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Report on Design of Concrete Wind Turbine Towers

Reported by ACI Innovation Task Group 9



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Report on Design of Concrete Wind Turbine Towers

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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.

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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

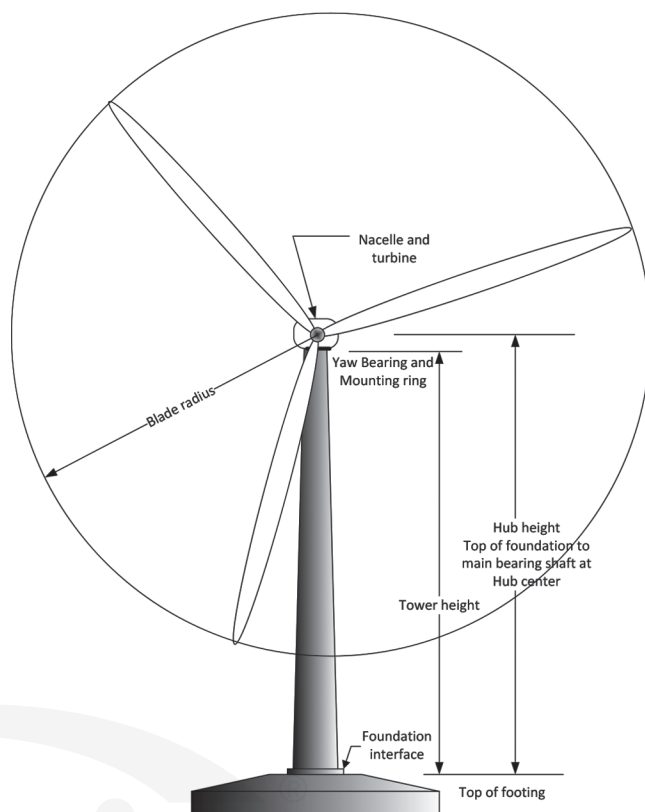


Fig. 1.1—Wind turbine tower.

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.

