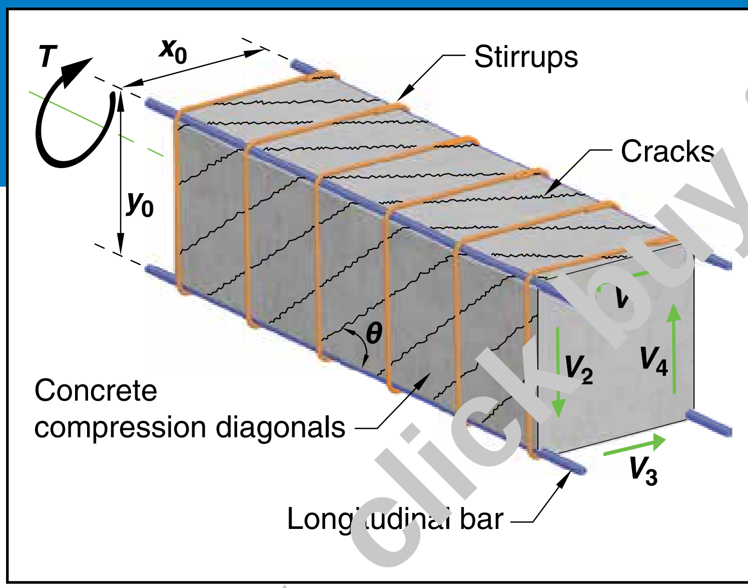
An ACI Technical Publication

SYMPOSIUM VOLUME



Examples for The Design of Reinforced and Prestressed Concrete Members Under Torsion

Editors:
Eva Lantsoght, Gary Greene, and Abdeldjelil Belarbi

SP-344

American Concrete Institute
Always advancing

Examples for the Design of Reinforced and Prestressed Concrete Members Under Torsion

Sponsored by
Joint ACI-ASCE Committee 445 and
Subcommittee 445-E

The Concrete Convention and Exposition
October 25-29, 2020

Editors:
Eva Lantsoght,
Gary Greene, and
Abdeldjelil Belarbi

American Concrete Institute
Always advancing

SP-344

First printing, October 2020

Discussion is welcomed for all materials published in this issue and will appear ten months from this journal's date if the discussion is received within four months of the paper's print publication. Discussion of material received after specified dates will be considered individually for publication or private response. ACI Standards published in ACI Journals for public comment have discussion due dates printed with the Standard.

The papers in this volume have been reviewed under Institute publication procedures by individuals expert in the subject areas of the papers.

Printed in the United States of America

Editorial production: Gail L. Tatum

ISBN-13: 978-1-64195-114-2

PREFACE

Examples for the Design of Reinforced and Prestressed Concrete Members Under Torsion

The design and analysis of structural concrete elements is a topic of practical interest. While sometimes the effect of torsion is only addressed based on simple examples, practicing engineers are faced with the need to include the effects of torsion in their designs of a variety of structures and load arrangements.

This Special Publication (SP) contains papers about the design of reinforced and prestressed concrete elements for torsion. The focus of the SP is on practical design examples according to different concrete bridge and building codes. In addition to the design examples, papers dealing with the current state of the art on torsion in structural concrete, as well as recent advances in the analysis and design of concrete elements failing in torsion, are added.

The objectives of this SP are to provide practicing engineers with the tools necessary to better understand and design concrete elements for torsion. The need for this SP arose after the development of the State-of-the-Art Report on Torsion of Joint ACI-ASCE Committee 445 "Shear and Torsion" and Subcommittee 445-E "Torsion". Usually, the attention that is paid to torsion in engineering education is limited to simplified textbook examples. The examples in this SP show applications in bridges and buildings, where the torsion design is combined with the design for flexure and shear. Additionally, the examples in this SP give insight on the different outcomes when using different bridge and building codes. Finally, the papers that include theoretical considerations give practicing engineers a deeper understanding and background on torsion in structural concrete.

The views from an international group of authors are included in this SP, subsequently representing a variety of building and bridge codes the engineer may encounter in practice. In particular, authors from the United States, Canada, Ecuador, the Netherlands, Italy, Greece, and the Czech Republic contributed to the papers in this SP. Views from academia and the industry are included.

To exchange experience in the design of torsion-critical structures as well as new research insights on torsion, Joint ACI-ASCE Committee 445 and Subcommittee 445-E organized two sessions titled "Examples for the Design of Reinforced and Prestressed Concrete Members under Torsion" at the ACI Fall Convention 2020. This SP contains several technical papers from experts who presented their work at these sessions, in addition to papers submitted for publication only.

