

ACI ITG-9R-16

Report on Design of Concrete Wind Turbine Towers

Reported by ACI Innovation Task Group 9



American Concrete Institute
Always advancing



Report on Design of Concrete Wind Turbine Towers

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 <http://concrete.org/Publications/DocumentErrata.aspx>. 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
Phone: +1.248.848.3700
Fax: +1.248.848.3701

www.concrete.org

Report on Design of Concrete Wind Turbine Towers

Reported by ACI Innovation Task Group 9

Charles S. Hanskat, Chair

Roger J. Becker
Rick Damiani
Charles W. Dolan*

Neil M. Hawkins
Kevin L. Kirkley
Gary J. Klein

Nina Kristeva
Dan A. Kuchma*
James D. Lockwood

Kirk B. Morgan*
Markus Wernli

*Principal authors.

This report examines the benefits of the design of concrete towers for land-based wind turbines with heights in excess of 325 ft (100 m), in comparison to those of round steel tubular towers. These benefits include reduced cost, increased stiffness, and superior service life performance. Construction alternatives, design criteria, design methodologies, and guidance for preliminary design of concrete towers are presented.

The report recognizes that final tower design requires close coordination with the turbine supplier. The report is intended for those involved in developing preliminary tower designs. Concrete towers designed for maximum wind forces can be satisfactory for preliminary design, but the final design requires checking for all loads, especially fatigue and dynamic effects from wind and turbine operations. Design of connections and their proportions require an understanding of fatigue requirements during preliminary design for the connection design to remain valid during final checks.

Keywords: concrete tower; full-height tower; hybrid tower; precast elements; prestressing; slipformed; spread footings; turbine; wind; wind farm.

CONTENTS

CHAPTER 1—INTRODUCTION, p. 2

- 1.1—Introduction, p. 2
- 1.2—Scope, p. 3

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 2—NOTATION AND DEFINITIONS, p. 3

- 2.1—Notation, p. 3
- 2.2—Definitions, p. 3

CHAPTER 3—WIND FARM DEVELOPMENT AND TOWER SUPPLY CHAIN, p. 3

- 3.1—Introduction, p. 3
- 3.2—Certification and design, p. 5

CHAPTER 4—CONCRETE TOWER TYPES, p. 6

- 4.1—Hybrid concrete towers, p. 6
- 4.2—Full-height concrete towers, p. 6
- 4.3—Construction types, p. 6
- 4.4—Construction considerations, p. 8
- 4.5—Tolerances, p. 9
- 4.6—Tower size and cost, p. 9

CHAPTER 5—TOWER DESIGN, p. 11

- 5.1—Tower frequency design, p. 11
- 5.2—Service level design, p. 12
- 5.3—Prestressing, p. 13
- 5.4—Modeling, p. 13
- 5.5—Fatigue, p. 15
- 5.6—Preliminary design guidance, p. 15

CHAPTER 6—DESIGN LOADS AND LOAD COMBINATIONS, p. 15

- 6.1—Loads and load combinations, p. 16
- 6.2—Load factors, p. 17

CHAPTER 7—DESIGN LOADS, p. 17

- 7.1—Basic weights and loads, p. 17
- 7.2—Wind profile, p. 18
- 7.3—Earthquake loads, p. 18

ACI ITG-9R-16 was adopted and published October 2016.

Copyright © 2016, 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.

- 7.4—Normal operating fatigue loads, p. 18
- 7.5—Temperature loads, p. 18
- 7.6—Abnormal operating conditions, p. 18

CHAPTER 8—CONCRETE RESISTANCE, p. 19

- 8.1—Strength design, p. 19
- 8.2—Serviceability design, p. 19
- 8.3—Joints and connections, p. 19

CHAPTER 9—FOUNDATION DESIGN, p. 19

- 9.1—Rock anchor foundations, p. 19
- 9.2—Pier-type deep foundations, p. 20
- 9.3—Spread footings, p. 20
- 9.4—Termination of reinforcement and prestress, p. 22
- 9.5—Tower-foundation structural integrity, p. 22

