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Preliminary study on the applicability of semi-geodesic winding in the design and manufacturing of composite towers

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Abstract. During last twenty years, wind turbine manufacturers took the path of building larger machines to generate more electricity. However, the bigger the size became, the more material was required to support the loads, leading to great weight increases. Larger turbines and higher hub heights also resulted in larger tower base diameters which are limited considering their logistics. In many countries, the limit for transports with special permits maximizes the diameter to 4.5 metres. Considering this fact, the wind turbine market dominated by welded steel shell towers is looking for new structural solutions for their future turbines. Although, composite materials are not used as the structural material in the towers of today's turbines, the demand for larger wind turbines forces engineers to seek for alternative material systems with high specific strength and stiffness ratios to be used in towers. Inspired by the applicability of filament winding in tower production, in the present article we investigated the effect of semi-geodesic winding on the winding angle, thickness, stiffness coefficients and vibration characteristics of filament wound composite conical shells of revolution which simulate wind turbine towers at the structural level. Present study showed that the preset friction applied during semi-geodesic winding is an important design parameter which can be controlled to obtain gradually increasing thickness from tower top to the base of the tower, and favourably alter the dynamic characteristics of the composite towers.

1. Introduction

As the steel dominated wind turbine towers face new challenges such as greater weight, increasing cost and low corrosion resistance, new structural solutions will have to be investigated. Even though, it is still technically possible to build steel towers with a less than optimal diameter, due to the high mass and the large wall thickness they tend to be uneconomical in comparison with other alternatives above a hub height of roughly 100 metres.

Currently considered tower alternatives in the wind market are:[1]

- Steel shell tower designed in a conventional way with flanges and both longitudinal and transverse welds. Due to transportation reasons the largest permitted diameter is 4.5 meters.
- Steel shell tower with bolted friction joints
- Concrete tower with pretensioned steel tendons.

- Hybrid tower with a lower concrete part and an upper part built as a conventional steel shell
- Wooden tower.

This paper investigates another alternative which is the use of advanced composite materials technology, specifically filament winding technique and exploitation of the use of composite materials in the manufacturing of wind turbine towers. Some of the advantages of composite material usage in wind turbine towers are prolonged life, improved dynamic damping characteristics, extended fatigue life, reduced maintenance cost and reduced logistic costs for installation as a consequence of smaller size and weight.

Furthermore, considering the offshore wind energy industry which is expected to dominate the future of the wind market, attractive attributes of composite materials for offshore service comes into focus. Composites are already used offshore in several critical load bearing applications, particularly for risers, spoolable tubular and tethers taking into account their high corrosion resistance, good thermal insulation, excellent damping and fatigue performance, and high specific stiffness [2].

Filament winding is one of the few automated processes for composites manufacture and can thus produce highly repeatable, high quality components at reduced manufacturing defects. It is considerably quick and proven technology for making high performance parts. Its biggest advantage is the use of continuous fibers leading to very good material properties for both strength and stiffness [3,4].

However, for a conical shell, the exploitation of the conventional continuous winding method along the geodesic pathsand starting winding from the smaller diameter end results in ever decreasing material thickness towards the larger diameter end. This is not desired for a wind turbine tower since the loads and moments are maximum at the base section and the thickness is required to increase constantly along the tower starting from the smaller diameter end.

In the present article we investigate the effect of semi-geodesic winding on the winding angle, thickness, stiffness coefficients and vibration characteristics of filament wound composite conical shells of revolution which simulate wind turbine towers at the structural level. With controlled friction applied during the winding process, winding angle and thickness can be varied continuously along the axis of conical shell of revolution. Thus, preset friction applied during the filament winding process offers more design freedom by providing alternative fiber paths known as semi-geodesic paths which can be exploited especially for optimization purposes. Semi-geodesic fiber paths slightly deviate from the geodesic paths counting on the friction to keep the fiber in its proper position. In this case,the winding law is expressed by a differential equation and is morecomplex than the winding law for geodesic winding [4]. Figure 1 shows schematic pictures of geodesic and semi-geodesic winding which are used in filament winding of a shell of revolution.

