PRESTRESSED CONCRETE WIND TURBINE SUPPORTING SYSTEM

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ABSTRACT

Wind energy is one of the most commercially developed and quickly evolving renewable energy technologies. Wind turbines are commonly supported on tubular steel towers. Recent studies established concrete as a more economic and durable alternative for tower height exceeding 240ft. Presently, concrete towers are not common due to their perceived heavy weight and assembly complexity. The current concrete solution consists of precast rings that are post-tensioned together and assembled at the turbine site. While the tubular shape is compatible with wind variation and behavior, its construction process can be burdensome, demanding and expensive. In this paper, an effort to reduce the construction cost is proposed by developing a precast prestressed concrete system that consists of simple precast elements. This system is easy to transport, assemble and erect, plus it reduces the post-tensioning costs. This paper presents an overview of the proposed system and its design process under dead, wind and seismic loading along with comparisons between the proposed system and the current tubular steel and concrete solutions. The proposed system achieved a competitive and cost-effective solution in terms of behavior, ease of construction and cost.

Keywords: Prestressed Concrete, Wind Turbines.

INTRODUCTION

Wind energy is abundant; it is a free source of renewable energy that has been used for decades. The introduction of wind turbines as means to generate electricity can be traced back to the late nineteenth century; however, they received little interest throughout the twentieth century. In the mid-seventies, the spike in oil prices aroused concerns over the limited fossil-fuel resources which were the main stimuli that drove a lot of government-funded programs and researches towards wind energy alternatives. After the emergence of the three-bladed, stall-regulated rotor and fixed-speed design, the industry flourished in USA, Europe and worldwide[1].

In today's society, the fact that harnessing wind power is a green energy makes it even a much more attractive solution, where the emphasis is on environmental issues, reduction of CO_2 emissions and limiting climate changes. Numerous efforts and accomplishments in engineering design, materials, aerodynamics and production pushed wind energy technologies to the next level and granted it a competitive edge among other energy sources. Now, wind energy is one of the most commercially developed and quickly evolving renewable energy technologies worldwide[2].

World Wind Energy Association[3] confirms that wind power is always growing and it follows the same trend; the installed capacity more than doubles every third year. Furthermore, with the increasing awareness of the economic, social and environmental benefits of wind power, the growth rate is predicted to increase exponentially in the near future and a global capacity of 600,000 megawatts (MW) is expected by 2015. Figure 1 shows the new and cumulative installed world capacity in the last decade and the predicted wind energy growth.

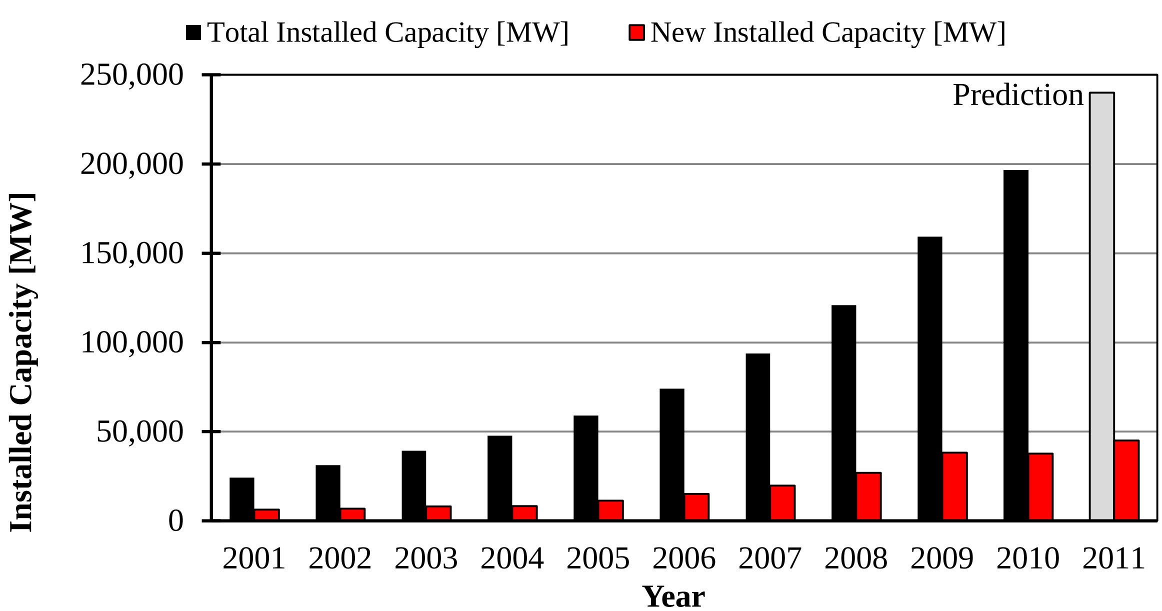


Figure 1: World's new and total installed capacity [MW][3].

The United States has established itself as one of the world's largest markets in wind energy. Despite of its market slowdown in 2010, the United States has maintained its status by producing a total of 40,180MW preceded only by China with 44,733MW. Among the fifty states, Texas is leading the way in total harnessed capacity followed by Iowa. From Figure 2 it's obvious that the mid-west has a lot of potential when it comes to wind energy. Most of the mid-west states already have a significant basis of operational wind farms that can be relied on for their energy production, and there is still a lot of room for further developments[4].