CHAPTER 10—CONCLUSION AND RECOMMENDATIONS, p. 22

CHAPTER 11—REFERENCES, p. 23

- Authored documents, p. 23

CHAPTER 1—INTRODUCTION

1.1—Introduction

Towers for wind turbines in North America typically have been constructed of steel and are of the round tubular types, although early towers for kW-rated turbines included lattice-type truss structures. Lattice tower designs are undergoing resurgence for multi-MW turbines, as the tubular towers have reached their shipping limitations. Steel has offered the industry several economic and production advantages for towers less than 325 ft (100 m) tall. Steel towers can be prefabricated, readily transported over existing highways, and efficiently erected on the wind farm site. Whereas concrete towers are widely used in Europe, many wind farm designers in North America have not considered concrete towers due to several perceived limitations, including the lack of:

- (a) Understanding the length of time to construct concrete towers
- (b) Familiarity with the fatigue properties of concrete
- (c) Industry standards for concrete tower design
- (d) Historical cost data

To address these concerns, this report describes the advantages and options for concrete towers greater than 325 ft (100 m) in height.

Figure 1.1 illustrates a tower and highlights several key terms used in this report. The tower height is measured from the foundation interface to the mounting ring. A yaw bearing, which permits the horizontal rotation of the turbine, attaches to the mounting ring. The turbine and main bearing shaft are located in the nacelle, which is attached to the yaw bearing. The blades are attached to the main bearing shaft and, for tower design purposes, are included in the nacelle weight. The hub height is measured from the top of the foundation to the center of the main bearing shaft. The swept area of the

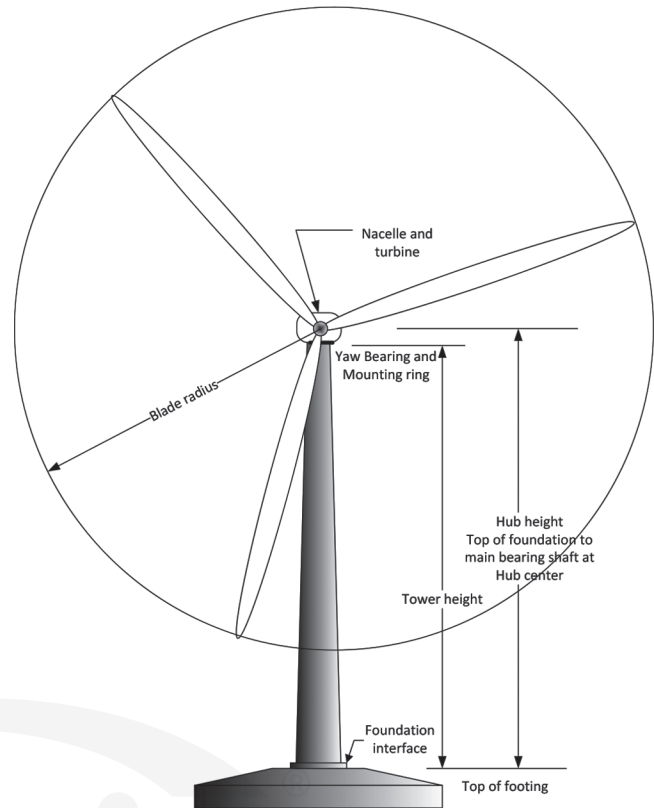


Fig. 1.1—Wind turbine tower.

blade is a circle based on the blade radius. Additional details of the top of the tower are given in [Chapter 4](#).

As the wind turbine power levels increase above 2.5 MW, the towers needed to support the turbines are exceeding 325 ft (100 m) in height. In moderate wind areas, such as the southeastern United States, taller towers are beneficial for 1 to 2.5 MW turbines to capitalize on the more desirable wind patterns. For turbines in the 5 to 10 MW range, turbines using a 325 ft (100 m) or larger rotor diameter are now under development. Towers for these turbines would exceed 325 ft (100 m) in height to the nacelle mounting ring interface. At this height, several of the advantages of the current steel towers are lost due to their larger size, their lower stiffness, and the necessity for on-site completion. Under these conditions, concrete towers become practicable alternatives and economically attractive. According to [Engström et al. \(2010\)](#), using a hub height of 410 ft (125 m), it is possible to save up to 30 percent of the tower cost by selecting a technology other than the conventional welded steel tower. Lattice towers and wooden towers were determined to be economical. [Engström et al. \(2010\)](#) concluded that there are several interesting tower alternatives worthy of further development, including steel towers with slip critical joints, concrete, hybrid concrete/steel, wood, and lattice construction. [Umut et al. \(2011\)](#) point out that as the height of the tower increases, the stiffness demands become critical. Concrete towers have greater ability than steel to adjust stiffness to meet the performance requirements of the original equipment manufacturer (OEM) suppliers.

