CODES AND STANDARDS

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Wind Farm Tower Design

Introducing ASCE/AWEA RP2011

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In the *CASE Business Practices* article titled, "Too Many Codes Spoil the Design? Conflicts and Hidden Requirements Can Hurt You!" published in the September 2012 issue of STRUCTURE® magazine, Kirk A. Haverland wrote about a topic familiar to US engineers in the wind energy industry. Mr. Haverland describes the situation where a professional structural engineer "if presented with the opportunity to design a structure that is a little different" hopefully should be able to do his homework and "research the idiosyncrasies of industry practice, design requirements, different codes and standards, etc." The piece further describes a problematic scenario where the building code (i.e., "Code" based on 2009 IBC and ASCE 7-05) may not necessarily govern the design. That is, various reference standards are in conflict, and design may be governed by undocumented and un-codified information known only to those engineers "in the know." Unfortunately, this accurately describes the situation faced by US engineers trying to engage in wind turbine support structure analysis, design and permitting.

The primary difficulty is the lack of a dedicated wind turbine generator system (WTGS) support structure design standard. The US wind industry has been developing utility-scale wind farms for over three decades, and yet in that time there has been no clear guidance in the US for the design and permitting of WTGS support structures. The domestic wind industry utilizes foreign design standards used by the European wind turbine original equipment manufacturers (OEM) who had initially dominated the global wind energy market.

Introducing RP2011

In the absence of specific domestic design guidelines or standards, demonstrating Code compliance has been a challenge. In 2009, the American Society of Civil Engineers (ASCE) and the American Wind Energy Association (AWEA) formed a joint committee to provide US design guidance. This article introduces one of the results of that effort: a new reference document for the analysis, design and permitting of utility-scale wind farm towers titled *ASCE/AWEA RP2011: Recommended Practice for Compliance of Large Land-based Wind Turbine Support Structures* (*Figure 1*). RP2011 is a resource for structural engineers engaged in utility-scale wind farm tower design or permitting. The recommended practices are intended to help engineers establish an appropriate design basis for producing tower and foundation designs that meet established wind industry standards and that comply with Code. RP2011 is also intended to assist Authorities Having Jurisdiction (AHJ) who are responsible for permit process plan review of WTGS towers and foundations. RP2011 is available as a free download at the AWEA website: **www.awea.org**.

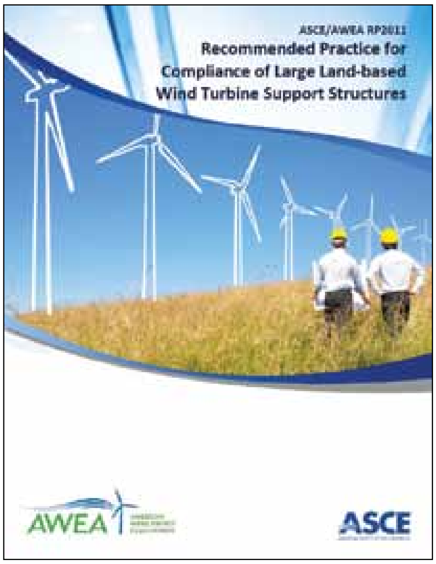

Figure 1: ASCE/AWEA Recommended Practice for Compliance of Large Land-based Wind Turbine Support Structures (ASCE/AWEA RP2011) © The American Wind Energy Association.

As an example, this article will describe some of the major idiosyncrasies of wind industry structural design practice for WTGS steel fabricated tube towers. Applying conventional Code provisions alone as a design basis would likely result in an under-designed structure. Similarly, applying Code provisions alone for plan review compliance would be too permissive and give a "pass" to that same under-designed structure. It has been argued that the Code is a minimum standard for compliance and that the wind industry is free to meet a higher standard. Unfortunately, that argument is misapplied, since the Code minimum standard does not capture the correct governing structural design basis in terms of loading, WTGS behavior, and industry norms.

