yielding of the stirrups. These specifications of the code calculated the nominal shear stress as $v = V/bjd$.

This procedure, which formed the basis for future ACI codes, lasted from 1921 to 1951 with each edition providing somewhat less-conservative design procedures. In 1951 the distinction between members with and without mechanical anchorage was omitted and replaced by the requirement that all plain bars must be hooked, and deformed bars must meet ASTM A 305. Therefore, the maximum allowable shear stress on the concrete for beams without web reinforcement (ACI 318-51) was $0.03f'_c$ and the maximum allowable shear stress for beams with web reinforcement was $0.12f'_c$.

ACI 318-51, based on allowable stresses, specified that web reinforcement must be provided for the excess shear if the shear stress at service loads exceeded $0.03f'_c$. Calculation of the area of shear reinforcement continued to be based on a 45 degree truss analogy in which the web reinforcement must be designed to carry the difference between the total shear and the shear assumed to be carried by the concrete.

The August 1955 shear failure of beams in the warehouse at Wilkins Air Force Depot in Shelby, Ohio, brought into question the traditional ACI shear design procedures. These shear failures, in conjunction with intensified research, clearly indicated that shear and diagonal tension was a complex problem involving many variables and resulted in a return to forgotten fundamentals.

Talbot (1909) pointed out the fallacies of such procedures as early as 1909 in talking about the failure of beams without web reinforcement. Based on 106 beam tests, he concluded that

It will be found that the value of v [shear stress at failure] will vary with the amount of reinforcement, with the relative length of the beam, and with other factors which affect the stiffness of the beam.... In beams without web reinforcement, web resistance depends upon the quality and strength of the concrete.... The stiffer the beam the larger the vertical stresses which may be developed. Short, deep beams give higher results than long slender ones, and beams with high percentage of reinforcement [give higher results] than beams with a small amount of metal.

Unfortunately, Talbot's findings about the influence of the percentage of longitudinal reinforcement and the length-to-depth ratio were not reflected in the design equations until much later. The research triggered by the 1956 Wilkins

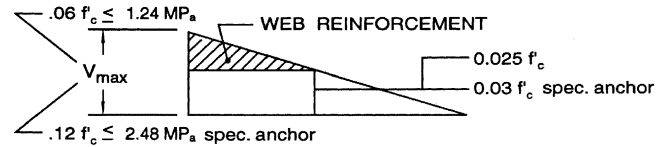


Fig. 1.1—American Specification for shear design (1920-1951) based on ACI Standard No. 23, 1920.

warehouse failures brought these important concepts back to the forefront.

More recently, several design procedures were developed to economize on the design of the stirrup reinforcement. One approach has been to add a concrete contribution term to the shear reinforcement capacity obtained, assuming a 45 degree truss (for example, ACI 318-95). Another procedure has been the use of a truss with a variable angle of inclination of the diagonals. The inclination of the truss diagonals is allowed to differ from 45 degree within certain limits suggested on the basis of the theory of plasticity. This approach is often referred to as the "standard truss model with no concrete contribution" and is complicated by the existence of aggregate interlock and dowel forces in the cracks, which allow a lower inclination of the compression diagonals and the further mobilization of the stirrup reinforcement. A combination of the variable-angle truss and a concrete contribution has also been proposed. This procedure has been referred to as the "modified truss model approach" (CEB 1978; Ramirez and Branson 1991). In this approach, in addition to a variable angle of inclination of the diagonals, the concrete contribution for nonprestressed concrete members diminishes with the level of shear stress. For prestressed concrete members, the concrete contribution is not considered to vary with the level of shear stress and is taken as a function of the level of prestress and the stress in the extreme tension fiber.

As mentioned previously, the truss model does not directly account for the components of the shear failure mechanism, such as aggregate interlock and friction, dowel action of the longitudinal steel, and shear carried across uncracked concrete. For prestressed beams, the larger the amount of prestressing, the lower the angle of inclination at first diagonal cracking. Therefore, depending on the level of compressive stress due to prestress, prestressed concrete beams typically have much lower angles of inclined cracks at failure than nonprestressed beams and require smaller amounts of stirrups.

Traditionally in North American practice, the additional area of longitudinal tension steel for shear has been provided by extending the bars a distance equal to d beyond the flexural cutoff point. Although adequate for a truss model with 45 degree diagonals, this detailing rule is not adequate for trusses with diagonals inclined at lower angles. The additional longitudinal tension force due to shear can be determined from equilibrium conditions of the truss model as $V \cot \theta$, with θ as the angle of inclination of the truss diagonals. Because the shear stresses are assumed uniformly distributed over the depth of the web, the tension acts at the section middepth.

The upper limit of shear strength is established by limiting the stress in the compression diagonals f_d to a fraction of the concrete cylinder strength. The concrete in the cracked web