

ACI 445.1R-12

**Report on Torsion
in Structural Concrete**

Reported by Joint ACI-ASCE Committee 445



American Concrete Institute®



American Concrete Institute®
Advancing concrete knowledge

First Printing
April 2013

Report on Torsion in Structural Concrete

Copyright by the American Concrete Institute, Farmington Hills, MI. All rights reserved. This material may not be reproduced or copied, in whole or part, in any printed, mechanical, electronic, film, or other distribution and storage media, without the written consent of ACI.

The technical committees responsible for ACI committee reports and standards strive to avoid ambiguities, omissions, and errors in these documents. In spite of these efforts, the users of ACI documents occasionally find information or requirements that may be subject to more than one interpretation or may be incomplete or incorrect. Users who have suggestions for the improvement of ACI documents are requested to contact ACI via the errata website at www.concrete.org/committees/errata.asp. Proper use of this document includes periodically checking for errata for the most up-to-date revisions.

ACI committee documents are intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. Individuals who use this publication in any way assume all risk and accept total responsibility for the application and use of this information.

All information in this publication is provided “as is” without warranty of any kind, either express or implied, including but not limited to, the implied warranties of merchantability, fitness for a particular purpose or non-infringement.

ACI and its members disclaim liability for damages of any kind, including any special, indirect, incidental, or consequential damages, including without limitation, lost revenues or lost profits, which may result from the use of this publication.

It is the responsibility of the user of this document to establish health and safety practices appropriate to the specific circumstances involved with its use. ACI does not make any representations with regard to health and safety issues and the use of this document. The user must determine the applicability of all regulatory limitations before applying the document and must comply with all applicable laws and regulations, including but not limited to, United States Occupational Safety and Health Administration (OSHA) health and safety standards.

Participation by governmental representatives in the work of the American Concrete Institute and in the development of Institute standards does not constitute governmental endorsement of ACI or the standards that it develops.

Order information: ACI documents are available in print, by download, on CD-ROM, through electronic subscription, or reprint and may be obtained by contacting ACI.

Most ACI standards and committee reports are gathered together in the annually revised ACI Manual of Concrete Practice (MCP).

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
U.S.A.
Phone: 248-848-3700
Fax: 248-848-3701

www.concrete.org

ISBN-13: 978-0-87031-810-8
ISBN: 0-87031-810-1

Report on Torsion in Structural Concrete

Reported by Joint ACI-ASCE Committee 445

Daniel A. Kuchma, Chair

Robert W. Barnes Jr., Secretary

Perry Adebar
Neal S. Anderson
Robert B. Anderson
Mark A. Ascheim
Oguzhan Bayrak
Zdenek P. Bazant
Abdeldjelil Belarbi**
Evan C. Bentz
John F. Bonacci

Hakim Bouadi
Michael D. Brown
Michael P. Collins
David Darwin
Walter H. Dilger*
Marc O. Eberhard
Catherine E. French
Robert J. Frosch
Gary G. Greene*

Neil M. Hawkins
Thomas T. C. Hsu*
Gary J. Klein
Zhongguo John Ma
Adolfo B. Matamoros
Denis Mitchell
Yi-Lung Mo*
Lawrence C. Novak
Carlos E. Ospina

Stavroula J. Pantazopoulou
Maria A. Polak
Julio A. Ramirez
Karl-Heinz Reineck
David H. Sanders*
Raj Valluvan
James K. Wight

*Subcommittee members who produced this report.

**Subcommittee Chair.

The committee would like to thank the following individuals for their contribution to this report: Mohammad Ali, Neal S. Anderson, Shri Bhide, Michael D. Collins, Maria Cristina Vidigal de Lima, Leonard Elfren, Christos Karayannis, Liang-Jenq Leu, Mohammad Mansour, Basile Rabbat, Khaldoun Rahal, and Paul Zia.

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.

CONTENTS

CHAPTER 1—INTRODUCTION AND SCOPE, p. 2

1.1—Introduction, p. 2

1.2—Scope, p. 3

CHAPTER 2—NOTATION AND DEFINITIONS, p. 3

2.1—Notation, p. 3

2.2—Definitions, p. 5

ACI 445.1R-12 was adopted and published April 2013.

Copyright © 2013, American Concrete Institute.

All rights reserved including rights of reproduction and use in any form or by any means, including the making of copies by any photo process, or by electronic or mechanical device, printed, written, or oral, or recording for sound or visual reproduction or for use in any knowledge or retrieval system or device, unless permission in writing is obtained from the copyright proprietors.

ACI Committee Reports, Guides, and Commentaries are intended for guidance in planning, designing, executing, and inspecting construction. This document is intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. The American Concrete Institute disclaims any and all responsibility for the stated principles. The Institute shall not be liable for any loss or damage arising therefrom.

Reference to this document shall not be made in contract documents. If items found in this document are desired by the Architect/Engineer to be a part of the contract documents, they shall be restated in mandatory language for incorporation by the Architect/Engineer.

CHAPTER 3—HISTORICAL OVERVIEW OF TORSION THEORIES AND THEORETICAL MODELS, p. 5

- 3.1—Navier's theory, p. 5
- 3.2—Thin-tube theory, p. 5
- 3.3—Historical development of theories for reinforced concrete members subjected to torsion, p. 6
- 3.4—Concluding remarks, p. 13

CHAPTER 4—BEHAVIOR OF MEMBERS SUBJECTED TO PURE TORSION, p. 13

- 4.1—General, p. 13
- 4.2—Plain concrete, p. 13
- 4.3—Reinforced concrete, p. 15
- 4.4—Prestressed concrete, p. 17
- 4.5—High-strength concrete, p. 18
- 4.6—Concluding remarks, p. 19

CHAPTER 5—ANALYTICAL MODELS FOR PURE TORSION, p. 20

- 5.1—General, p. 20
- 5.2—Equilibrium conditions, p. 20
- 5.3—Compatibility conditions, p. 20
- 5.4—Stress strain relationships, p. 22
- 5.5—Compression field theory, p. 23
- 5.6—Softened truss model, p. 25
- 5.7—Graphical methods, p. 26

CHAPTER 6—MEMBERS SUBJECTED TO TORSION COMBINED WITH OTHER ACTIONS, p. 28

- 6.1—General, p. 28
- 6.2—Torsion and flexure, p. 29
- 6.3—Torsion and shear, p. 33
- 6.4—Torsion and axial load, p. 36
- 6.5—Torsion, shear, and flexure, p. 37

CHAPTER 7—ADDITIONAL DESIGN ISSUES RELATED TO TORSION, p. 39

- 7.1—General, p. 39
- 7.2—Compatibility torsion and torsional moment redistribution, p. 39
- 7.3—Precast spandrel beams, p. 47
- 7.4—Torsion limit design, p. 48
- 7.5—Treatment of open sections, p. 51
- 7.6—Size effect on the strength of concrete beams in torsion, p. 53

CHAPTER 8—DETAILING FOR TORSIONAL MEMBERS, p. 53

- 8.1—General, p. 53
- 8.2—Transverse reinforcement, p. 55
- 8.3—Longitudinal reinforcement, p. 57
- 8.4—Detailing at supports, p. 58

CHAPTER 9—DESIGN EXAMPLES, p. 59

- 9.1—Torsion design philosophy, p. 59
- 9.2—Torsion design procedures, p. 59
- 9.3—Introduction to design examples, p. 67

9.4—Design Example 1: solid rectangular reinforced concrete beam under pure torsion, p. 67

9.5—Design Example 2: Prestressed concrete box girder under combined torsion, shear, and flexure, p. 74

CHAPTER 10—REFERENCES, p. 86

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,