1.2—Scope

All references to turbine technology in this report are limited to horizontal axis turbines of the upwind, three-blade variety. Other variants of the horizontal axis turbines, such as the two-blade and down-wind blade orientation, have advantages and disadvantages in the categories of dynamic loads and blade/tower interference, but they are not addressed in this report. Refer to Wind Vision 2015 (U.S. Department of Energy 2015) for more information regarding horizontal axis turbines. This report is primarily for land-based towers, although reference is made to offshore towers when those data are applicable.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

E_c	=	modulus of elasticity of concrete, lb/in. ² (Pa)
E_{sec}	=	secant modulus of elasticity of concrete, lb/in. ² (Pa)
f_{cmax}	=	maximum stress in the concrete stress-strain curve occurring at ϵ_0 , lb/in. ² (Pa)
k	=	parameter based on modulus of elasticity and strain conditions
n	=	ratio of actual strain-to-strain at maximum stress
V_{hub}	=	velocity of wind at height of hub, mph (km/h)
V_{in}	=	cut-in wind speed; lowest wind speed at the hub height at which the wind turbine starts to produce power in the case of a steady wind without turbulence
V_{out}	=	cut-out wind speed; highest wind speed at the hub height at which the wind turbine is designed to produce power in a steady wind without turbulence
V_p	=	wind speed for power generation of the turbine, mph (km/h)
V_{ref}	=	reference or design wind speed for the turbine, mph (km/h)
W_i	=	weight of segment i , lb (N)
y_i	=	lateral deflection of a segment, ft (m)
z	=	height above ground level, ft (m)
ϵ_0	=	strain in concrete corresponding to maximum stress
ϵ_c	=	strain in concrete
ϵ_{cu}	=	maximum concrete strain
ω	=	tower natural frequency, 1/s

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology (CT-16),” <https://www.concrete.org/store/productdetail.aspx?ItemID=CT16>.

CHAPTER 3—WIND FARM DEVELOPMENT AND TOWER SUPPLY CHAIN

3.1—Introduction

3.1.1 Wind farm development—A wind farm consists of several wind turbines distributed over a large area (Fig. 3.1.1a). Because the visual impact and land requirements are significant, the development of a wind farm is complex and often requires considerable public input. Figure 3.1.1b presents



Fig. 3.1.1a—Typical row of turbines in a wind farm and their access road, Arlington, WY.

a simplified schematic of wind farm development that is typical of the hub heights of wind farms erected in the United States. Although the schematic suggests linear development, interaction between the developer, turbine original equipment manufacturer (OEM), tower designer, contractor, and other parties is more complex. For example, some site evaluations, such as wind profiles, are ongoing activities that are simultaneous with obtaining the final project funding.

A licensed design professional (LDP) for wind farms may have one of many roles, including tower design for the OEM supplier, independent engineer, or tower designer for the contractor. Each role varies by project and the time the engineering service is required. A tower design LDP may enter the project early or late, depending on the OEM background with concrete tower design. An independent engineer LDP may be retained during the finding process or by the certification agency to validate the design. The independent engineer certification role is shown as a dashed line in Fig. 3.1.1b for early involvement and a solid line as part of final approval. If the towers are procured on a design-build basis, the tower design LDP may work directly for the contractor.

The towers are typically provided under the turbine OEM contract and are not within the scope of the LDPs retained for the project. The towers, however, are a significant part of the project cost and, therefore, could require input at the evaluation stage of the project, particularly with higher hub heights.

Early identification of the tower type and construction method may offer more economical solutions than inferred in the flowchart, and may be essential for developing a reliable cost basis for the project. For current typical hub heights of 260 to 360 ft (80 to 110 m), the towers usually run approximately 10 percent of the total cost. For taller wind turbines, however, that percentage could approach 30 percent. If design-build options are under consideration, the necessary feedback among the developer, contractor, turbine OEM, and tower designer is not reflected in Fig. 3.1.1b.