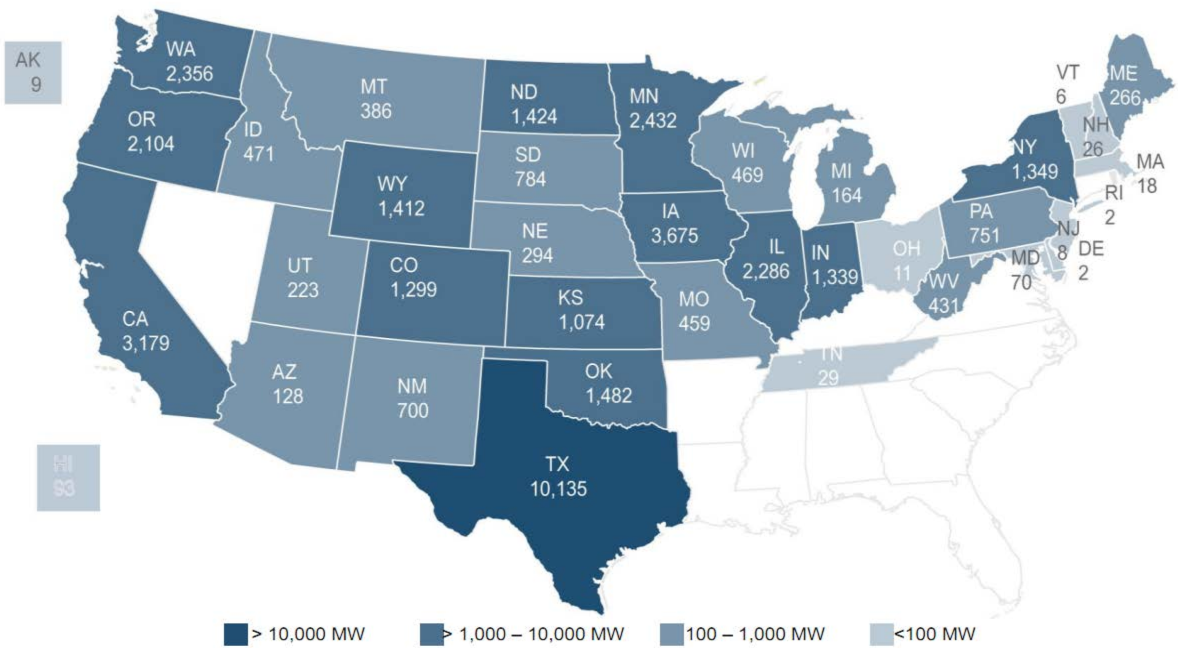


Figure 2: United States installed capacities map [MW][4].

Between the constant attention that the industry is receiving and the continuous advancement in technology, the future is bound to be even brighter than ever featuring taller, bigger and more efficient wind turbines. The US Department of Energy[5] confirms that the US wind industry is on track to achieve a 16,000MW/year growth approaching 2030 consistent with the expectation of supplying 20% of the US energy from wind energy by 2030 year end.

PROBLEM STATEMENT

Concrete has always been the competitive choice for tower like structures including tall chimneys, poles and bridge piers. However that is not the case for wind turbine towers as tubular steel towers have monopolized the market. The reason for steel dominance is due to its fast construction time; steel towers are light and fast. However the global wind market now trends toward higher and larger wind turbines to reduce energy cost and the tubular steel solution cannot keep up with this trend as its erection speed is tied to transportation of complete tube segments to the site which limits the maximum tower diameter to 14.5ft.

Almost every wind turbine exceeding 320ft hub height and rated power over 2 to 3MW has employed an alternative tower solution, and turbine manufacturers are investigating new feasible and cost-effective solutions for these turbines. Although precast concrete solutions were initially implemented to reach height where conventional steel tower could not, they proved to be a profitable solution for conventional hub heights. Figure 3 shows the transportation and erection of complete steel tube segments.

Figure 3: Transportation and erection of complete steel tube segments[6].

Many manufacturers and researchers have experimented with new concepts involving precast concrete that can overcome the transportation issues plaguing the tubular steel tower including; General Electric, Nordex, Enercon, Inneo Torres[7], Vries[8], LaNier[9] and The Concrete Center[2]. Most of the available solutions revolve around the same tubular concept used for steel towers. This solution consists of precast concrete rings that increase in diameter the closer they are to the tower base with the lower rings split vertically for logistical purposes. After placement, the rings are post-tensioned in the vertical direction. Figure 4 shows the precast ring panels used in the tubular concrete solution and Figure 5 illustrates its construction sequence. After the delivery of the ring segments to the construction site, vertical segments are assembled on the ground then post-tensioned with minimum force to maintain its stability while hoisting the segment into its place. After placement, the segment would then be fixed with the bottom of the tower with enough force to maintain stability. After the whole tower is constructed, the main post-tensioning is then applied throughout the height of the tower.

The Spanish company “Inneo Torres” developed a similar concept that consists of few large precast elements in the form of long narrow panels. The tower is divided into large segments and each segment is divided vertically into panel-ring sectors. During erection, sectors are assembled then hoisted in place. By reducing the number of precast elements this system managed to achieve a rate of two towers per week, similar to the erection rates of its tubular steel counterpart.

Figure 4: Concrete precast ring panels[9].

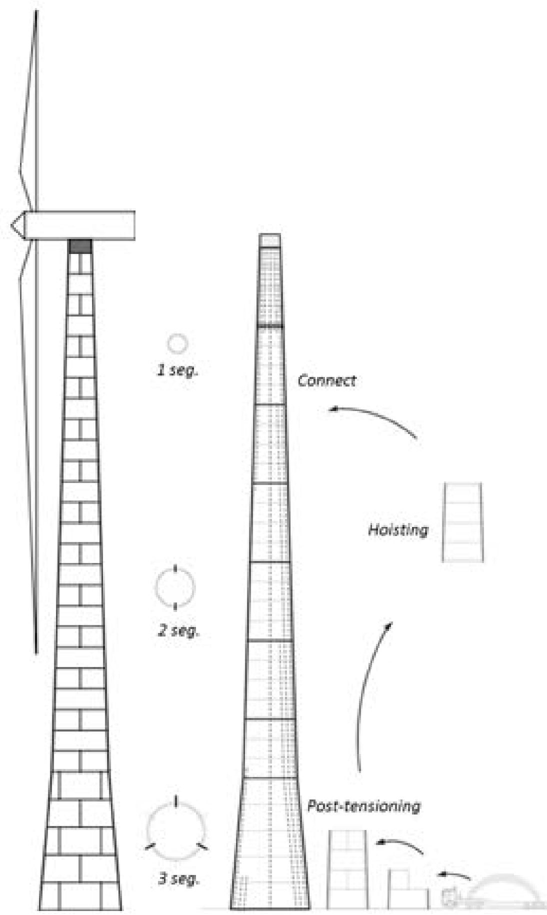


Figure 5: Concrete solution and construction Process[2].

