Report on Design of Concrete Wind Turbine Towers

Reported by ACI Innovation Task Group 9

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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

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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 blade is a circle based on the blade radius. Additional details of the top of the tower are given in Chapter 4.

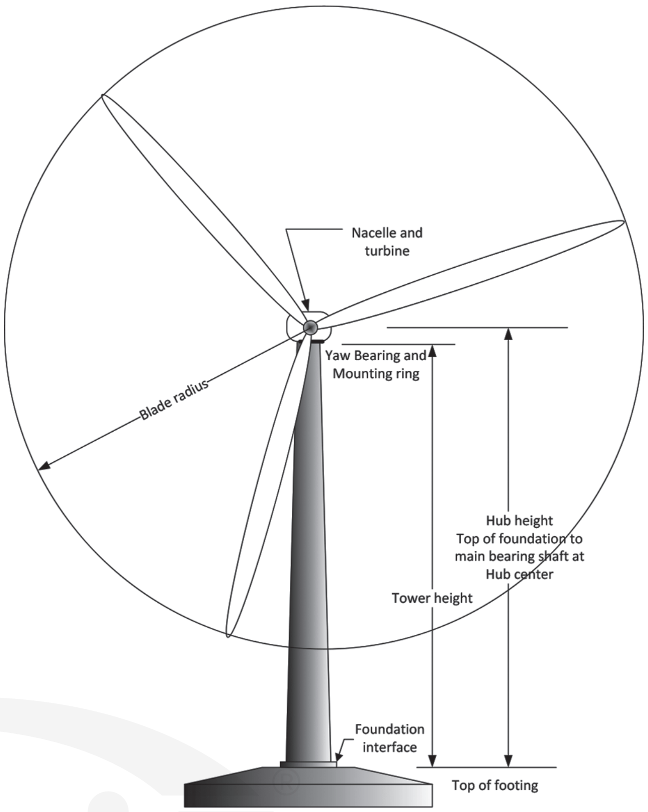

Fig. 1.1—Wind turbine tower.

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 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.

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

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.

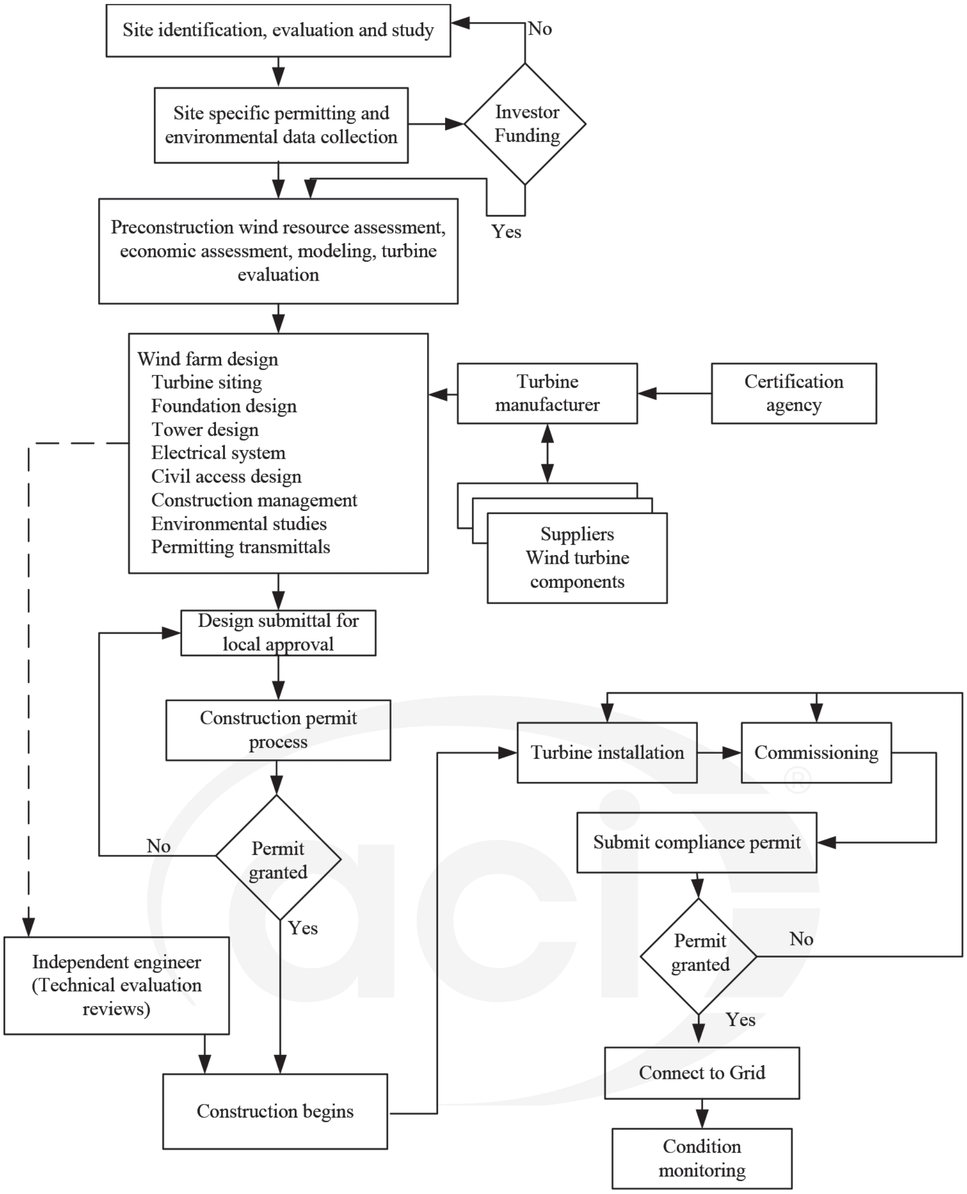

Fig. 3.1.1b—Schematic of wind farm development (adapted from ASCE/AWEA RP2011).

In this report, development of a wind farm is reduced to two broadly defined steps. The first is site selection and approval; the second is design and certification. As indicated previously, concrete tower designs are likely to be an integral element to each step of development. This report assumes that final design of the concrete wind turbine towers will include detailed interaction among the wind farm developer, contractor, and turbine manufacturer.

3.1.2 *Site approval*—Site approval agencies vary by location in the United States. For example, an offshore wind farm project in Delaware was approved by the Delaware Public Utility Commission. In Wyoming, the site approval on federal lands is largely under the jurisdiction of the Bureau of Land Management. Major tasks such as environmental impact statements, public input, and establishment of design criteria vary accordingly. Participation by tower suppliers at these early stages can provide credibility to feasibility of the project.

The appearance of wind turbines and their towers at any given site is usually subject to review and public input. Turbine OEM and their tower suppliers should be involved in the site selection and approval process when turbine and tower appearances are different from more common generic designs.

Higher foundation loads imparted by larger turbines on taller towers can also be expected to magnify the importance of site selection relative to geotechnical conditions. The approval of turbine support structures will vary by region in the United States due to the absence of minimum standards for fatigue design of reinforced concrete, as well as a relatively limited body of design guides and standards for wind turbine generator systems (WTGSs). Regional variations between sites may require input from tower designers to assist local authority's decision making as project approvals are obtained.