Engineering Structures 196 (2019) 109338

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Structural and durability assessment of ECC/concrete dual-layer system for tall wind turbine towers

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ARTICLE INFO

Keywords:
Wind turbine tower
Engineered cementitious composites (ECC)
Concrete
Double-layer system
Structural design
Durability

ABSTRACT

The increasing consumption of wind energy necessitates the development of taller concrete turbines towers with larger installed rotors. A previous study demonstrated that a dual layer system that incorporates protective layers made from engineered cementitious composites (ECC) improves the durability performance of these towers (Jin and Li, 2019 [1]). However, the introduction of ECC layers could affect the tower design due to its low elastic modulus relative to concrete. This paper first studies the structural impacts of the concrete towers with added ECC layers. An iterative method is employed to examine the requirements of strength, deflection, natural frequency and fatigue. The results show that ECC protective layer produces nonconsequential effects on tall concrete towers with less than 4% increase in tower diameter. After satisfying the aforementioned requirements, a durability analysis is conducted to compare the tower designs with and without ECC layers. The results indicate that the application of ECC layers significantly delays the initiation of chloride-induced corrosion of steel reinforcement and prolongs the service life of concrete wind turbine towers by four times. Therefore, this study allays the concerns that ECC protective layers may compromise the tower's structural performance and confirms its potential application in tall wind turbine towers for improved durability performance.

1. Introduction

The increasing costs of fossil fuels combined with a growing awareness of how their harvesting and use negatively impacts global climate have propelled a drastic growth in renewable and cleaner energy production [2,3]. Amongst these renewable energies, wind energy is considered one of the most important [4]. Globally, the cumulative wind energy production has experienced exponential growth, increasing from 40,000 MW in 2000 to 432,419 MW in 2015 [4]. In the U.S. alone, the percentage of total generated electricity produced from wind increased from virtually 0% in 2000 to 4.1% in 2015 [2]. This increase in the U.S. is expected to continue into the next decade as the Department of Energy aims to generate 20% of all energy production through wind energy by 2030 [5].

To address the growth in the wind energy market, taller wind turbine towers with larger installed rotors are being constructed to utilize greater and more stable wind at higher altitudes [6]. In order to achieve these taller and more powerful wind turbines, concrete has been considered as the primary construction material [7,8], using slip-form construction and prefabrication methods [9,10]. When the height of the wind turbine tower reaches above 100 m, the tower stiffness has to be designed carefully to avoid excitation and damage from resonant oscillations due to wind, earthquakes, and turbine operations. Therefore, high strength concrete (HSC) [6,11] and post-tensioned concrete tower designs [12] have become of interest to address the need for tall wind turbine towers. Moreover, the implementation of the post-tensioned HSC can help reduce tower cross-sectional dimensions, which allow for a more cost-effective tower design.

Although the use of concrete makes the construction of tall wind turbine towers feasible, both normal strength concrete (NSC) and HSC are prone to cracking [13,14]. Such risks in the durability of NSC and HSC drives a concern for high maintenance costs. This concern is further amplified if the towers are located in coastal regions and are exposed to an aggressive environment, which can be the case for wind turbines that aim to capture high-speed winds along the coast lines and ocean shore [15].

To improve durability performance, the previous study conducted by Jin and Li [1] developed a novel lightweight engineered cementitious composites (ECC) material to serve as a protective layer to partially replace the tall concrete wind turbine towers. Previous research has suggested that the ECC layer can be used as permanent formwork for cast-in-place concrete towers [1,16]. Studies have shown that with a