The Tower

The steel fabricated tube tower is currently the most typical structure type in use in the domestic and international utility-scale wind industries. While WTGS machine components may fail and be repaired or replaced through maintenance, the tower support structure must perform more reliably and without failure (*Figure 2*). At this time, RP2011 addresses only this tower structure type. To most engineers and others who are wind industry outsiders, the tube tower appears to be a simple structure. In reality, structural engineers "in the know" understand that the simple appearance belies the inherent design complexities.

Primary Design Issues

Wind Design

Typical application of the Code's wind provisions would entail ASCE 7's Section 6.5 *Method 2 – Analytical Procedure*. However, this loading may not be the governing wind loading for the WTGS tower. In fact, the Code's extreme wind (1-in-50 year, 3-second gust) represents only one of many design load combinations (DLC) considered by the wind industry standard IEC 61400-1 published by the International Electrotechnical Commission (IEC). While the Code's extreme wind may result in high design forces, the turbine OEM's loads may contain other DLCs that produce *even higher* design loads that have no parallel in the Code, such as "turbine emergency stop" or "extreme annual operating gust plus electrical fault." Code loading alone may be insufficient for WTGS tower design. Complete IEC WTGS design loading is obtained from a complex time series simulation, modeling the turbine's proprietary aerodynamic, mechanical and physical properties. This analysis is usually performed by the turbine OEM's specialists who compile the design loading into a comprehensive "loads document." RP2011 Sections 5.4.8 and 5.4.9 provide strategies for reconciling building Code wind design loading with IEC site class extreme loading and recommends appropriate ASCE 7 design parameter values. Section 13 provides guidance on understanding the turbine OEM's loads document. Section 14 also discusses the differences in wind speed and turbulence intensity profiles between ASCE 7-05 and that of the IEC standard wind site class definitions.

Earthquake Design

Applying Code seismic provisions is immediately problematic because a steel fabricated tube WTGS support structure does not appear in ASCE 7-05 Table 15.4-2, *Seismic Coefficients for Nonbuilding Structures not Similar to Buildings*. Faced with this, the engineer may use engineering judgment to apply the *R* factor for a similar structure: perhaps a steel stack with *R*=3, an inverted pendulum with *R*=2; or a steel pole telecommunications tower with *R*=1.5. Note that "all other self-supporting structures …" with *R*=1.25 has a 50 feet height limitation in *SDC D* and greater, which would be too short for utility-scale towers. This is a reasonable approach, but there are other considerations. Virtually all utility-scale WTGS towers are thin-shell steel tubes whose design strength is governed by the limit state of local buckling and, therefore, they have very low ductility and little overstrength. Moreover, there are other unfavorable characteristics: the tower is a single member with no redundancy; the system is top heavy with the wind turbine concentrating up to one-half of the total system mass at the tower top; and, the tower itself has very little inherent structural damping. Finally, the Code earthquake load combinations do not capture the wind industry's governing earthquake load combination.

Figure 2: WTGS with steel fabricated tube tower. Courtesy of Rolando Vega.

RP2011 Section 5.4.4.5 recommends the consideration of two earthquake loading conditions:

- IBC-compatible loading: gravity plus earthquake.
- IEC-compatible loading: gravity plus earthquake plus operational load.

For the IBC loading, RP2011 recommends *R*=1.5 along with the Code design response spectrum adjusted to a 1%-damped spectrum. The earthquake load is used in Code seismic load combinations. The wind turbine is assumed to be at standstill, so there is no effective structural damping contribution from the turbine's interaction with the wind in the form of aerodynamic damping. For this reason, RP2011 recommends adjustment of the Code's 5%-damped design response spectrum to a level of 1% damping, resulting in an increase in spectral ordinates by a factor of about 1.4.