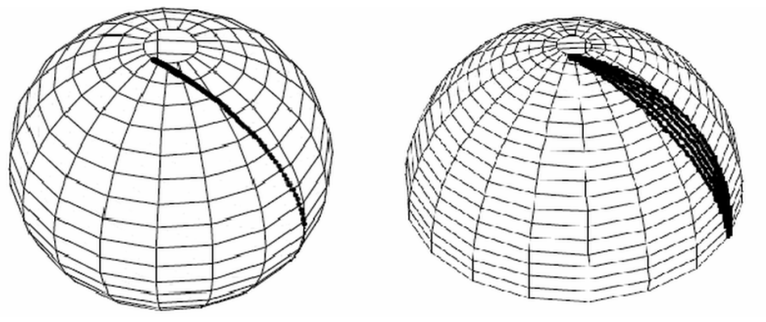

Figure 1. Geodesic path on a sphere *(left)* and semi-geodesic paths with different friction coefficients on a semi-sphere *(right)* [5]

The effect of semi-geodesic winding on the stiffness coefficients and free vibration characteristics of filament wound conical shells of revolution is studied by a numerical integration based solution method. For this purpose, multi-segment numerical integration technique is extended to the solution of the free vibration problem of composite shells of revolution which are wound along the semi-geodesic fiber paths counting on the preset friction used during the winding process [6,7].

2. Filament winding laws

In this section filament winding laws are briefly reviewed to aid the understanding of the variation of the winding angle and the thickness of filament wound shells of revolution along the meridian. It should be noted that the geometry and winding patterns are the basic parameters governing the manufacturing of a filament wound shell of revolution. Figure 2 shows a typical fiber path on the surface of a shell of revolution. In Figure 2, *R* represents the radius of the shell of revolution perpendicular to the shell axis and α represents the local winding angle. Slippage tendency is defined by the ratio of the tangential and normal components of the force directed towards the local radius of curvature of the fiber path denoted by f_r in Figure 2.

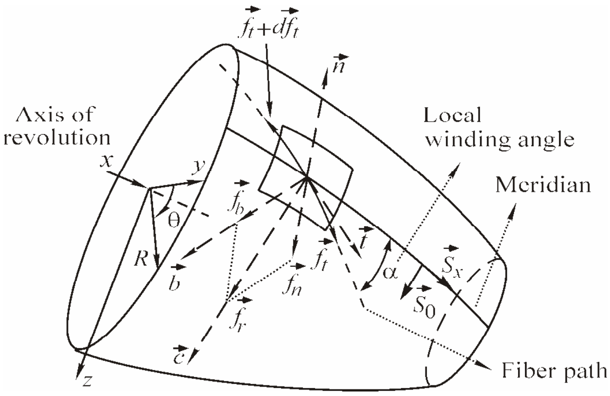

Figure 2. Fiber path on the surface of a general shell of revolution

2.1. Geodesic winding

Due to the fiber path stability requirements in the filament winding, the trajectory of the fiber path and the corresponding winding angles cannot be selected freely. Fibers are wound onto the mandrel along different paths which require stability and no slippage. The trajectory connecting two points on a surface according to the shortest distance over that surface is defined as the geodesic path. As this path represents the shortest distance, a fiber placed along this line will not slip when being pulled and no friction will be required to keep the fiber stable.

2.1.1. Winding angle. Winding angle at any axial location *(x,R)* for a conical shell of revolution is given in Eq. (1) [6]:

$$sin\,\alpha = sin\,\alpha_1 \frac{x_1}{x} = sin\,\alpha_1 \frac{R_1}{R} \tag{1}$$

where α_1 is the starting winding angle at one edge of the shell.

2.1.2. Thickness. In filament winding operation, any unit length of the fiber at any location on the surface of the shell of revolution brings with itself the same amount of matrix, and the number of fibers in a cross-section is always constant. Therefore, the amount of material in a circumferential slice of the shell of revolution, with unit fiber length at a fiber orientation angle of *α*, should remain constant.