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https://doi.org/10.1016/j.engstruct.2019.109338
Received 23 March 2019; Received in revised form 21 June 2019; Accepted 24 June 2019
Available online 28 June 2019
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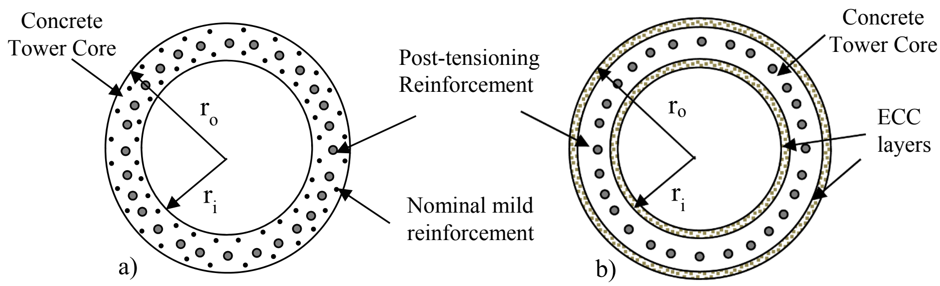

Fig. 1. Schematic view of tower's cross-section: (a) Type I and II; (b) Type III and IV.

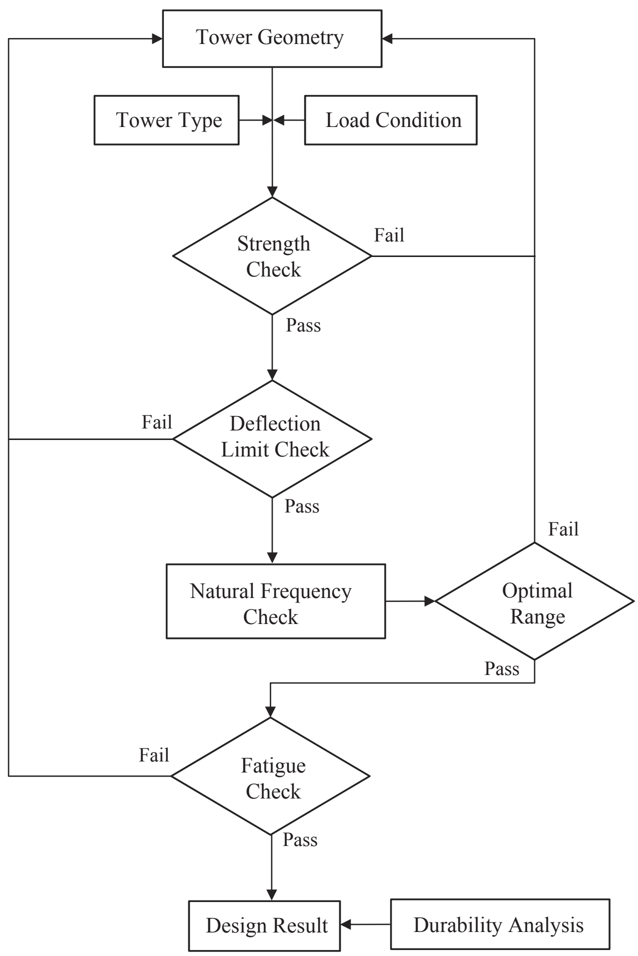

Fig. 2. Iterative design process for tall concrete wind turbine towers.

thickness of only 50 mm (equivalent to the thickness of concrete cover in reinforced concrete design [17]), ECC layer with its high cracking resistances could turn a wide concrete crack into multiple tight cracks with crack widths less than 100 µm. The self-healing nature of ECC will further reduce the crack width [18]. This strategic use of ECC layers helps reduce the penetration of water and aggressive chemicals, delaying the initiation of steel corrosion [19]. For example, the layer helps mitigate chloride-induced corrosion, which is considered the leading cause of reinforced concrete deterioration [20,21]. In addition to excellent cracking resistance, the ECC also exhibits both high flexural fatigue resistance against bending and ultra-high tensile ductility (more than 200 times than that of normal concrete) [1]. The high cracking resistance and ultra-ductility also promote the elimination of nominal mild reinforcement (Fig. 1), whose main purpose is to limit the cracking of concrete [12]. Therefore, this hybrid ECC/concrete system not only extends the tower's service life with its improved durability performance but also simultaneously eliminates the use of nominal mild reinforcement.