RESEARCH OBJECTIVE AND SCOPE

The objective of this research is to develop a precast prestressed concrete wind turbine supporting system solution that is competitive for hub height exceeding 240ft where construction methodology and logistics are optimized. This objective can be broken down into smaller tasks:

- Simplify concrete fabrication by reducing the complexity of the precast sections.
- Prescribe design procedures compatible with the new shape.
- Optimize the design of the concrete elements in terms of concrete dimensions and steel reinforcement.
- Consider transportation restraints.
- Reduce or eliminate the need for post-tensioning.
- Achieve a fast erection time.
- Maintain the desired aesthetics of the wind turbine tower.

This research is intended for wind turbines located in the Mid-West region of the US using wind speeds and seismic acceleration accordingly. Concrete applications are the main focus of this research; some steel applications are presented for comparative illustrations. This paper presents an overview of the proposed system and its design process under dead, wind and seismic loading along with comparisons between the proposed system and the current tubular steel and concrete solutions.

PROPOSED SYSTEM

The proposed wind turbine supporting system is a triangular cross-section, precast concrete tower that consists of three columns in each corner of the triangle. The columns are connected together with panels along the height to enclose the interior for the tower shaft and ensure that the columns are resisting the applied actions as one composite section. Along the height the columns are divided into vertical segments for transportation and erection purposes. In keeping with the current wind turbine supporting systems, the tower has a tapered profile that varies linearly with each vertical segment. This tapered profile will reduce the total weight and the area subjected to wind thus lower the applied moment. It will also enhance the dynamic response of the tower and improve its overall stability. The triangular cross section can accommodate a skeleton type construction composed of columns and panels. This shape has an attractive aesthetic view and a good aerodynamic shape that reduces wind pressure and tower vibrations. Contrary to ring sections used in current concrete wind towers, columns and panels are easy to fabricate in the precast plant. Transportation and erection are also simplified. Figure 6 shows the cross section of the tower and the columns.

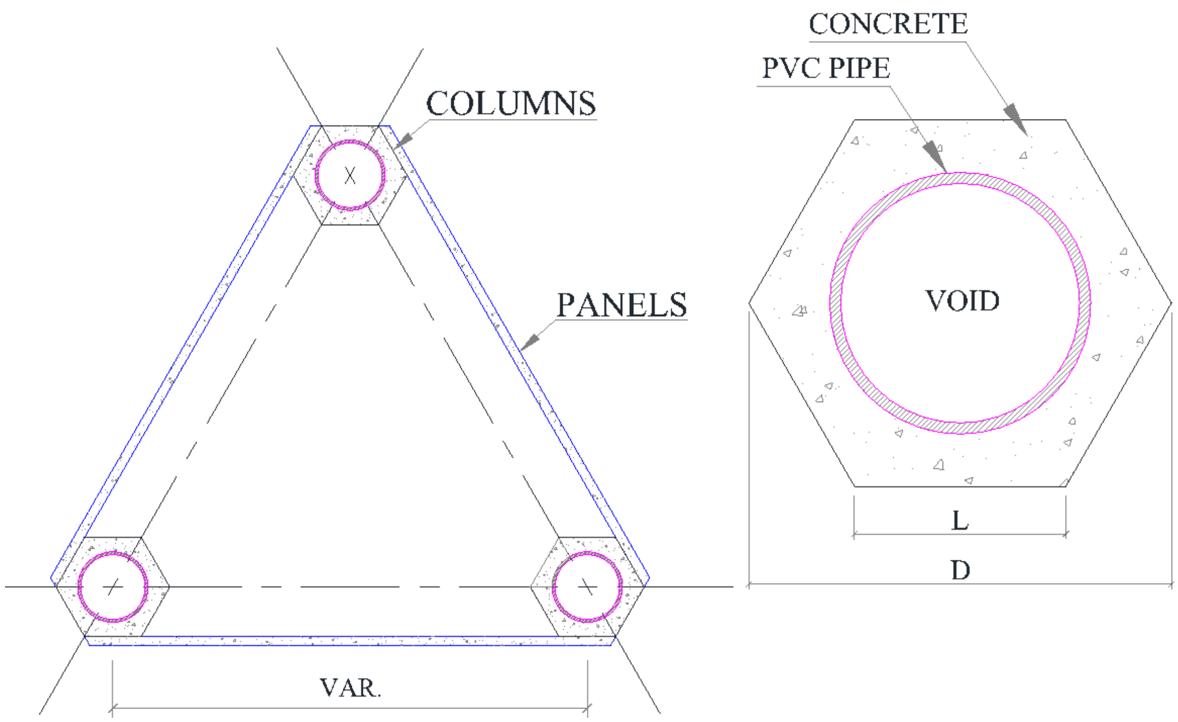


Figure 6: The cross section of the tower and the columns.

The columns have a hexagonal cross section to facilitate their connection with the panels. This shape also allows a doubly symmetrical reinforcement pattern that can accommodate the variations in wind direction. The column has a hollow circular void at its center to reduce its weight. The hollow void inside the column is achieved using a PVC pipe. However, it could be achieved using any alternative method such as Styrofoam or collapsible forms. For the lower segment of the tower, filling the void inside the columns with plain concrete can help stabilize the tower and resist the overturning moment. The panels' role is to enclose the tower and connect the columns together through shear connections using steel bolts. The panels were design as reinforced concrete having a constant vertical height that can be adjusted to accommodate transportation, erection or different tower dimensions.

The tapered profile of the proposed system should mimic the expected bending moment's shape so that the columns would only be subjected to axial forces. Moreover, the footprint of the system determines the magnitude of these forces. The larger the footprint becomes, the overturning moment would be resisted by a larger lever arm which decreases the loads. However, the increase of the tower's girth will attracted more wind pressure which, in turn, increases the forces. Therefore the tower's profile should was tailored with care to achieve an optimal design. Tweaking the tower's profile adds a lot of flexibility to the design of the proposed system. Transition between slopes was accommodated in the columns splices.

The construction process of the proposed system is much simpler than that used for current tubular concrete solutions. It is accomplished by simply erecting the columns and then connecting them by the panels; after the construction of the foundation, the columns of the first segment are put into place as shown in Figure 7. Their slope is then controlled by fixing them into the base and using steel temporary beams at the top of the segment. The first segment panels are then installed and fixed in the columns. After the installation of the panels, the temporary beams can then be removed and the same procedure is repeated for next segments as shown in Figure 8.