Thus, it follows that the thickness of a general filament wound shell of revolution, at any axiallocation, can be calculated from Eq. (2) [6].

$$t = t_1 \frac{R_1\,cos\,\alpha_1}{R\,cos\,\alpha} \tag{2}$$

where t represents the thickness of a single ply at the axial location where the radius is R, and t_1 represents the thickness of a single ply at one edge of the shell of revolution where the radiusis R_1.

2.2. Semi-geodesic winding

Filaments do not necessarily have to be wound geodesically to be stable. Stable non-geodesic winding, often called semi-geodesic winding, can also be performed. This requires a little deviation from the geodesic paths, depending on the required friction to hold the fiber at the desired position. Semi-geodesic winding offers more design freedom but still remains limited to the available friction during the winding process.

2.2.1. Winding angle. For a conical shell of revolution starting with an initial winding angle $\alpha_1$at one edge of the shell (x_1,R_1), the application of friction coefficient *(fst)* yields Eq.(3) for the winding angle at the axial location*(x,R)* [8].

$$sin\,\alpha = \frac{R_1\, sin\,\alpha_1\, tan\,\beta}{fst(\,R_1 - R\,)\,sin\,\alpha_1 + R\,tan\,\beta} \qquad (3)$$

where β represents the cone angle of the shell structure. The friction coefficient (*fst*) can range from 0 (geodesic case) to 0.4 in practice [4].

2.2.2. Thickness. The thickness variation presented in Eq. (2) does not depend on the friction coefficient explicitly and it is valid for both geodesic and semi-geodesic winding. However, it should be noted that the winding angle at any axial location will change depending on the friction coefficient, which will vary the local thickness.

3. Tower dimensions

Five different size of tower chosen for the initial analysis is summarized in Table 1. Given numbers are only representative and they are based on the dimensions of the steel towers currently used in the wind energy market. Although, the size of a composite tower is expected to be notably different from its steel counterpart, these numbers are considered to be a good reference to check the validity of the presented model. Note that, five tower types selected for the analysis represent an increasing base diameter to height ratio. The effect of this non-dimensional parameter will be discussed in the coming sections.

Table 1. Analyzed tower dimensions

Type	**TurbinePower [kW]**	**Height [m]**	**Base Diameter [m]**	**Top Diameter [m]**
1	500	60	1.80	1.17
2	800	60	2.50	1.87
3	1500	80	3.50	2.66
4	3000	80	4.00	3.16
5	5000	80	4.50	3.66

For all tower types, cone angle is selected as 0.3^{o} and the wall thickness at hub height is assumed to be thicker than steel shell towers. The first reason for the thicker wall choice is the allowance for safer tower connection to the hub. The second reason is to prevent having thin sections after the winding process. As it will be discussed in the next section, for some configurations semi-geodesic winding doesn't show its effect until that filaments get close to the larger end. In those cases the thickness slightly drops or stays constant for a section of tower. A thicker start is a safety precaution to avoid weak sections.

For the results presented in this paper, the winding process assumed to be started from the small radius end and moves toward the larger end.

4. Semi-analytical method for frequency determination

In the current study, the effect of semi-geodesic winding on the free vibration characteristics of filament wound composite shells of revolution with variable radii of curvature is investigated. The analysis is performed by a semi-analytical solution method which is based on the numerical integration of the finite exponential Fourier transform of the fundamental shell of revolution equations. The governing equations for the free vibration analysis are initially obtained in terms of fundamental shell variables, and they are reduced to a system of first order ordinary differential equations by the application of finite exponential Fourier Transform, resulting in a two point boundary value problem. The boundary value problem is then reduced to a series of initial value problems, and the multi-segment numerical integration technique is used in combination with the frequency trial method in order to extract the natural frequencies and determine the mode shapes within a given range of natural frequencies.

Detailed explanation of the solution methodology is given by Kayran and İbrahimoğlu [7].