However, it should be noted that the elastic modulus of ECC is lower than NSC or HSC due to the lack of coarse aggregate [22]. This may affect the tower stiffness attributable to its partial replacement of material in the cross-section of the concrete tower. Therefore, this paper investigates the effects of ECC layers on the design of concrete wind turbine towers in terms of strength, deflection limit, natural frequency, and fatigue resistance [8,12,23]. Since it is a preliminary study, this paper employs a simplified design method for the purpose of demonstration. A cylindrical tower with a circular hollow cross section is selected for aerodynamic reasons as it allows the tower to be designed functionally for wind load in all directions (Fig. 1) [12]. The more comprehensive designs for commercial concrete wind turbine towers with other shapes and loading conditions can be found in other research [12,24–26].

In this paper, the design method will be discussed first, followed by the key design parameters. The materials discussed in this paper are normal strength concrete (NSC), high strength concrete (HSC), and two types of ECCs are selected for protective layers: lightweight (LW) ECC [1] and M45 ECC, the most commonly studied version of ECC [27]. Three tower heights are investigated for each tower type: 100 m, 150 m and 200 m. Four types of tower designs are analyzed and illustrated in Fig. 1: I) NSC wind turbine towers, II) HSC wind turbine towers, III) hybrid HSC tower with LW-ECC layers, and IV) hybrid HSC tower with M45-ECC layer. For Type I and II tower design, nominal mild reinforcement is used for cracking control while for Type III and IV, the mild reinforcement is assumed to be eliminated due to the contribution of ECC layers [1]. All towers are post-tensioned. The design results in terms of the material selection and tower geometry will be compared and the durability analysis will be carried out to demonstrate the advantages of ECC layers on concrete wind turbine towers.

2. Design method

Wind turbine towers are designed to sustain multiple loads during their service life, including the self-weight of the tower, wind turbine loads, direct wind loads on the tower, and seismic loads, if applicable. The detailed load conditions are defined and can be found in LaNier 2005 [12], which is based on ASCE 7-05 [28] and IEC 61400-1 [29]. As discussed in the introduction, ECC layers may raise the concern of compromising structural performance due to its lower elastic modulus. Therefore, a design method using an iterative process is employed to determine material selection and tower geometry that satisfy the required strength, deflection limit, natural frequency, and fatigue resistance (Fig. 2).

The results of the tower design methodology include the tower height, type, and geometry. The tower geometry is represented by the outer diameter of concrete tower design, since the tower wall thickness is assumed to be constant for the purpose of comparison and demonstration. As discussed in the introduction, the optimization of tower design, including tower wall thickness and tapered tower design can be found in other resources [8,26].

Table 1
Material properties.

Material Property	NSC	HSC	LW-ECC	M45-ECC	MR	PT
Density, ρ (kg/m^3)	2400	2500	1500	2300	7800	7800
Compressive Strength, f_c (MPa)	50	150	30	50	NA	NA
Tensile Strength, f_t (MPa)	NA	NA	3	5	420	1860
Elastic Modulus, E (MPa)	33,500	57,900	12,500	25,000	196,500	196,500

Based on material selection for each tower type and initial tower geometry with load conditions, the required ultimate strength can be checked first. The tower can be considered a large, vertically installed cantilever beam. The bending moment for each tower type can be calculated by multiplying the applied loads by the corresponding height. The moment capacity can be calculated through determining the stress areas and distributions in the pole cross-sections through the height of the tower [30]. Based on the moment capacity, the required tensile and compressive forces can be determined. The tensile force is used to determine the required amount of post-tensioning reinforcement since the post-tensioning reinforcement will be the only member taking tensile force. As illustrated in Fig. 1 and in other design reports [8,12,23], the post-tensioning reinforcement is installed in the middle of the tower wall. Although ECC's tensile strength could contribute to the tension force, for a conservative design, it is assumed to be carried by post-tensioning reinforcement in this paper. The compressive force is used to determine the compressive stress on concrete materials, which is then used to check if it exceeds the compression strength used for the design. If the compressive strength is exceeded, the geometry has to be modified to start another iteration of verifying the design inputs.