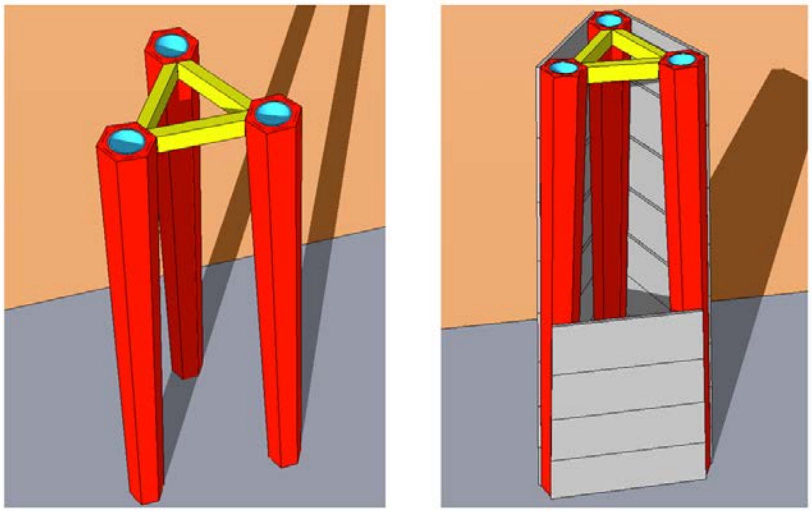


Figure 7: Lower segment construction sequence.

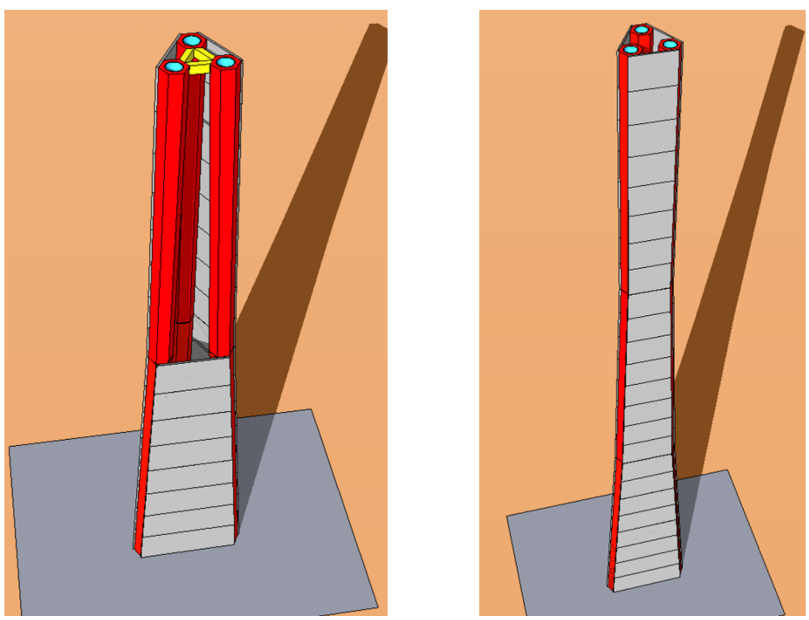


Figure 8: Upper segments construction sequence.

ANALYSIS AND DESIGN

Figure 9 illustrates the design procedure followed when designing the proposed system. After specifying the material properties and concrete dimensions the natural frequency of the tower has to be in the acceptable range. The next step is calculating the loads imposed on the system and constructing a model. Finally, every element of the system in then designed or checked against the standard's limits.