5. Variation of the thickness

Thickness variation of a shell structure is governed by the winding angle and from Eq. (2) it can be concluded that the thickness of the shell of revolution increases substantially when the fiber orientation angle approaches to 90^o. Practically, the increase in the thickness of the shell of revolution is caused by fiber concentration on a relatively small area due to the repetitive rotation of the fiber around the circumference.

For the geodesic winding, it is clear from Eq. (1) that if the winding starts at the small radius edge of the shell, as long as the initial winding angle is less than 90^o, then the winding angle will decrease along the meridian and it will always be less than 90^o. It means that the thickness will decrease along the meridian independent from the initial winding angle. Figure 3 shows the variation of the normalized thickness of the conical shell along the meridian for the tower types given in Table 1. In Figure 3, non-dimensional axial location is measured from the tower top which the small radius end of the tower. Axial location '0' corresponds to tower top which is the lower radius end of the tower and axial location '1' corresponds to the base of the tower which is the larger radius end. It should be noted that in case of geodesic winding, thickness of the shell decreases towards the large radius edge. In real tower systems such a thickness decrease is unacceptable, because although the radius of the tower increases towards the base of the tower, higher wall thickness is required to prevent local buckling and local failures.

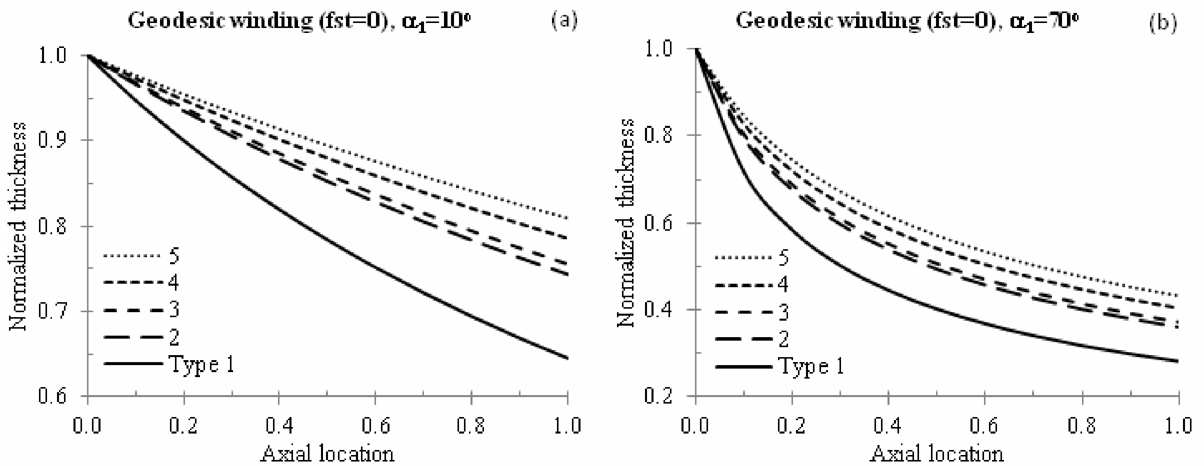

Figure 3. Variation of thickness for geodesic winding for all types of towers and two different initial winding angles (a)$\alpha_1=10^o$, (b)$\alpha_1=70^o$

On the other hand, Figure 4 shows that, for the semi-geodesic winding, depending on the shell geometry, initial winding angle and the available friction, the winding angle, hence the thickness may increase along the shell axis. This effect resulting from the selection of the semi-geodesic fiber paths makes semi-geodesic desirable for the tower application as an increasing thickness starting from the small radius end is required structurally.