After satisfying the strength requirement, it is required to check the limit of the deflection at the top of tower, where the turbine is installed. Currently, there are no standardized deflection limits for tall concrete wind turbine towers, but two references were found to address this question. Studies [8,23] use ACI 307 [31], which is a standard for the design of reinforced concrete chimneys because there are many similarities between wind turbine towers and concrete chimneys in terms of the tower height, structure and loading conditions. According to ACI 307 [31], the maximum allowable deflection is set to be 4% of tower height. Nicholson [32] alternatively uses 1% of tower height as the maximum allowable deflection for a more conservative design and adequate turbine performance. Therefore, this paper adopts the conservative value of 1%. As the elastic modulus of each material is known, the tower's stiffness can be calculated by using previously determined tower geometry and configuration. The calculated tower stiffness is checked against the required tower stiffness, which can be derived from the previously determined moment capacity. If the calculated tower stiffness fails to meet the required design parameter, the tower geometry has to be updated again to fulfill the deflection limit requirement.

After fulfilling the required deflection limit, the tower design has to satisfy the required natural frequency constraint to avoid excitation and damage from resonant oscillations due to wind, earthquakes, and blade operations. The natural frequency of the tower can be calculated using the mass of the tower, the mass of the tower head, the height of the tower, and the estimated stiffness. The natural frequency of the tower is then checked to see if the natural frequency falls into the optimal range, which will be further elaborated in Section 3.4. If it does fall within the optimal range, the tower geometry is accepted for fatigue check. If not, the tower geometry has to be updated until the natural frequency requirements are met.

The fatigue loads that a wind turbine tower experiences are attributed to wind, earthquake and turbine operations [8,12]. Based on the results from LaNier [12], the effects of fatigue loads are more critical on steel reinforcement, including both mild and post-tensioning reinforcement, than on concrete. Since this paper focuses on the effect of ECC layers on concrete wind turbine towers, the design of reinforcement for post-tensioned concrete wind turbine towers to sustain fatigue load is beyond the scope of the study. The detailed fatigue design can be referred to other research [12,24,25]. For concrete materials and ECC, it is understandable that they are more susceptible to flexural tensile fatigue from wind load than to compressive fatigue from the turbine operation because the compressive fatigue stress is insignificant when compared to their compression strength. For flexural fatigue, the concern is the formation of cracks on the surface of concrete tower, which in turn compromises the durability performance [20,21]. This concern has been addressed by the exceptional cracking and fatigue resistance of ECC layers [1]. Based on [12], the compressive fatigue stress is less than 10% of the compressive strength of concrete materials [12]. According to Model Code 1990 [33], the concrete fatigue reference design strength is about half of the compressive strength of concrete materials. Therefore, it is safe to say that the fatigue load is not critical for the design of concrete wind turbine towers, even with ECC layers. However, the influence of fatigue loading on wind tower durability remains a topic of discussion among wind turbine tower design experts [12,24,34].

Based on this iterative design approach, the final design results in terms of tower geometry and configuration for each tower type can be determined. A durability analysis will be performed to examine the durability performance of the different tower design types.

3. Parameters for tower design

3.1. Materials

Based on the design method, the required material properties for determining design parameters are density, compressive strength, tensile strength, and elastic modulus, which are listed in Table 1. The material properties of NSC and HSC are borrowed from LaNier [12] and Wille et al. [35] respectively. The compressive force from turbine and tower's self-weight is assumed to be distributed by concrete and the result is checked against compressive strength. Their elastic moduli are estimated based on their compressive strength (Eq. (1) [17]):

$$E = 4730 \times f_c^{1/2} \tag{1}$$

where E: elastic modulus (MPa); f_c: compression strength (MPa).

The material properties of LW-ECC are based on the mix design and results developed by Jin and Li [1]. The material properties of M45-ECC are based on the mix design and results from Wang [27]. As recommended by LaNier [12], the post-tensioning reinforcement (PT) comprises 7-wire low relaxation strands with a diameter of 15 mm, and their material properties are based on ASTM A416/A416M [36].