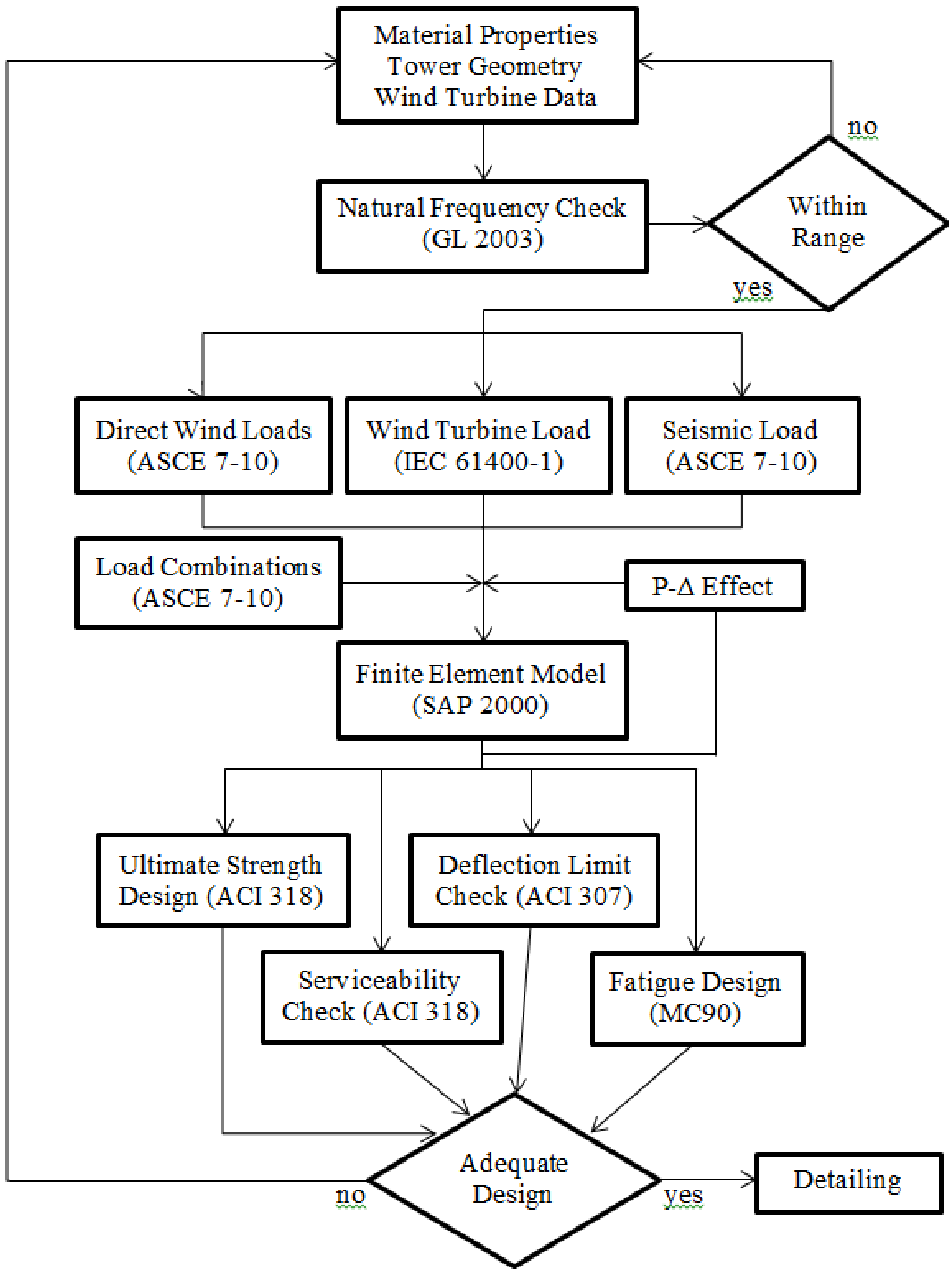


Figure 9: Design procedures for proposed system.

DYNAMIC ANALYSIS

The wind turbine structure should be designed with sufficient separation between the turbine operational frequencies and the structure natural frequency to avoid any resonance. These turbine operational frequencies results from any harmonic loading including the turbine rotor operational frequency and the blade-pass frequency. Turbine operational frequencies resulting from any transient loading are negligible as there are only applied for a short duration. In the practical wind industry, a total of 15% separation is usually required between the natural and operational frequencies. Figure 10 illustrates the allowable frequency range and the structure's natural frequencies for different tower setups.

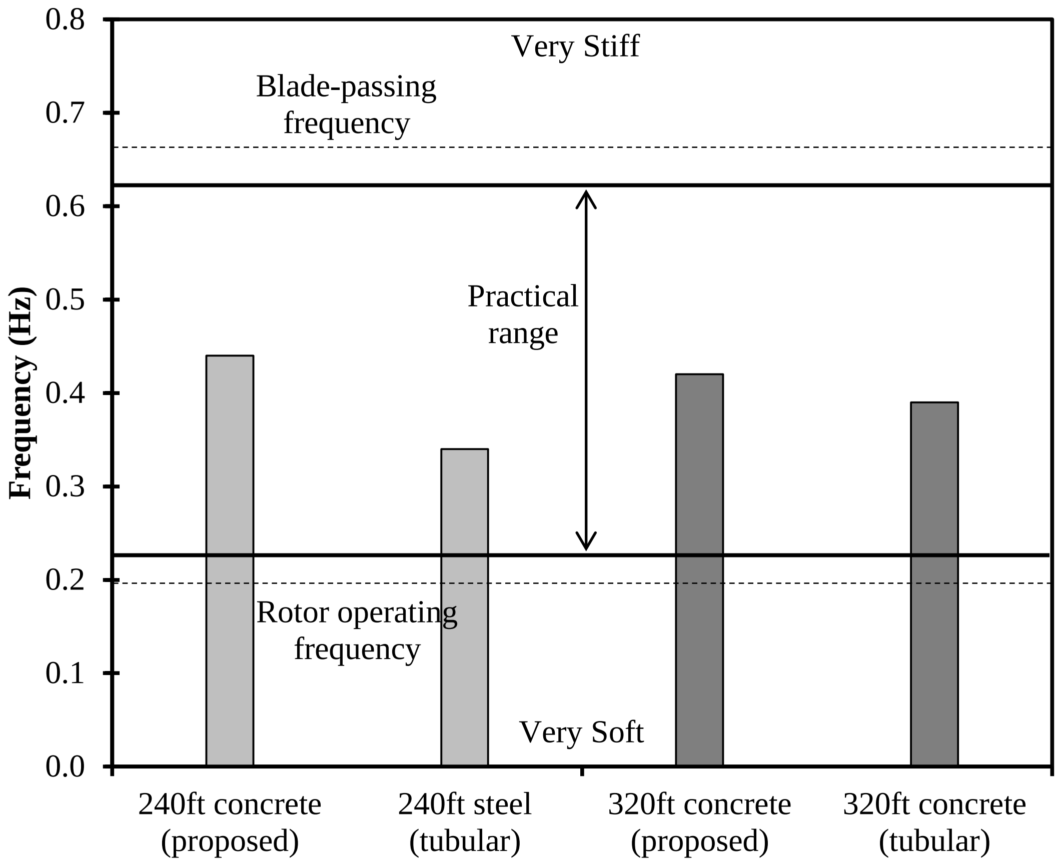


Figure 10: Natural frequencies of different towers and operational frequency range.

The difference between the steel and concrete systems is obvious; the proposed concrete tower is much stiffer than the steel tower having a higher frequency and smaller period. Consequently, the steel tower would undergo larger deflections than the concrete proposed system. To determine the difference between the proposed system and the tubular concrete solution currently being used, a complete dynamic analysis was performed. From the results it can be concluded that the two systems have very similar modal properties. The tubular system has slightly higher periods than the proposed system which means that it is more flexible and will experience greater deformations and vibrations.

LOADING

Wind and seismic loading were considered during the system's design. The straining actions imposed by the wind turbine generator were applied as equivalent static forces on the top of the tower considering two cases; operational and stationary cases. Direct wind pressure on the system was determined using the appropriate factors considering both cases. Seismic acceleration was applied accordingly on the base of the tower and the lateral forces distribution was calculated using the equivalent lateral forces method.

DESIGN

The design concept of current tubular wind turbine towers is relatively simple as the structure can be modeled as one cylindrical cantilever column. Moreover variation in wind directions is rendered unproblematic due to its circular cross section. One the other hand, a more challenging design approach should be adopted for the proposed system as its new innovative shape along with its unpredictable behavior result in an interesting and unconventional load path. Therefore, every element in the proposed system should be analyzed and design separately. Interactions between different elements have to be accounted for depending on their relative stiffness, load direction and connectivity.

Reinforced with all of the prestressing forces, the columns are the main force resisting elements in the tower. To endure the loads applied on the tower, the three columns have to work together as one composite section connected by the panels. Each column was designed to withstand biaxial bending moments, shear and axial force, either tension or compression depending on the wind direction. A fully prestressed and a partially prestressed/post-tensioned option are available along with two shear reinforcement options. Figure 11 shows the cross section of the column at the base for the 240ft proposed system for the two options.