In summary, this SP addresses numerous practical examples of structural elements under torsion in bridges and buildings, as well as insights from recent research applied to practical cases of elements under torsion. The co-editors of this SP are grateful for the contributions of the authors and sincerely value the time and effort they invested in preparing the papers in this volume, as well as the contributions of the reviewers of the manuscripts.

Eva Lantsoght, Gary Greene, and Abdeldjelil Belarbi
Co-editors

TABLE OF CONTENTS

OVERVIEW OF TORSION DESIGN METHODS

Camilo Granda Valencia and Eva Lantsoght

Synopsis: Large torsional moments, which need to be considered in a design, can result among others, in structures with an asymmetric layout or loading. To find the required longitudinal and transverse reinforcement to resist these torsional moments, the link between the three-dimensional action of the torsional moment and sectional analysis methods is necessary. This paper reviews the existing methods and code provisions for torsion. First, an overview of the principles of torsion from the mechanics perspective is given. Then, a survey of the available mechanical models for torsion is presented. Finally, the code provisions for torsion of ACI 318-19, CSA-A23.3-04, AASHTO-LRFD-17, EN 1992-1-1:2004, and the fib Model Code 2010 are summarized. Additionally, current research topics on torsion in structural concrete are summarized. It is expected that with this paper, engineers will have a useful overview and background knowledge for the design and assessment of torsion-critical elements.

Keywords: codes, concrete, reinforcement, shear, torsion

NEGLECTING COMPATIBILITY TORSIONS IN THE DESIGN OF CONCRETE STRUCTURES

Giorgio T. Proestos, Evan C. Bentz, Michael P. Collins

Synopsis: The traditional approach in the design of reinforced and prestressed concrete building structures has been to design each of the two orthogonal directions independently. In calculating the distribution of moments in a structure, this two-dimensional approach neglects the effects of the intersecting members. That is, in the case of compatibility torsions, the torsional stiffness is neglected. This paper provides a summary of the progression of the ACI code and commentary pertaining to the zero torsional stiffness assumption and its origins. The paper then introduces a recently developed nonlinear finite element analysis tool, VAST II, capable of predicting the response of reinforced and prestressed concrete structures in three-dimensions. The tool, based on the Modified Compression Field Theory, is capable of modelling entire structures or large portions of structures in order to assess their performance in a manner that accounts for three-dimensional effects, such as compatibility torsions. VAST II is then used to model a case study transit center. The transit center is a post-tensioned concrete structure that was designed using the traditional approach of neglecting the effects of compatibility torsions. The results indicate that the traditional approach recommended by the ACI code and commentary, to neglect compatibility torsions, is appropriate and gives robust designs. The paper concludes by providing recommendations for future studies that could be conducted using three-dimensional nonlinear tools such as VAST II.

Keywords: assessment, compatibility torsion, design, finite element, prestressed concrete, shear

HOW TO MODEL POST-CRACKING TORSIONAL STIFFNESS AND WHY IT MATTERS IN DESIGN

Edvard P.G. Bruun, Allan Kuan, and Evan C. Bentz

Synopsis: Post-cracking stiffness is an important parameter in determining the proper distribution of forces in the analysis of statically indeterminate reinforced concrete structures. While the ACI 318-19 code specifies typical values to use in modelling flexural cracking, the same guidance is not available when calculating post-cracking torsional stiffness. This paper presents a summary of the academic literature on the topic as the basis for developing a novel stiffness-based design procedure, which is then implemented in the design case study of a spandrel beam supporting a cantilevered roof slab. This example demonstrates a situation where a specific torsional stiffness is required to satisfy serviceability requirements. The design method is general and, therefore, applicable to any situation where an accurate measure of torsional stiffness or moment redistribution is required – this removes the need to iteratively model and design to capture post-cracking effects in structural members.