Figure 4 shows that, for the initial winding angles less than 30^o, it is still not possible to get a continuously increasing thickness along the meridian using geodesic or semi-geodesic paths. For larger starting angles, with the careful selection of the friction coefficient, the desired thickness increase can be obtained. However, it should be noted that increasing starting angles result in high friction sensitivity. In Figure 4(d), when a friction coefficient of 0.006 is applied there is no thickness increase along the meridian. Once the friction is increased to 0.007, desired thickness increase along the shell is obtained. Sensitivity of the thickness to friction is a direct outcome of Equations (2) and (3) which give the thickness and winding angle variation along the shell axis, respectively. Friction sensitivity may require further investigations about the applicability and the capability of the winding machine. However, it is noted that if the winding operation is intercepted at intervals and winding is repeated in sections, gradually increasing thickness can be achieved with a wider range of friction coefficient. Another limitation is due to the sharp increase of the winding angle up to 90^o, meaning local thickness going to infinity during the winding process. In Figure 4, if the friction coefficient is increased carelessly, the winding process will have to be stopped due to the local fiber accumulation.

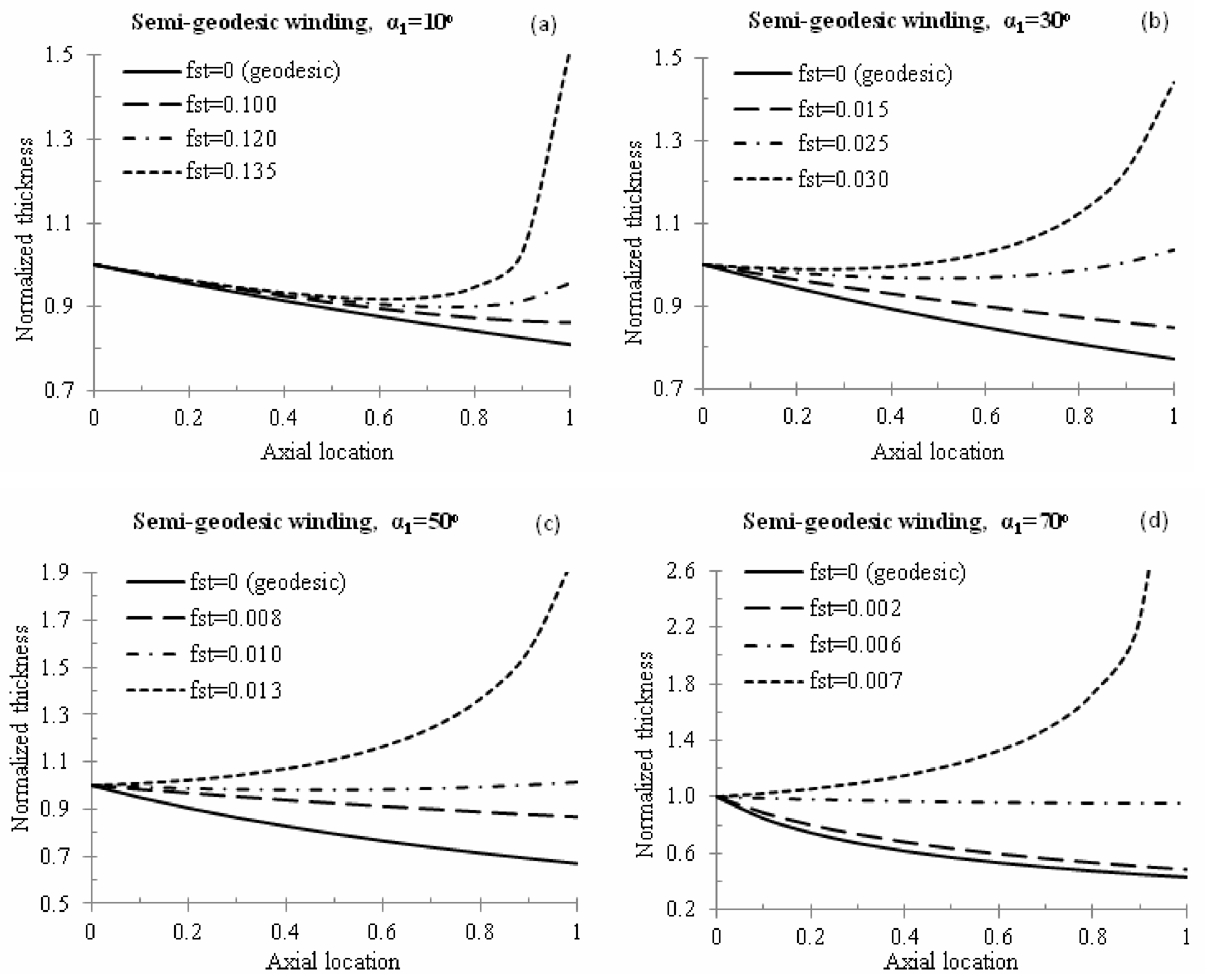

Figure 4. Effect of semi-geodesic winding on thickness for tower *type 5* and initial winding angles (a)$\alpha_l=10^o$, (b)$\alpha_l=30^o$, (c)$\alpha_l=50^o$, (d)$\alpha_l=70^o$.

Figure 5 shows the variation of the thickness for tower *types 1, 3 and 5* for three different friction settings. It is assumed that winding process starts with 50^o from the small radius edge for all three cases. From Figure 5, it can be seen that *type 1* tower is affected more by the application friction during the winding process. Similarly, *type 3* tower is more sensitive to the variations in friction coefficient compared to *type 5*. Having the same cone angle, one can conclude that as the base diameter to height ratio increases, application of higher friction is required to be able to increase the thickness along the meridian.

Also comparing Figure 4(c) with Figure 5(c), it is seen that as the base diameter to height ratio increases, a more continuous thickness increase rate is achievable, rather than a very sharp increase at the large end.