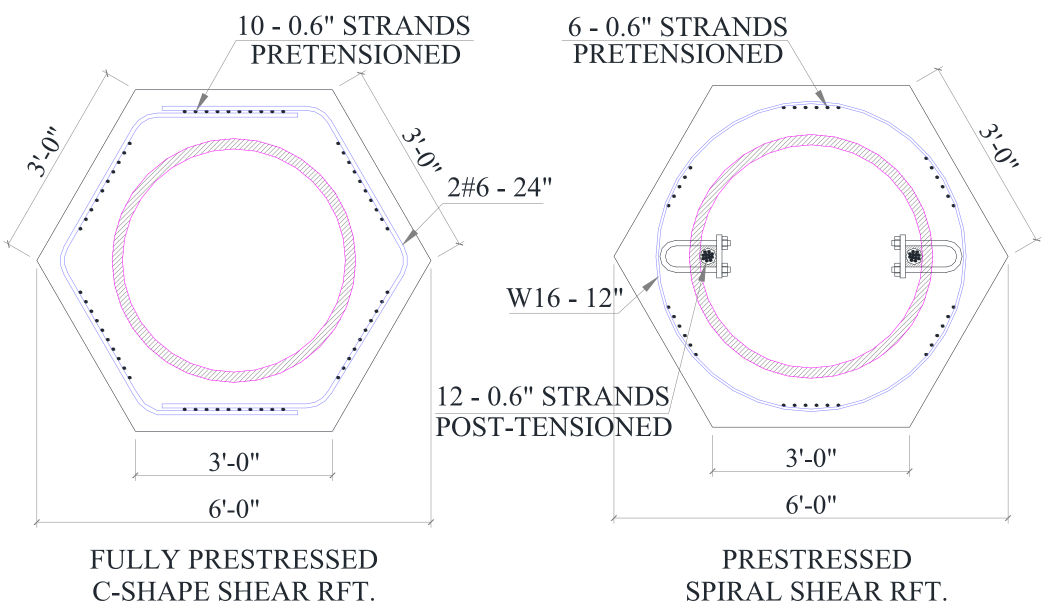


Figure 11: Base column cross section for the 240ft proposed system for the two options.

The panels serve a dual purpose; distribute the wind load among the columns and connecting the columns together to enable composite action. In the latter case, the panels behave as deep beams enduring in plane bending moments and shearing forces, however, in the former case, out of plane bending moments are the actions governing their design as they mimic the behaviors of one way slabs. It can be inferred that their slab action will dictate their behavior and control their reinforcement as the panels stiffness resisting these actions is very small compared to their strong axis stiffness resisting in plane bending stresses. It should be noted that the panels won't be subjected to the maximum in plane and out of plane actions in the same time. Figure 12 shows the panel's reinforcement details.

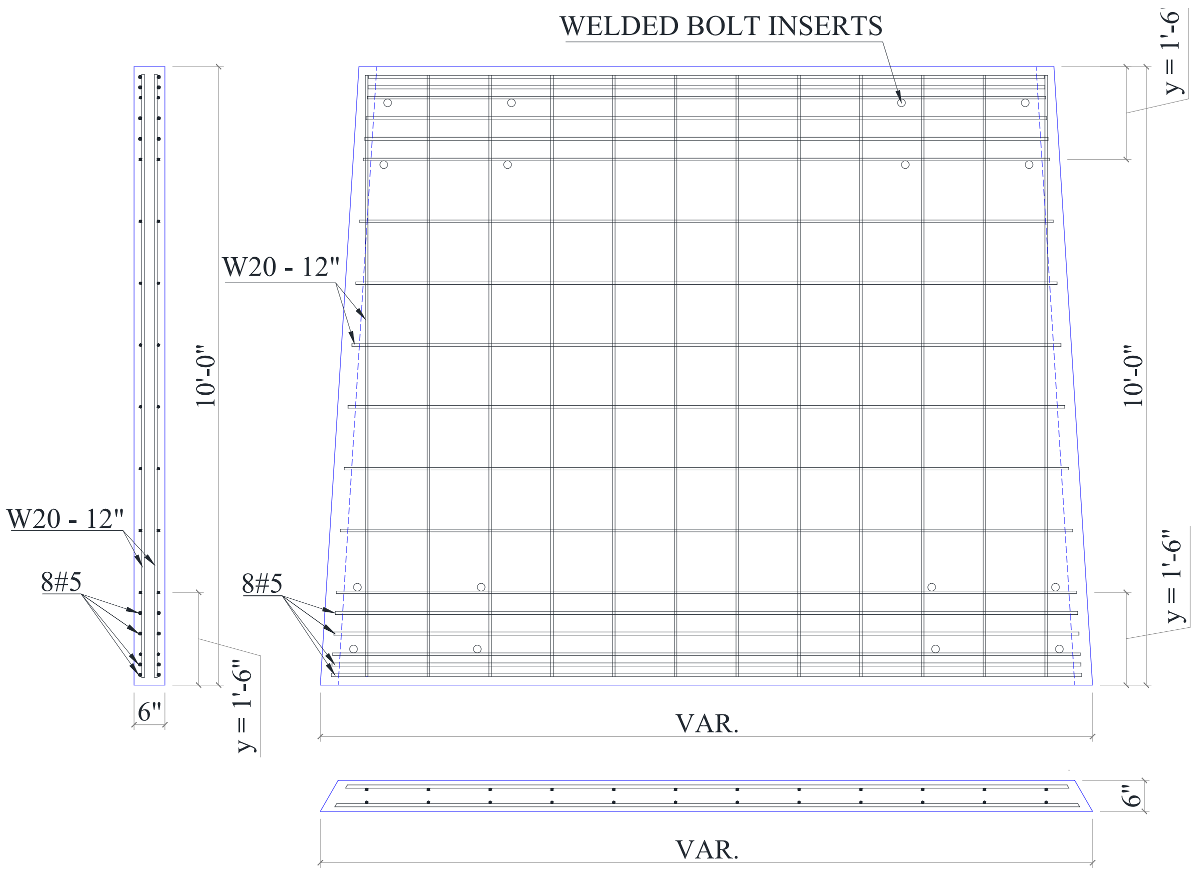


Figure 12: Panel reinforcement details.