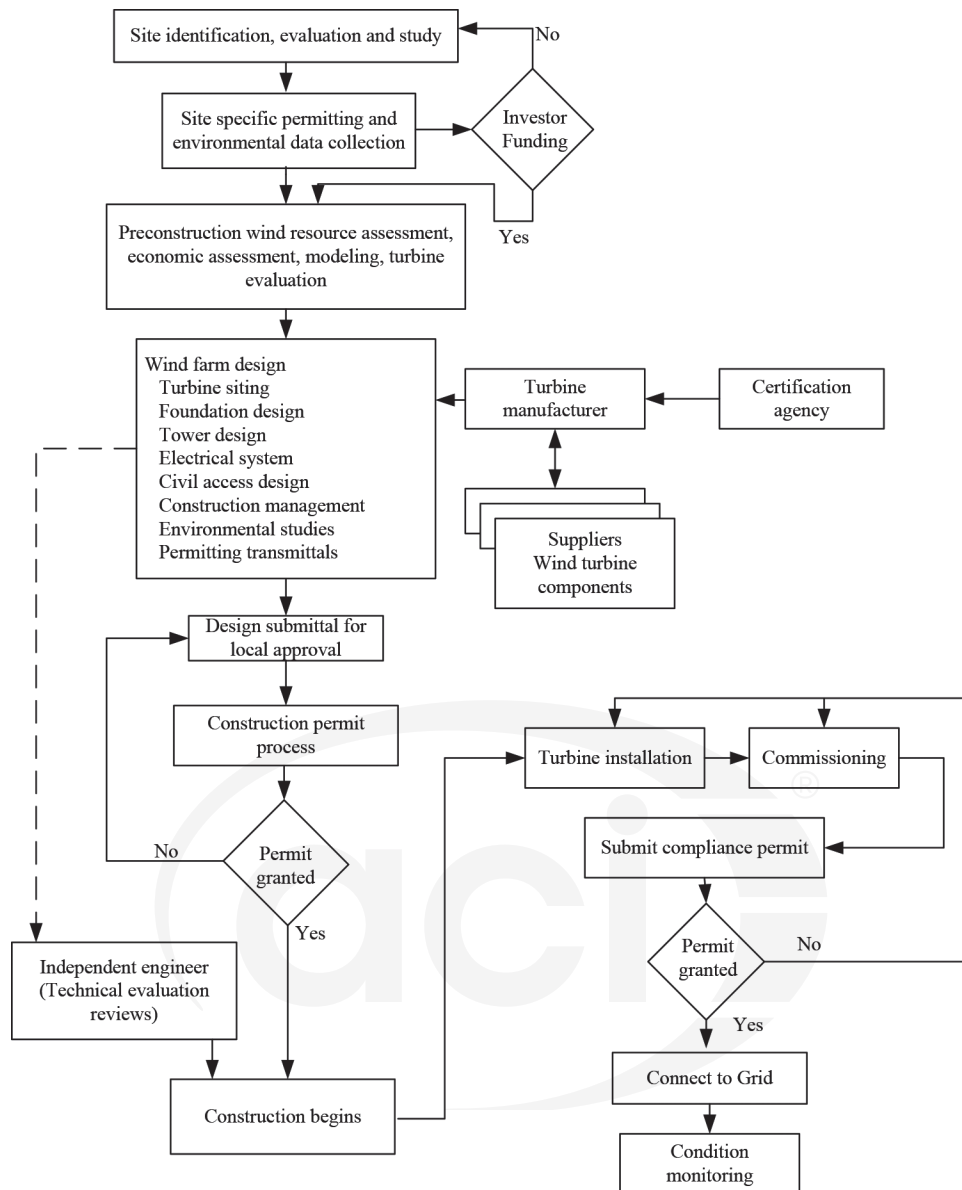


Fig. 3.1.1b—Schematic of wind farm development (adapted from ASCE/AWEA RP2011).

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.

3.2—Certification and design

3.2.1 Certification—[ASCE/AWEA RP2011](#) and [IEC 61400-1](#) refer to the certification process for wind farms. Certification involves design review, prototyping, and production quality management during serial production. Certification is carried out by independent bodies that are accredited by their national governments and mutually recognized worldwide. The process culminates in issuance of a type certificate specifying the item in question and the normative standards against which that item was evaluated. European examples of certification bodies include DNV-GL, Bureau Veritas, TÜV SÜD, and TÜV NORD, with the latter two having branches in the United States. Although the United States lacks a uniform national certification process for wind turbine generator systems (WTGSs), UL, a global independent safety science company, and the American Bureau of Shipping (ABS), a provider of classification services to the global marine and offshore industries, have become involved with wind fields in recent years. Certification of the tower and turbine components is normally required worldwide for project insurance, bonding, and overall project confidence. WTGS certification centers on a turbine mounted on a particular tower. Turbine original equipment manufacturers (OEMs) develop and certify turbines and towers for certain wind conditions. In the case of offshore projects, certification of the entire project will be required due to varying water depth and sea states.

Independent engineers, as indicated in Fig. 3.1.1b, play a similar role as the certification bodies previously defined, but with some important differences, particularly in the scope of their review. Some certification bodies are affiliated or joined with independent engineers, although the two entities are not interchangeable. Independent engineering review is normally a requirement of financial partners on larger projects for technical due diligence and risk management. Smaller projects often do not involve independent engineers. Independent engineers are normally requested to issue certification statements at the time of project commissioning or financial closing, although this differs from that of the accredited certification bodies previously discussed.