As recommended by [12], the minimum mild reinforcement (MR) used in Type I and II concrete towers for cracking control is #4 rebar with a diameter of 13 mm and installed at a spacing of 300 mm. The material properties of #4 rebar is based on ASTM A615/A615M [37].

3.2. Stiffness

Although the lateral deflection and natural frequency of a wind turbine tower could be influenced by the flexibility of the foundation and soil system, the tower is assumed a fixed support cantilever in this study for evaluating its structural performance using different materials. The main factor that affects the lateral deflection and the natural frequency of the tower is the tower stiffness. As a fixed support cantilever, the stiffness comes from two parts: the elastic modulus (E), which is based on the material properties, and the moment of inertia (I), which depends on the tower geometry. In this paper, all materials are assumed to deform compatibly. Therefore, based on the material properties and tower type and geometry, the tower stiffness (E_tI_t) can be determined in the following manner.

$$E_t I_t = E_C I_C + E_{ECC} I_{ECC} + E_S I_S \tag{2}$$

where E is elastic modulus for each material, the value of which can be found in Table 1, and I is moment of inertia for each material, the value of which can be determined as below.

For a circular-shaped hollow sectional tower, the second moment of inertia for the concrete (I_C) tower core is based on Eq. (3).

$$I_C = \frac{\pi(r_{Co}^4 - r_{Ci}^4)}{4} - nI_S \tag{3}$$

where r_{Co} and r_{Ci} are outer and inner radiuses of the concrete tower core respectively (Fig. 1); n is the number of reinforcement bars and I_s is the second moment of inertia for the reinforcement.

The second moment of inertia for ECC layers (I_{ECC}) is based on Eq. (4).

$$I_{ECC} = \frac{\pi(r_{ECCo}^4 - r_{ECCi}^4)}{4} \tag{4}$$

where r_{ECCo} and r_{ECCi} are outer and inner radii of ECC layers respectively (Fig. 1). The second moment of inertia for the inner and outer ECC layers can be calculated separately and added together. As recommended by Jin and Li 2019 [1], the thickness of both inner and outer ECC protective layers is set to be 50 mm for improving the durability performance. This value is also the thickness of concrete cover in the design of reinforced concrete [17]. Therefore, the difference between r_{ECCo} and r_{ECCi} is 50 mm in this paper.

The moment of inertia for steel reinforcement (I_s) is based on Eq. (5).

$$I_S = \frac{\pi r_S^4}{4} + \pi r_S^2 \times L^2 \tag{5}$$

where r_S is the radius of reinforcement; L is the distance between the center of concrete wind turbine tower and the center of steel reinforcement.

For the purpose of demonstration, this paper alters the outer radius of concrete tower with a fixed wall thickness to determine the moment of inertia for the required tower stiffness. Based on the Eq. (2), the HSC tower with its higher stiffness is expected to have smaller cross-sectional dimensions than NSC tower. Based on the design in LaNier [12], the wall thickness of 1 m is assumed in this paper for tower design. In this way, the outer radius of concrete tower can represent the tower geometry. The optimization of the tower design, including wall thickness and tapered-shaped towers, and the detailed designs can be referred to other research [12,24,38].

3.3. Deflection

In this study, approximate static expressions are used for calculating the tower's deflection. With the calculated tower stiffness (E_tI_t), the deflection at the top of the tower can be estimated by Eq. (6). As discussed in Section 2, the maximum allowable deflection is 1% of tower height.

$$\delta = \frac{F_W H^3}{3E_t I_t} \tag{6}$$

where δ is deflection at the top of tower; F_w is wind load; and H is tower height.