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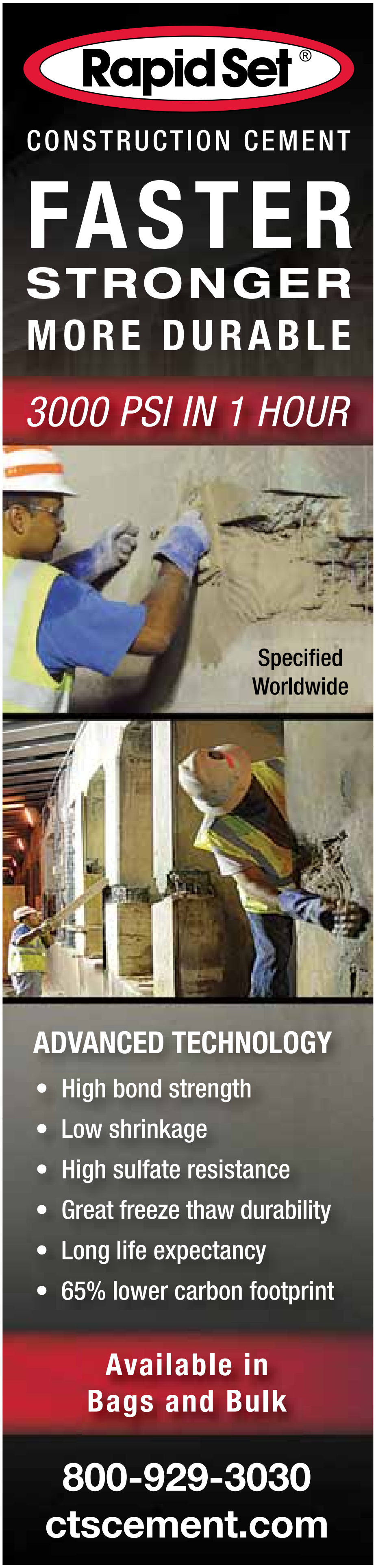

For the IEC loading, RP2011 recommends *R*=1.5 in conjunction with the IEC seismic plus operational load combination that considers the somewhat likely situation where the WTGS is operating in a power production mode when the design earthquake event strikes. In this case, the effective damping contribution from the operational turbine is considered sufficient to allow use of the Code's standard 5%-damped design response spectrum. However, the operational load of the turbine must be included. One such operational load is the "emergency stop load." In this scenario, sensors (accelerometers) within the operating turbine detect the excessive tower top motions induced by the earthquake event. The "emergency stop" protocol is triggered, engaging the rotor and yaw brakes to rapidly halt the turbine so that it can ride out the excessive tower top motions. It so happens that this creates large tower design loads.

The industry idiosyncrasies do not end here, as there are different ways to combine the earthquake and operational loads. Without an actual full-blown time series simulation, in practice the engineer separately calculates the Code's design seismic force and then combines these with the maximum operational loads provided by the turbine OEM. Recognizing that these peak loads do not necessarily occur at the same point in time nor in the same direction, RP2011 recommends a square-root-sum-of-squares (SRSS) combination. In contrast, the IEC standard suggests an absolute sum of the peak loads, but it recognizes that this is conservative.

Fatigue Design

At this stage of the design, the engineer may have applied Code wind and earthquake provisions along with the additional related IEC criteria. Nevertheless, the tower or portions of the tower may still be under-designed because fatigue may be the governing design condition. Even if the engineer were to have applied American Institute of Steel Construction (AISC) fatigue provisions, the design would still be unconservative with respect to wind industry practices. RP2011 Section 7.3.1 describes and reconciles Eurocode (EN 1993-1-9) fatigue S-N curves with the AISC (ANSI/AISC 360-05) S-N curves. Section 7.3.2 discusses the additional fatigue safety factors required by IEC that do not appear in AISC. Sections 7.3.4 and 7.3.5 introduce the Miner's Rule linear damage summation method and the fatigue damage equivalent load (DEL) concept, respectively. The point is worth repeating that fatigue often governs all or part of the WTGS tower.