While towers are normally certified for specific turbines, foundations in the United States have typically not been certified. Foundations are site-specific and their design, through a simplified specification of dynamic requirements (stiffness), can be easily separated from the more iterative design for the dynamics of the tower and turbine. Historically these have been very simple specifications just requiring rotational and horizontal stiffness at the base of the tower. On large projects, therefore, independent engineers are commonly asked to review foundation designs and other project facility components. However, towers are less easily divorced from the system dynamic design requirements, and market norms in the United States have grown in a way that reflects this by excluding independent engineers from tower design reviews, relying instead on the turbine OEM certification process. One aspect common to both towers and foundations in the United States, however, is the legal- and insurance-based need for sealed drawings stamped by the licensed design professional

(LDP). The core mission of [ASCE/AWEA RP2011](#) is to aid authorities having jurisdiction in the assessment of the work of the LDP with regard to WTGSs.

Designs should be prepared so that the certification bodies or independent engineers can validate the designs in a predictable way. Designers and producers of concrete towers in the United States should recognize how to interface with the market with respect to certification and independent engineering. Figure 3.1.1b highlights some of the interactions that may be required. Producers should understand the relevant standards, modeling practices, as well as the responsibilities of the turbine OEM, tower designer, and contractor so if they are to be included in site selection, preliminary design, and independent validation. Early engagement with a particular certification body may prove critical to the commercialization of any given tower product. Additional guidelines for certification are given by [Germanischer Lloyd Industrial Services GmbH \(2010\)](#).

3.2.2 Design—This report identifies commonly used design specifications. Tower design is greatly affected by the overall design criteria. Final selection of design criteria occurs in the site approval and certification process. This selection can be under the direction of the authority having jurisdiction or in coordination with the certification agency.

Major design standards include [ASCE/SEI 7](#), [ACI 318](#), [IEC 61400-1](#), and [ASCE/AWEA RP2011](#). The International Electrotechnical Commission (IEC) standard, [IEC 61400-1](#), is the most widely cited international standard for large-scale wind turbines. [ASCE/SEI 7](#) and [ACI 318](#) provide loads and nominal strength for towers and are calibrated so the loads, load combinations, load factors, and strength reduction factors are consistent between documents. Provisions in [IEC 61400-1](#) may conflict with both [ASCE/SEI 7](#) and [ACI 318](#), making it an important step in the tower preliminary design process to resolve conflicts and develop unified design criteria. An upcoming international standard in development, [IEC 61400-6](#), will include considerations for steel and concrete towers, as well as gravity-based and rock-anchor foundations. Technical annexes to the IEC documents compare differences in national and regional design standards.

[ASCE/AWEA RP2011](#) does attempt to address the conflict between [ASCE/SEI 7](#) and [ACI 318](#), and [IEC 61400-1](#). [ASCE/AWEA RP2011](#) documents how the shore-based wind industry in the United States has attempted to reconcile the relevant international standards and local codes. [ASCE/AWEA RP2011-11](#) highlights several key issues affecting the design of wind turbine towers. They are summarized in the following:

(a) The Recommended Practice section applies to only fabricated circular steel towers and may be extended to 24-sided polygonal steel towers based on the engineer's judgement.

(b) Steel lattice or space frame towers are excluded from the Recommended Practice section.

(c) Local building codes are not sufficiently specialized for WTGS tower design.



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(d) Even though local building codes may not be sufficient for WTGS tower design, the certification agency may require that their requirements be satisfied.

(e) Where a proven tower design already exists in service and the tower was designed in accordance with existing certification agency guidelines, a limited design assessment or plan review to show compliance with the local building code may be considered sufficient.

(f) Any less stringent standard in the local building code should not undercut or violate the certification agency guidelines.

(g) It is the owner's or client's responsibility to determine the effect of local building code compliance on the conditions of commercial certification.

CHAPTER 4—CONCRETE TOWER TYPES

Concrete towers are divided into two categories: hybrid and full-height. Although the definition of each category is somewhat arbitrary, it reflects the difference in both design and connection locations with the wind turbine. All wind turbine towers require steel components at the top of the tower to form a mounting ring that supports the nacelle at the level of the yaw bearing. When the steel interface height becomes more than a connection, the tower can be considered a hybrid. A concrete tower extending from the foundation to the mounting ring is considered a full-height concrete tower.