The wind load (F_w) is calculated based on Eq. (7).

$$F_w = P_w \times A \times C_d \tag{7}$$

where P_w is wind pressure; A is the area that is subjected to the wind; C_d is the drag coefficient. The wind pressure is calculated based on Eq. (8). The maximum wind pressure is determined from the maximum wind speed, also known as survival speed. According to Jha [39], the maximum allowable wind speed for wind turbine operation is 60 m/s.

$$P_w = 0.611 \times V^2 \tag{8}$$

where V: wind velocity.

3.4. Natural frequency

As discussed in Section 2, it is critical to design the natural frequency of tall wind turbine towers to avoid excitation and damage from resonant oscillations due to wind, earthquake, and blade operations. Sources of resonant oscillations from wind can be referred to [40,41], who suggest that tall structures normally lie between 100 and 1000 cycles per hour for wind loads, further suggesting it is easier to design structures with natural frequency that is at higher end. Therefore, a natural frequency of tall wind turbine tower greater than 1000 cycles per hour, equivalent to 0.3 Hz, is desirable to avoid resonant oscillations from wind.

In order to avoid resonant oscillations due to earthquakes, wind turbine towers are designed to have natural periods larger than 2 s, avoiding large inertial forces induced by tower acceleration (given the tower mass) [42,43]. As natural period is the inverse of the natural frequency, a natural frequency that is lower than 0.5 Hz is desirable. The detailed earthquake design for concrete wind turbine towers can be found in [8,43].

In addition, the wind turbine tower should also be designed with adequate natural frequency to avoid any resonant oscillations from turbine operations. The turbine operational frequencies can occur from the blade's passing frequency and rotational frequency. The passing frequency of a three-blade rotor is lower than 0.2 Hz, while the rotational frequency is higher than 0.6 Hz for a 5 MW wind turbine. These are typical energy outputs for tall wind turbines with a height greater than 100 m [8,12]. Therefore, the natural frequency for the tall wind turbine tower should be within a safe range of 0.2 and 0.6 Hz to avoid oscillations from the blade operations [8,12].

Based on the above discussions, the optimal natural frequency of a tall wind tower can be determined. The value should be between 0.3 and 0.5 Hz, which also coincides with the design value from LaNier [12].

According to Harrison, Han and Snel [44], the method for estimating the natural frequency of a wind turbine tower (ω_t) is stated below.

$$\omega_t = 1.75\sqrt{\frac{E_t I_t}{H^3(m_h + \frac{m_t}{4})}} \tag{9}$$

$$NF = \frac{\omega_t}{2\pi} \tag{10}$$

where ω_t is tower natural frequency in rad/s, and NF is natural frequency in Hz; H is the tower height; $E_t I_t$ is tower stiffness; m_h is mass of the wind turbine head, and m_t is the mass of tower, which can be derived from the material properties and tower geometry.

3.5. Durability analysis

The major deterioration for reinforced concrete is the chloride-induced corrosion of steel reinforcement, which directly relates to the service life of concrete wind turbines. For concrete wind turbines, even those reinforced by mild reinforcement [12], the width of a crack can be expected to increase from 150 μm to 300 μm throughout its fatigue life [45–47] and under steel corrosion. In contrast towers with ECC layers only experience microcracks with widths below 50 μm throughout their fatigue life, regardless of the use of mild reinforcement [1]. When concrete cracks, chloride ions can easily travel through these cracks to the steel reinforcement during the initiation phase (e.g. when the wind turbine tower is exposed to a marine environment). After the chloride concentration level reaches a critical threshold value, depassivation occurs in the protective layer surrounding the steel. Therefore, ECC layers with their ultra-high cracking and fatigue resistances can help reduce chloride transportation, delaying the initiation of chloride-induced corrosion of steel reinforcement.

To quantitatively investigate the benefits of ECC layers on delaying the initiation phases of chloride-induced corrosion, this paper uses Crank's solution to Fick's second law (Eq. (11)) to estimate the initiation phase (t_i) [48].

$$C_I = C_S[1 - \mathrm{erf}\left(\frac{x}{2\sqrt{D_e t_i}}\right)] \tag{11}$$

where C_I is the chloride concentration required to initiate steel corrosion; C_s is the surface chloride concentration; x is the distance from the concrete surface to the surface of steel reinforcement, which is considered to be the same as the thickness of the concrete cover, or of the ECC layer in this report; D_e is the effective chloride diffusion coefficient; and *erf()* is the error function.