The panels are bolted to the columns at its four corners using shear connections to simulate a hinged connection. Figure 13 show the panel to column connection details.

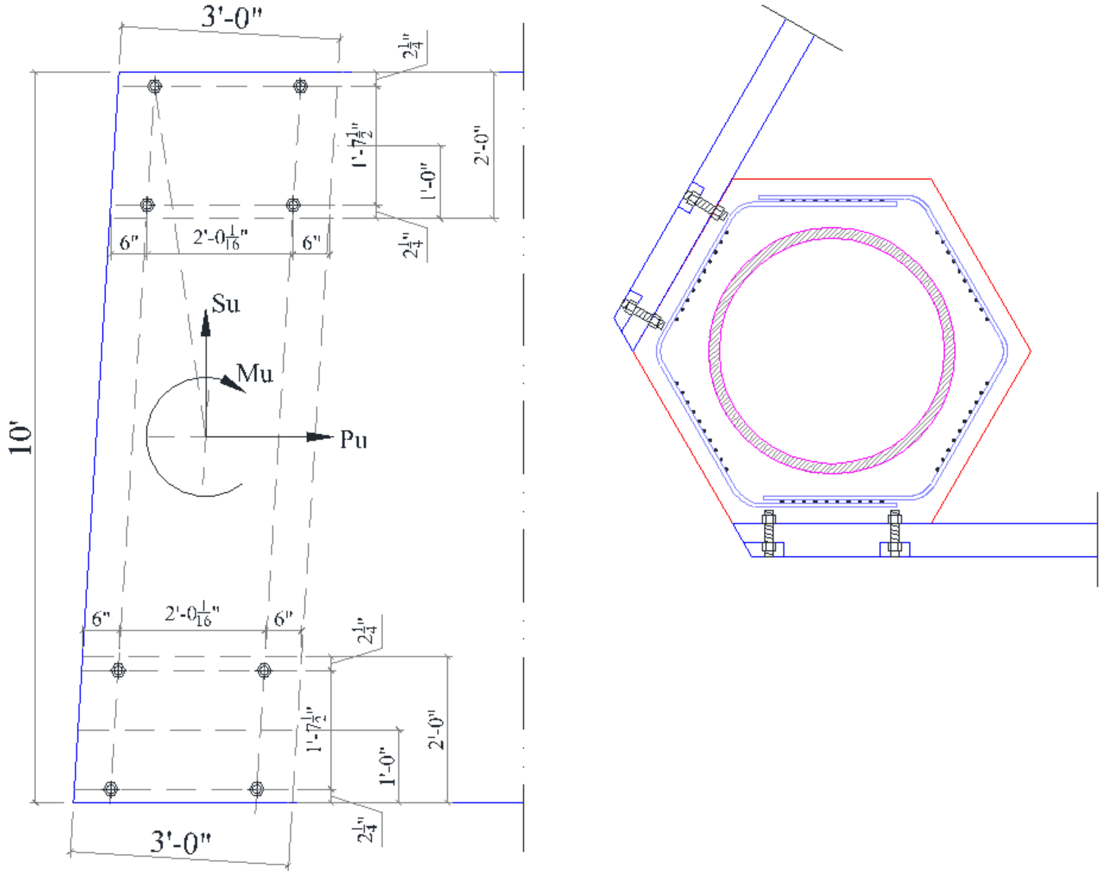
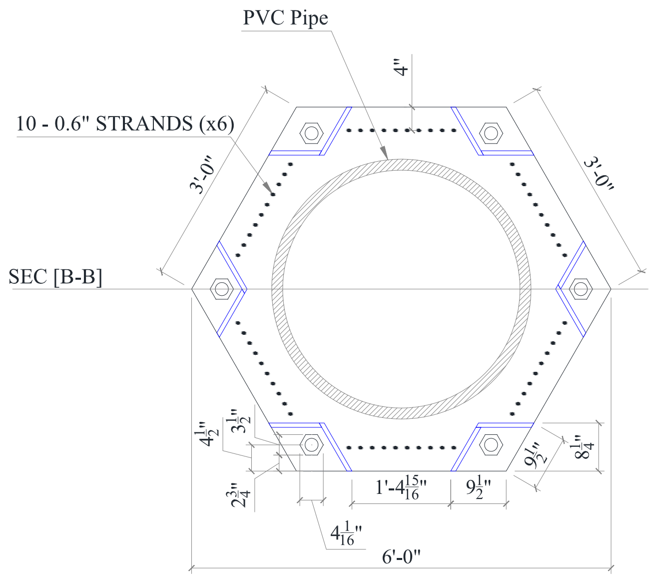


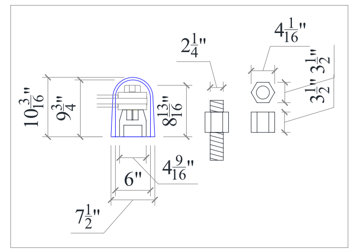
Figure 13: Panel to columns connection details.

Columns splices are used to connect two column segments together. The splices were not designed to withstand the applied loads but rather the nominal capacity of the columns. This approach will eliminate failure at splice locations along the columns. Figure 14 shows the columns splice connection details along with the threaded rod dimensions. The threaded rods have to extend into the columns to overcome the transfer length of the strands so that the force throughout the connection does not drop. Another alternative to the extension of the threaded rods is to fix the strands in a base plate at the end of the segments using chucks. That way the threaded bars do not have to extend in the columns as the transfer length will be drastically reduced. Due to the tapered profile of the tower, the two segments of the columns, connected by the splice, are not perfectly aligned. Shims are used between the two segments to adjust the tapering angle. After the threaded bars are tightened, the pockets can be grounded or covered with plastic caps to maintain the aesthetic view.