Frequency Separation

Assuming all the aforementioned design calculations were performed, the engineer may assume that the tower design is complete. Unfortunately, it is still possible that the tower design may be completely unusable if it does not meet frequency separation criteria. RP2011 Section 5.4.7 states that "to avoid resonance, WTGS should be designed with sufficient separation between system natural frequencies and turbine operational frequencies." The section provides separation criteria that are in current widespread use in the wind industry practice. Adequate frequency separation is an imperative serviceability condition for WTGS. Upon start of operation, a WTGS with inadequate frequency separation will undergo large and violent back-and-forth resonant oscillations. Sensing this, modern turbines will then shut down, preventing any further power production. However, older turbines without such a detection system could reach resonant oscillations large enough to damage or fail the tower. Inadequate frequency separation is remedied during the tower design phase by thickening the tower shell or widening the overall diameter of the lower sections to stiffen the tower, thereby increasing the system mass and natural frequency.

Design for Stress Concentrations

Localized portions of the wind tower may still be under-designed. In particular, tower shell areas subject to stress concentrations, i.e., "hotspot" stresses, usually require thickening. For example, stress concentrations occur around wall penetrations such as doorways and cable openings. The wind industry utilizes specific methods of finite element analysis (FEA). RP2011 Section 7.4.2 references an International Institute of Welding (IIW) standard, which gives guidelines on FEA mesh sizes and recommended hotspot stress extrapolation functions.

Other Design Issues

Specialized Design Procedures

RP2011 Section 7.4 briefly mentions specialized design procedures used in the wind industry for the strength and fatigue design of bolted ring flanges. These bolted flange design methods (such as the "Petersen Model" or "Seidel Method," so named for their inventor) are more amenable to hand calculation in lieu of FEA.

Foundation Design

Like the tower, the WTGS foundation design has its idiosyncrasies. RP2011 Section 8.6.1.5 describes "ground gap" limitations that amount to additional overturning stability requirements. One ground gap criterion requires that under IEC DLCs such as normal power production, no ground gap (i.e., zero bearing pressure) shall occur at the foundation-soil contact. Stated differently, this means that the contact stresses under the entire foundation footprint must remain in compression. Another ground gap criterion states that under service extreme loads, the ground gap shall not extend beyond the center of gravity of the foundation bottom area. Fatigue design of a reinforced concrete foundation is atypical in conventional building design, but WTGS foundations must be designed for high-cycle fatigue loading. This includes anchor rods and non-prestressed steel reinforcement bars. RP2011 Section 8.5 mentions a few alternative international standards used in the wind industry.

The Future of RP2011

Although RP2011 is a first-of-its-kind design guidance document for WTGS support structures in the US, as a "recommended practices" document it is certainly far from being a design standard. At this time, there are two goals for RP2011's future:

(1) The first goal would be the evolution of RP2011 or its future successor document into a standard, specifically into an ANSI standard to give the document credibility in the structural engineering community. Next would be an effort to achieve the status of a "code referenced standard" in future editions of the IBC. This would give the standard some "teeth," i.e., the regulatory authority of Code.

(2) The second goal would be the incorporation of future research to address and improve current gray areas in design knowledge. These include the following topics: a more comprehensive scope to include alternative tower structural systems and materials; improved understanding of tower response to earthquake plus operational loads; better understanding of seismic response and performance at near-fault locations; effective supplementary damping systems; improved understanding of concrete anchor bolt resistance to fatigue; a reliability-based soil-structure interaction framework for Load and Resistance Factor Design of WTGS foundations and improved coordination with future Code editions.

Conclusion

WTGS support structure design is subject to many idiosyncratic wind industry practices. It is of critical importance that structural engineers and plan reviewers recognize that many of those practices are beyond Code (from international standards) and may often be above Code (more conservative). RP2011 is an excellent resource to learn about current wind industry design practices and un-codified requirements.▪