It should be noted that this paper assumes the elimination of mild reinforcement due to ECC's ultra-high tensile ductility and cracking resistance. In this way, the steel corrosion can be fundamentally eliminated and the service life of towers with ECC layers lasts forever. However, for a conservative durability analysis, the mild reinforcement is included in the hybrid ECC/concrete wind turbine towers so that a finite service life can be estimated to compare with towers without ECC layers.

4. Results and discussion

The tower geometry (represented by outer radius) has to be designed adequately to provide the stiffness that satisfies the design requirements for each tower type and height. Based on design method and design parameters, the tower geometry can be determined. These results are listed in Table 2. Due to its higher elastic modulus, high strength concrete (HSC), which is used in Type II tower design, can drastically decrease the tower size by 20% compared to normal strength concrete (NSC) tower design (Type I).

As previously mentioned, the inclusion of ECC protective layers could affect the tower design due to its low stiffness. According to Table 2, the inclusion of ECC protective layers only have a minor impact on the tower design. For an HSC tower of 200 m, the inclusion of LW-ECC protective layer only increases the outer diameter by 3.5%, and M45-ECC only increases the diameter by 2%.

It should be noted that the lower bound of the optimal natural frequency (0.3 Hz) is employed in this study (based on Section 3.4, the optimal natural frequency for a tall wind turbine tower design is between 0.3 and 0.5 Hz). This choice was made because designing for an unnecessarily high natural frequency is not economical. For example, the outer radius increases from 8.9 m to 14.5 m for the concrete tower of 200 m height if the designed natural frequency is increased from 0.3 Hz to 0.5 Hz. This design would result in a 60% increase in consumption of construction materials, increasing costs.

Table 3
Amount of concrete materials used for a single tower (m^3).

Tower type	100 m	150 m	200 m
I	879	2475	5434
II	722	1978	4334
III	738	2049	4492
IV	738	2025	4428

With the confirmation of tower design, the total amount of concrete materials, including NSC, HSC, and ECCs, used for different tower types and heights can be estimated and the results are listed in Table 3. The comparison between NSC and HSC towers shows that the use of HSC could result in 17% savings in construction material for the 100 m tower and 20% for the 200 m tower. For the construction of a single tower, the volumetric measurement of construction material saved for the 100 m tower is approximately 157 m^3, and 1100 m^3 is saved with the 200 m tower design. The employment of ECC protective layers does not significantly increase the consumption of concrete materials. The amount of concrete material used for a 200 m hybrid HSC/ ECC tower compared to the HSC tower increases less than 3%.

It should be noted that the cost of each concrete material is different. For cost analysis, the material cost and consumption for each material used in a single tower should be provided and the detailed analysis will be included in another manuscript [49]. It should also be noted that using a tapered tower design could further save construction materials. However, as discussed in the introduction, for the purpose of this comparison and feasibility study, the design of cylindrical tower is used. In future studies (e.g. designing a tower prototype), the design of a tapered tower with optimized configuration should be carried out as the tapered tower is considered more popular in industrial practice since it uses less material and is easier to lift due to the decreased size at the top [26,38].

After allaying the concerns that using ECC protective layers may affect the design of tall concrete wind turbine towers, the durability analysis is carried out to demonstrate the advantages of using ECC layers. For estimating the time (t_i) for the initiation of chloride-induced corrosion, a $C_{I,}$ of 1.4 kg/m^3 is used according to [50]. C_s is equal to 12 kg/m^3 according to [51]. D_e depends on crack width and the number of cracks. Sahmaran et al [52] have summarized D_e for ECC and reinforced mortar with different crack widths. In that study, D_e of ECC was found to increase linearly with the number of microcracks, while D_e of reinforced mortar is proportional to the square of the crack width. In this report, the D_e of cracked reinforced mortar is considered to be the same as that of cracked reinforced concrete, providing that their crack widths are the same.