Keywords: reinforced concrete; torsion; post-cracking stiffness; serviceability; spandrel beam; redistribution

ALTERNATIVE DESIGN PROCEDURES FOR TORSION IN ACI 318-19: A COMPARATIVE STUDY

Allan Kuan, Edvard P.G. Bruun, Evan C. Bentz, and Michael P. Collins

Synopsis: Although the torsion design procedures in ACI 318-19 are simple and broadly applicable, the resulting designs tend to be conservative. To address this, clause 9.5.4.6 in ACI 318-19 permits the use of an alternative design procedure when designing members with an aspect ratio ≥ 3 for torsion, provided that the alternative procedure has been shown to agree with the results of comprehensive tests. This paper evaluates and compares the torsion design procedures in CSA A23.3:19 and the PCI Design Handbook 8th edition with those in ACI 318-19. Each of the three methods are found to show good agreement with 282 tests found in the literature. A comparison of the three concludes that the designs obtained using the ACI method generally require the most reinforcement. More economical designs for members subjected to relatively low and high torques can be obtained by using the PCI and CSA methods respectively. A design example of a spandrel beam using the three methods is presented, and then further conclusions are stated to guide practicing engineers on the relative strengths and weaknesses of each procedure.

Keywords: reinforced concrete; prestressed concrete; torsion; design codes; shear; moment

Application of Special Reinforcement Arrangements for RC Members under Torsion – Design Examples

Constantin E. Chalioris, and Chris G. Karayannis

Synopsis: Recently the use of special reinforcement arrangements has been extended in reinforced concrete members under torsion. These arrangements include (a) continuous rectangular spiral reinforcement, (b) epoxy bonded Carbon Fiber Reinforced Polymer (C-FRP) sheets as external transverse reinforcement and (c) short steel fibers as mass reinforcement. In this study an extended experimental program of 14 beams tested under torsion is presented. All specimens have the same geometrical characteristics but different transverse reinforcement arrangements. Six beams are used as pilot specimens; three of them have no transverse reinforcement and three have conventional steel stirrups. Further, two specimens have continuous steel spirals; four specimens have steel fibers as mass reinforcement and two specimens have externally bonded C-FRP sheets. The torsional behavior of these specimens is presented and compared to the behavior of the pilot specimens. Discussion and explanatory design examples about the application of these reinforcements are also included.

Keywords: torsion; reinforced concrete; spiral reinforcement; Fiber Reinforced Polymers; steel fibers; stirrups

TORSION OF RECTANGULAR CONCRETE SECTIONS

Jan L. Vítek, Lukáš Boháček, Jaroslav Průša, Vladimír Křístek

Synopsis: The paper deals with torsion of rectangular concrete sections. The pre-cracking stage and post-cracking stage are discussed. The various design procedures are briefly mentioned and compared. The deficiencies of some methods are identified and discussed. The major part of the paper deals with the results of an experimental program executed at the Czech Technical University. The large-scale elements were tested under loading by torsion and by interaction of torsion and compression. The results showed that the effect of the compression force on the load carrying capacity of the elements in torsion differs according to the stage of performance. While at the pre-cracking stage the contribution of the compression is rather significant, when approaching the failure, it becomes reduced. Simplified technical methods of design of reinforcement were also discussed. It has been proved that the effect of the angle of the compressed diagonal in code models is rather important. The study showed that this effect is sometimes overestimated. Finally, in conclusions, some recommendations for future research are proposed.

Keywords: arch bridge, concrete, cracking, rectangular section, reinforcement, torsion.

Design Example of Bridge Pier Cap Beam Considering Torsional Effect

Yang Yang, Ruili He, and Lesley Sneed

Synopsis: A bridge pier cap beam supporting girders of two unequal spans was designed per AASTHTO LRFD Bridge Design Specifications (AASHTO LRFD BDS-17) and the ACI 318 Building Code Requirements for Structural Concrete (ACI 318-19) with consideration of torsional effect. Envelopes of bending moment, shear, and torsional moment are given in the problem statement as the result of a comprehensive structural analysis on the bridge. Flexural design is presented firstly based on the bending moment envelope to determine the required area of longitudinal reinforcement. Then shear and torsion design is presented to determine the required area of transverse reinforcement and additional longitudinal reinforcement. Based on the design calculations, the arrangement of reinforcement is illustrated in a cross-section view for the cap beam. Comparison between the two approaches is also included in terms of the equations used and areas of shear and torsion reinforcement determined.