Apart from material and design limitations, selection of concrete tower type will be strongly influenced by crane capacity and economics at the given project location. Long crane idle time is generally a target for cost reduction for wind farm contractors.

Concrete tower shapes may range from round-form to panel- and column-frame-based systems. To control wind-induced vibrations, some towers have been produced with a large volume of concrete at the top of the tower in the manner of a tuned mass. The wide variety of shapes possible in concrete, notwithstanding the selection of full-height or hybrid towers, results in differences in construction procedures for towers for each project. The ability to select an optimum shape will have a positive impact on the efficiencies gained in an industry that has grown accustomed to round steel towers with bolted flange connections.

4.1—Hybrid concrete towers

Hybrid concrete towers consist of a concrete tower base with a steel tower installed on top, which in turn supports the turbine, as shown in Fig. 4.1. Hybrid tower systems are typically designed to optimize the economics of the steel tower portion for off-site fabrication and on-site erection. The concrete tower provides the additional height. The design elements in this report are applicable to the design of the concrete portion of a hybrid tower. Engström et al. (2010) suggest that for a 410 ft (125 m) tower, a 160 ft (50 m) steel tower could be mated to a 250 ft (75 m) concrete tower. The literature refers to concrete base element as a concrete tower or a concrete pedestal interchangeably.

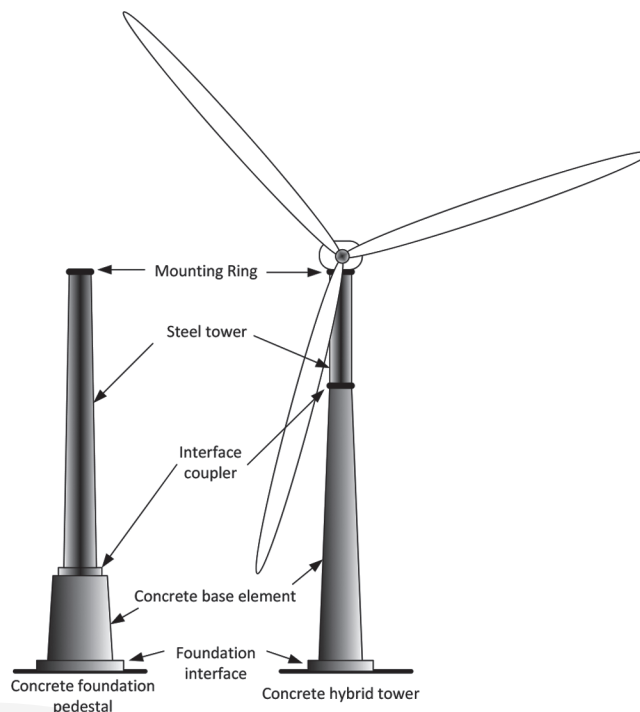


Fig. 4.1—Hybrid concrete tower system.

4.2—Full-height concrete towers

Full-height concrete towers are connected to the foundation and rise to the mounting ring. The tower hub height is given as the height from the top of the foundation to the main bearing axis, as shown in Fig. 1.1. The height of the concrete tower is to the mounting ring. For constructed tower heights of 328 to 492 ft (100 to 150 m), the base diameter of the tower is between 26 and 33 ft (8 and 10 m). The diameter at the mounting ring is between 9 to 16 ft (3 to 5 m). It is common to need a base diameter of 20 to 23 ft (6 to 7 m) for a 328 ft (100 m) tower with reference to turbines in the 2 to 3 MW range. The maximum dimension plays a major role in the segmentation, transportation, and assembly costs in the lower portions of the tower. Load eccentricities for a 5 MW turbine are given in Fig. 4.2.

4.3—Construction types

A number of different techniques are available for the construction of concrete towers. The examples that follow are based on current or proposed use. Specialty structures, such as wind turbine towers, can be procured on a design-build basis, where the contractor and their engineer work directly with the wind farm developer to provide a structure that meets project requirements. This arrangement allows for creativity and maximum productivity for meeting project schedules and budget constraints. Time estimates given in the following may be shortened when an optimal design and construction process is selected.