The effective chloride diffusion coefficients for both concrete and ECC are calculated and listed in Table 4. The estimation of t_i is also provided in Table 4. For concrete towers (both NSC and HSC), it is assumed that only one crack with a crack width of 300 μm occurs on the surface. This assumption is based on fact that a single major crack tends to form on the surface of concrete [1]. In contrast, for ECC/concrete tower the ECC protective layer helps diffuse the major crack into

Table 2
Tower geometry based on tower type and height.

Tower type	NSC	HSC	LW ECC	M45 ECC	MR	PT	Outer radius (m)		
							100 m	150 m	200 m
I	√				√	√	3.1	5.5	8.9
II		√			√	√	2.5	4.5	7.2
III		√	√			√	2.6	4.6	7.4
IV		√		√		√	2.6	4.6	7.3

Table 4
Results of D_e and t_i of concrete and ECC with different crack width, assuming both include reinforcing steel.

Material	Effective chloride diffusion coefficient, D_e ($m^2/sec \times 10^{-12}$)	Initiation phase, t_i (days)
Concrete	142.2	41
ECC	30.4	194

multiple microcracks [1,53]. Therefore, for ECC/concrete towers, it is assumed that multiple microcracks (15 microcracks) occur on the surface with crack widths of 50 μm. Based on Eq. (11), the estimated initiation time of chloride-induced steel corrosion is 41 days for concrete and 194 days for ECC. Therefore, the introduction of ECC layer can increase the tower's service life by four times before repair is needed [25]. However, this estimation does not take into account the combined effects of crack width evolution and chloride diffusion. For future work, a numerical approach must be developed to accurately estimate the duration of this initiation phase for concrete. The current analysis also does not account for the fact that corrosion associated with larger cracks in concrete tend to reduce the effective diameter of steel reinforcement much more than the slight and spread-out effect of corrosion associated with microcracks in ECC [54].

As a result, the inclusion of ECC layers can drastically delay the initiation of chloride-induced corrosion and increases the tower's service life. As discussed in Section 2, there is potential that the mild steel reinforcement could be completely eliminated through the introduction of ECC layers. In this case, the chloride-induced deterioration of wind turbine towers could be fundamentally eliminated. The ECC/concrete tower systems enables its potential for the reuse of the tower for extended service life [55]. This system could also be beneficial in wind turbine foundations, especially when they are subjected to crack-induced deteriorations [56].

5. Conclusions and future works

This paper presents preliminary design results for concrete wind turbine towers using different materials: normal strength concrete (NSC), high strength concrete (HSC), and two types of Engineered Cementitious Composites (ECCs). The results show that the ECC layer poses nonconsequential effects on the tower design and material consumption even with a lower elastic modulus compared to concrete materials. When subject to a chloride-induced deterioration, the hybrid ECC/concrete wind turbine towers show longer service lives than concrete ones. Due to ECC's exceptional ductility and excellent cracking and fatigue resistance, which extends the duration of the initiation phase, added ECC layers have the potential to completely remove mild reinforcement for cracking control. This addresses any concerns that ECC layers may compromise structural performance despite its superb contribution to a tower's durability.

This paper also quantitatively demonstrates that HSC makes tall wind turbine towers more efficient by saving up to 20% construction material while meeting the design requirements. In the future study, a comprehensive design and optimization of the hybrid HSC/ECC wind turbine tower should be a priority and the project can be geared towards designing a prototype of this type of hybrid towers. A cost-benefit analysis, including cost, availability, serviceability, and constructability of ECC materials for constructing ECC protective layers should be studied further to comprehend the feasibility of using ECC protective layers on tall concrete wind turbine towers.

Acknowledgements

This research is supported by the Electric Power Research Institute (EPRI) under Agreement No. 10004070 to the University of Michigan. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the EPRI.

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