Keywords: bridge pier cap, flexure, shear, torsion, reinforcement design, AASHTO LRFD BDS, ACI 318

TORSION DESIGN EXAMPLE: PRESTRESSED CONCRETE GIRDER BRIDGE

Kevin S. Benítez C. and Eva O. L. Lantsoght

Synopsis: The design of a cast-in-place, post-tensioned concrete, multi-cell box girder bridge under combined torsion, shear, and flexure is presented in this example. The bridge covers three spans of different lengths, supported by two abutments and two bents; its cross-section consists of three 12 ft (3.7 m) lanes, two 10 ft (3.0 m) shoulders, and two concrete barriers. The detailed procedure for the design based on ACI 318-14 is presented, and a comparison is done with the design results for: AASHTO LRFD 2017, EN 1992-1-1:2004, and MC-2010. With this example, the authors illustrate the differences between provisions of the aforementioned codes for design of torsional effects, outlining the different theories and approaches used for each of these.

Keywords: box girder bridges; prestressed concrete; shear; torsion.

Torsion Design Example: Inverted Tee Bent Cap

Camilo Granda Valencia and Eva Lantsoght

Synopsis: This paper provides a practical example of the torsion design of an inverted tee bent cap of a three-span bridge. A full torsional design following the guidelines of the ACI 318-19 building code is carried out and the results are compared with the outcomes from CSA-A23.3-04, AASHTO-LRFD-17, and EN 1992-1-1:2004 codes. Then, a summary of the detailing of the cross-section considering the reinforcement requirements is presented. The objective of this paper is to illustrate the application of ACI 318-19 when designing a structural element subjected to large torsional moments.

Keywords: bridge, codes, concrete, design, inverted tee bent cap, reinforcement, shear, torsion

DESIGN OF A GRADE BEAM TO RESIST TORSION DUE TO WIND LOADING ON CMU WALL

Gary G. Greene, Jr. and David L. Hartmann

Synopsis: The Joint ACI-ASCE Committee 445 published a document titled *Report on Torsion in Structural Concrete* that contained an in-depth review of historical theory development, design models, and simplified design procedures for the effect of torsion in concrete structures. That document contained three design examples that were relatively simple. An important goal of this ACI Special Publication is to provide more realistic design examples that are usable by design professionals. This paper satisfies that goal by showing a detailed solution to a realistic example that has been encountered on several occasions by one of the authors. Another goal of the ACI Special Publication is to show applications where torsion is combined with flexure and shear. In this example, the torsional effects are combined with biaxial flexure and biaxial shear forces. This example includes a check of the new provisions in ACI 318-19 for bi-axial shear effects.

This paper shows a detailed solution for the design of a reinforced concrete grade beam subjected to torsional effects combined with biaxial shear and biaxial flexure. The grade beam is a portion of a structural screen wall system. A $25\ psf$ $(1.20\ kPa)$ strength level wind pressure acts on a $20\ ft$ $(6.10\ m)$ tall CMU wall supported by a continuous grade beam. The $21\ in$ $(533\ mm)$ wide by $18\ in$ $(457\ mm)$ deep grade beam is isolated from an expansive soil and is supported by drilled shafts $21\ ft$ $(6.40\ m)$ on center. The wind load and gravity loads induce torsion, biaxial bending moments, and biaxial shear forces in the grade beam. This example shows how to calculate the internal forces in the grade beam at the critical section and design the required longitudinal and shear reinforcement according to the ACI 318-19 code.

The design of the grade beam includes closed stirrups of #4 (Ø 12) bars spaced at $5.5\ in$ $(140\ mm)$, five #8 (Ø 25) bars used near the top and bottom faces and one #6 (Ø 16) bar used at mid-height near the side faces.

Keywords: grade beam; reinforced concrete; shear; torsion.

DESIGN OF A CANTILEVER CANOPY AND ITS SUPPORTING BEAM FOR A SPORT STADIUM

Thomas T. C. Hsu and Yagiz Oz

Synopsis: This paper presents the design of a cantilever canopy and its supporting beam for a sport stadium. The reinforced concrete beam is analyzed and designed under the effects of shear load, bending moment, and torsion. The design was carried out following the American Concrete Institute's most recent standard (ACI 318-19). When there is torsion on reinforced concrete sections, the design steps become more complicated. The formula to design and the minimum requirements for both the longitudinal and transverse bars are changed since the torsion is included. The design of flexural longitudinal bars is not affected from torsion however, there are needed more longitudinal bars against torsion which affect the spacing and the detailing of longitudinal bars. For transverse bars, when the torsion is considered, the stirrups are designed as the sum of transverse and shear requirement. The main focus of the paper is to show the design steps and detailing of structural concrete elements under the effect of torsional moment.

Keywords: beams; reinforced concrete design; shear; torsion