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Report on Torsion in Structural Concrete

Reported by Joint ACI-ASCE Committee 445

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A clear understanding of the effects of torsion on concrete members is essential to the safe, economical design of reinforced and prestressed concrete members. This report begins with a brief and systematic summary of the 180-year history of torsion of structural concrete members, new and updated theories and their applications, and a historical overview outlining the development of research on torsion of structural concrete members. Historical theories and truss models include classical theories of Navier, Saint-Venant, and Bredt; the three-dimensional (3-D) space truss of Rausch; the equilibrium (plasticity) truss model of Nielson as well as Lampert and Thürlimann; the compression field theory (CFT) by Collins and Mitchell; and the softened truss model (STM) by Hsu and Mo.

This report emphasizes that it is essential to the analysis of torsion in reinforced concrete that members should: 1) satisfy the equilibrium condition (Mohr's stress circle); 2) obey the compatibility condition (Mohr's strain circle); and 3) establish the constitutive relationships of materials such as the "softened" stress-strain relationship of concrete and "smeared" stress-strain relationship of steel bars.

The behavior of members subjected to torsion combined with bending moment, axial load, and shear is discussed. This report deals with design issues, including compatibility torsion, spandrel beams, torsional limit design, open sections, and size effects. The final two chapters are devoted to the detailing requirements of transverse and longitudinal reinforcement in torsional members with detailed, step-by-step design examples for two beams under torsion using ACI (ACI 318-11), European (EC2-04), and Canadian Standards Association (CSA-A23.3-04) standards. Two design examples are given to illustrate the steps involved in torsion design. Design Example 1 is a rectangular reinforced concrete beam under pure torsion, and Design Example 2 is a prestressed concrete girder under combined torsion, shear, and flexure.

Keywords: combined action (loading); compatibility torsion; compression field theory; equilibrium torsion; interaction diagrams; prestressed concrete; reinforced concrete; shear flow zone; skew bending; softened truss model; spandrel beams; struts; torsion detailing; torsion redistribution; warping.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Accounting for the effects of torsion is essential to the safe design of structural concrete members, requiring a full knowledge of the effects of torsion and a sound understanding of the analytical models that can easily be used for design. For over three decades, considerable research has been conducted on the behavior of reinforced concrete members under pure torsion and torsion combined with other loadings. Likewise, analytical models have been developed based on the truss model concept. Several of these models were developed to predict the full load history of a member, whereas others are simplified and used only to calculate torsional strength. Many models developed since the 1980s account for softening of diagonally cracked concrete.

This report reviews and summarizes the evolution of torsion design provisions in ACI 318, followed with a summary of the present state of knowledge on torsion for design and analysis of structural concrete beam-type members. Despite a vast amount of research in torsion, provisions of torsion design did not appear in ACI 318 until 1971 (ACI 318-71), although ACI 318-63 included a simple clause regarding detailing for torsion. Code provisions in 1971 were based on Portland Cement Association (PCA) tests (Hsu 1968b).

These provisions were applicable only to rectangular nonprestressed concrete members. In 1995, ACI 318-95 adopted an approach based on a thin-tube, space truss model previously used in the Canadian Standards Association (CSA-A23.3-77) code and the Comité Euro-International du Béton (CEB)-FIP code (1978). This model permitted treatment of sections with arbitrary shape and prestressed concrete (Ghoneim and MacGregor 1993; MacGregor and Ghoneim 1995). The ACI 318-02 code extended the application of the (ACI 318) 1995 torsion provisions to include prestressed hollow sections. ACI 318 allows the use of alternative design methods for torsional members with a cross section aspect ratio of 3 or greater, like the procedures of pre-1995 editions of ACI 318 or the Prestressed Concrete Institute (PCI) method (Zia and Hsu 1978).

This report reviews and summarizes the present state of knowledge on torsion and reviews their use as a framework for design and analysis of structural concrete beam-type members. Chapter 3 presents a historical background outlining the development of research on torsion of structural concrete members. The general behavior of reinforced and prestressed concrete members under pure torsion is discussed in Chapter 4. In Chapter 5, the compression field theory (CFT) and softened truss model (STM) are presented in detail. Chapter 5 also includes a description of two graphical methods (Rahal 2000a,b; Leu and Lee 2000). The behavior of members subjected to torsion combined with shear, flexure,