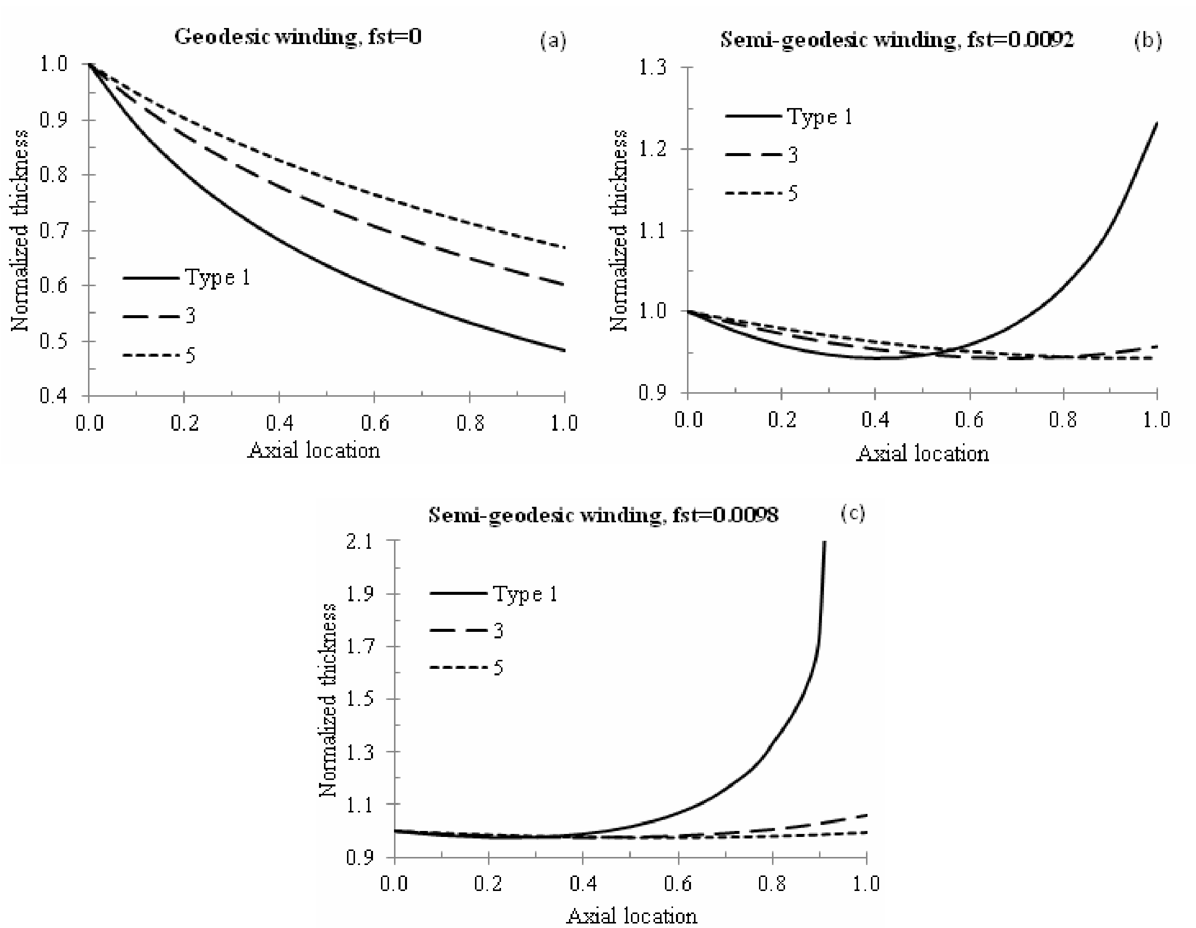

Figure 5. Variation of thickness for tower *types 1, 3 and 5* for an initial winding angle of 50^o (a)*fst=0(geodesic),* (b)*fst=0.0092,* (c)*fst=0.0098*

6. Variation of the stiffness coefficients

Due to the space limitations, only the results for tower *type 5* will be presented in this paper for both stiffness coefficients and natural frequencies. The shell studied is assumed to be manufactured from high modulus graphite epoxy with the following properties:

Modulus in the fiber direction: E_1=213.74 GPa, Modulus transverse to fiber: E_2=18.62 GPa, Poisson's ratio: ν_{12}=0.28, Shear moduli: G_{12}=G_{13}=5.171 GPa, G_{23}=4.137 GPa, Mass density: ρ=2051.88 kg m^{-3}, shell with symmetric layout $[(\theta, -\theta)_{10}]_S$ and with equal ply thickness at the starting edge of the winding which is the small radius edge. Ply thickness is selected such that the tower thickness at the hub height is 2.4 cm which is considered to be a reasonable thickness in order to carry out the calculations in the present study.

Figure 6 presents the variation of the meridional extensional (A_{11}) and meridional bending stiffness (D_{11}) coefficients along the shell axis. In Figure 6, A_{11} and D_{11} values are normalized with respect to their respective values at the small radius end.

Figure 6 shows that, the selection of semi-geodesic paths during the winding process, give control to the material designer to modify the stiffness coefficients along the meridian of the shell. Investigating Figure 6(b), one can conclude that the application of higher friction coefficient can result in increasing bending stiffness terms along the meridian. The effect of friction on the bending stiffness term can be explained by the layer thickness variation, since bending stiffness is proportional to the third power of the thickness, and higher thickness attained by the higher friction causes bending stiffness terms to be higher.