Four construction types are presented: precast concrete; cast-in-place concrete; shotcrete; and spin-cast concrete. All concrete towers discussed in this report are assumed to be prestressed (pretensioned, post-tensioned, or both), as

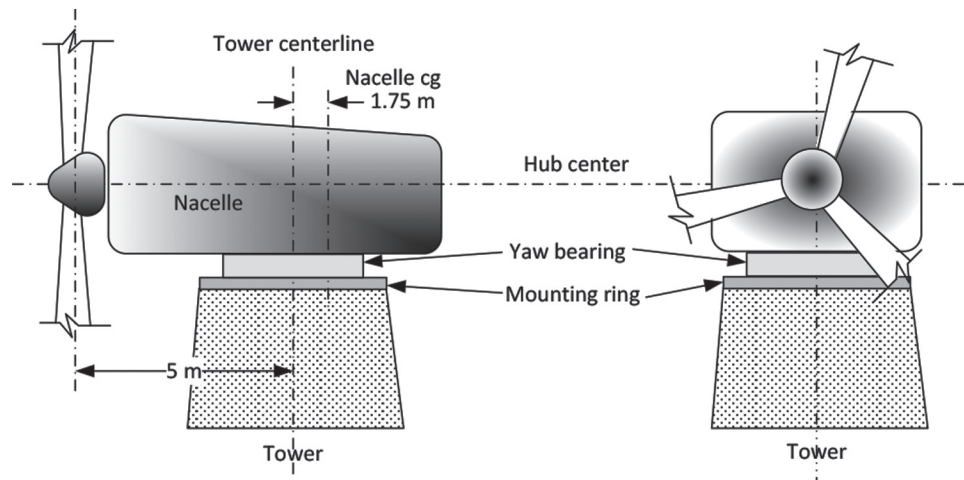


Fig. 4.2—Turbine-tower interface (5 MW). (Note: 1 m = 3.3 ft.)

prestress is usually necessary to satisfy service and fatigue requirements.

4.3.1 Precast concrete systems—Precast elements are manufactured in advance of their placement onsite. Their fabrication, therefore, can be initiated shortly after the site contract is agreed to and may proceed while site preparation and foundation construction is under way. Precast elements can be either complete annular sections (Fig. 4.3.1(a)) or shell corner elements making up a portion of the tower, with variable width panels elements as shown for the advanced tower systems (Fig. 4.3.1(b)). The tower systems in Fig. 4.3.1(a) and (b) involve patented technology. Element size is coordinated with the crane size required for the project, with smaller pieces brought in for smaller lifting equipment and vice versa for larger pieces.

The size of the precast element also affects where they are fabricated. If large elements are precast, the entire precast operation can be moved onto the wind farm site to avoid over-highway transportation. This implies that site quality control equivalent to that of plant operations is also transferred. Economic consideration with precasting will be affected by the number of casting forms required to meet the construction schedule. Early initiation of precast contracts requires fewer forms and more reuses. A shorter construction schedule may require duplicate sets of forms and, therefore, higher mobilization costs.

As an example, one precast system has been used to construct 440 ft (135 m) hub height towers using 35 precast segments. The base diameter of these towers is 48 ft (14.5 m); the circular segments were split in half to facilitate shipping. The top five segments were complete rings (Grünberg and Göhlmann 2013).

Erection times for 440 ft (135 m) precast towers are estimated at 3 days per tower, assuming all components are onsite and readily available. The total wind farm construction time is attributable to the availability of casting beds and cranes.

4.3.2 Cast-in-place systems—Two conventional cast-in-place options can be applied to tower construction: jump forms and slipforming. Cast-in-place construction requires



(a) Circular elements



(b) Advanced tower systems

Fig. 4.3.1—Precast concrete elements (photos courtesy of: (a) Tindall Corporation; and (b) Renewable Energy World).