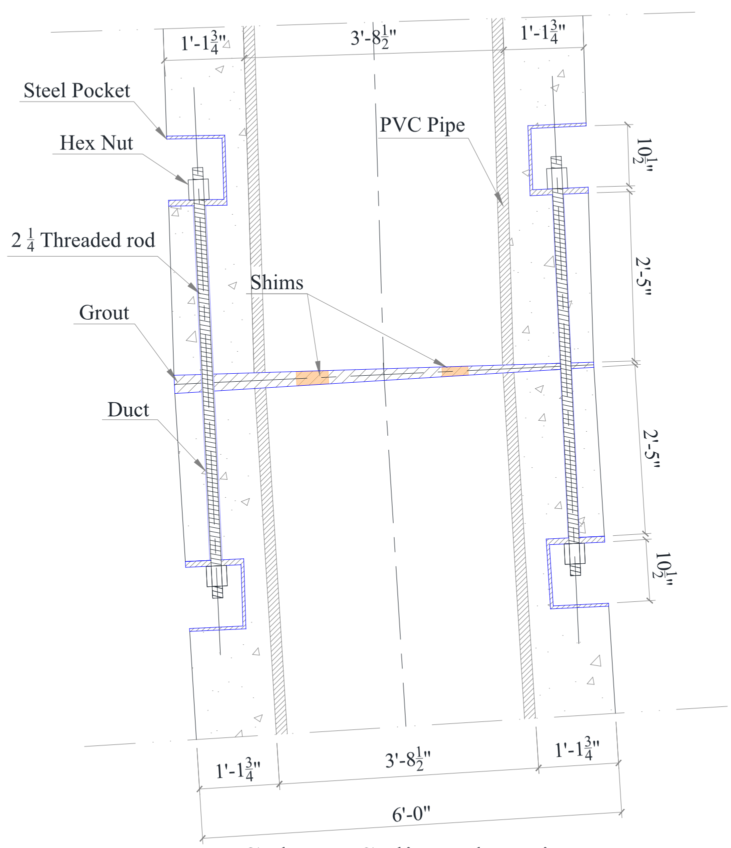
Base connections are used to connect the columns to the foundation. They are designed to withstand the base reactions from the columns. Like the columns splice, six threaded rods are used for the base connection, one in each corner of the column. The angle of inclination of the columns is formed in the concrete foundation to simplify column fabrication and erection procedures.



Column Splice Cross Section



Threaded rod and pocket dimension



Column Splice Elevation
Sec [B-B]

Figure 14: Column splice details.

SYSTEM COMPARISON

System	Tubular Steel	Tubular Concrete	Proposed Concrete
Governing load (failure)	Fatigue/Local buckling (brittle)	Tension (ductile)	Tension (ductile)
System's footprint	Small	larger	largest
Weight	Light (susceptible to overturning – big gravity foundation)	Heavy (resistant to overturning – smaller gravity foundation)	Heavy (resistant to overturning – smaller gravity foundation)
Vertical weight distribution profile	Normal stability	Better stability	Best stability
Dynamic Performance	Normal (high deformations and vibrations)	Better (less deformations and vibrations)	Best (least deformations and vibrations)
Durability	Low (susceptible to weathering conditions)	High (resilient to weathering conditions)	High (resilient to weathering conditions)
Service life	Low (20-30 years)	High (40-60 years)	High (40-60 years)
Concrete fabrication	---	Hard (ring sections require special forms)	Easily accommodated (concentrically prestressed columns and flat panel with slope edges)
Transportation	limited by tube section diameter	limited by ring sector dimensions	Unlimited (any restrictions can be accommodated)
Shipping and handling	Normal (big tube segments)	Easier (ring segments)	Easiest (flat panels and straight columns)
Erection time	Fast (complete steel tube segments)	Slow (ring sectors – multiple post-tensioning operations)	Normal (column splices eliminate post-tensioning)
Erection ease	Normal (complete steel tube segments)	Hard (unique ring sections – multiple post-tensioning)	Easy (column and panels – bolted connections)
Flexibility	limited by tower diameter	limited by ring dimensions	Very flexible

CONCLUSIONS

The proposed concrete system achieves a competitive solution, for wind turbine tower having a hub height of up to 320ft. It was optimized to include the following features:

- An enhanced life cycle value with low initial cost.
- An optimized design in terms of concrete dimensions, reinforcement, weight distribution and dynamic performance.
- A flexible design concept that can accommodate any logistics or specific conditions.
- Simple concrete fabrication procedures featuring non-complex precast elements.
- A fast erection time and simple construction sequence.
- A design where shipping and handling limitations were rendered unproblematic.
- Attractive aesthetics.

As a result, it can be shown that the proposed system has the potential to have low initial cost, little maintenance cost, fast un-complicated erection and excellent aesthetics in comparison with the dominantly used steel shaft system and the recently introduced precast concrete segmented system. In addition, the system is highly adjustable to accept different geometries. Above all, there is no need for expensive factory initial capital as most US plants have been making similar panels and can easily make a concentrically prestressed column.

REFERENCES

1. Burton, T., Sharpe, D., Jenkins, N., Bossanyi, E., “Wind Energy Handbook”, John Wiley & sons, Ltd. New York, NY, 2001.
2. The Concrete Center, “Concrete Towers for Onshore and Offshore Wind Farms”. *Technical Report*, Camberley, Surrey, 2007.
3. World Wind Energy Association, “World Wind Energy Report 2010”, *10th World Wind Energy Conference & Renewable Energy Exhibition*, Cairo, Egypt, 2011.
4. American Wind Energy Association, “US Wind Industry First Quarter Market Report”, Washington, DC, 2011.
5. US department of energy, “20% Wind Energy by 2030 Increasing Wind Energy’s Contribution to U.S. Electricity Supply”, *Technical Report DOE/GO-102008-2567*, Oak Ridge, TN, 2008.
6. Sri, S., “Wind Turbine Systems – Soils, Foundation and Tower”, 2011, <http://home.eng.iastate.edu/~JDM/wind/REU_Course_-_Tower_and__Foundation_-_June_2011.pdf> (Apr. 16, 2012).
7. Jimeno, J., “Concrete Towers for Multi-Megawatt Turbines”, *windsystemsmag.com*, February 2012, pp.40-45.
8. Vries, E., “Concrete–Steel Hybrid Tower from ATS”, *Renewable Energy World*, September – October 2009, pp. 109-111.
9. LaNier, M.W, “Evaluation of Design and Construction Approaches for Economical Hybrid Steel/Concrete Wind Turbine Towers”, *Technical Report NREL/SR-500-36777*, National Renewable Energy Laboratory, Golden, Colorado, 2005.