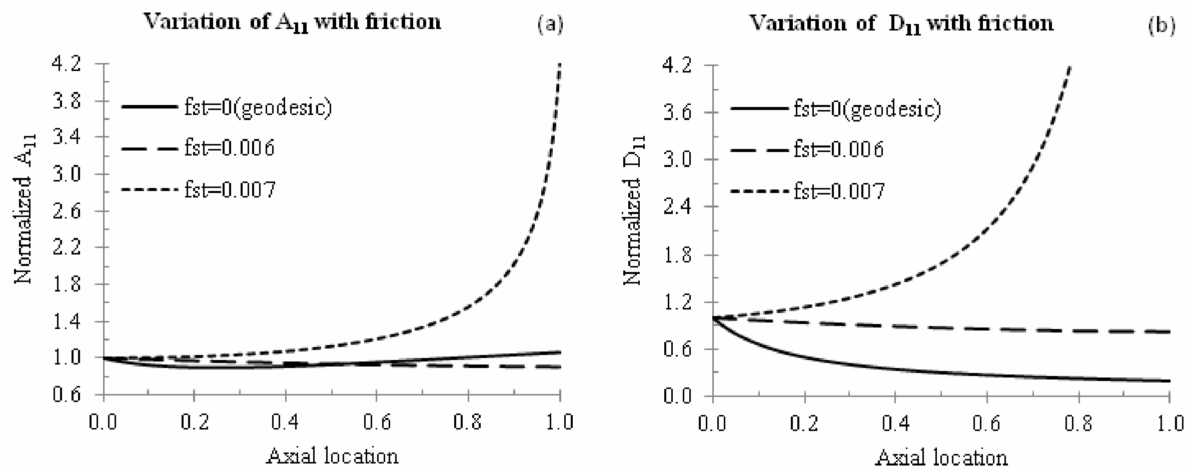

Figure 6. Variation of two critical stiffness coefficients (a) A_{11}, (b) D_{11} calculated for tower *type 5* assuming an initial winding angle of 70°.

7. Free vibration characteristics and mode shapes

For the conical shell of revolution, which represents the tower, Figure 7 gives the variation of the non-dimensional fundamental natural frequency, calculated by Eq. (4), with respect to initial winding angle for different friction coefficients for a structure which is clamped at the large radius end and free at the small radius end.

$$\Omega = \omega h\left(\frac{\rho}{E_1}\right)^{1/2} \tag{4}$$

For the tower type 5, Figure 7 shows the variation of the lowest natural frequencies for the circumferential wave number 1. It should be noted that circumferential wave number 1 corresponds to the beam mode of vibration of the conical shell of revolution which represents the composite tower. Figure 7 shows that unlike the geodesic winding, in case of semi-geodesic winding if the initial winding angle is increased further than 50°, the natural frequencies can be increased for the beam mode of vibration corresponding to n=1. For initial winding angles less than 50°, it is seen that for the particular tower, in case of geodesic winding frequencies are higher. It should be noted that in case of geodesic winding, thickness of the shell decreases towards the large radius edge. In real tower systems such a thickness decrease is unacceptable. However, frequency results given in Fig. 6 show that for initial winding angles less than 50°, towers wound by geodesic winding have higher frequencies than the towers wound using semi-geodesic fiber paths utilizing the preset friction. This behavior is not unrealistic, since frequency of the tower depends also on the inertia of the tower which is less for the geodesic winding case due to lower thickness.

Preliminary results on the effect of preset friction on the beam mode of vibration mode of the tower show that with the preset friction one can alter the dynamic characteristics of the tower. Therefore, preset friction applied during the filament winding process, is not only necessary to achieve an increasing thickness towards the larger radius edge of the tower, but it can also be utilized to change the dynamic characteristics of the tower favorably depending on the initial winding angle selected.

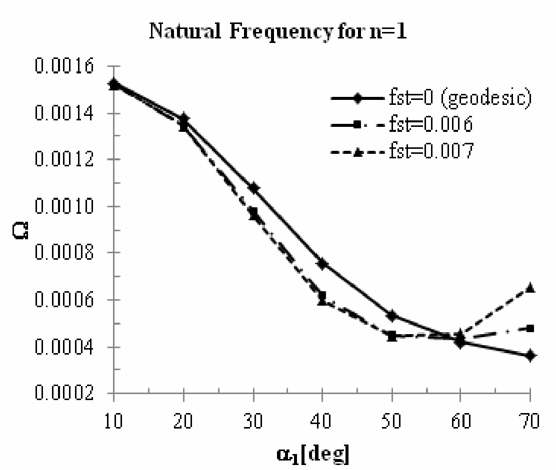

Figure 7. Lowest natural frequency vs. initial winding angle for tower *type 5*; *n=1*.

8. Effect of material selection

In this section the main goal is to compare the weight for towers manufactured from high modulus graphite/epoxy analyzed in previous sections with considerably cheaper glass composite materials and steel. Considered materials and their properties are given in Table 2. For composite materials, wall thickness of the tower is composed of symmetric layout $[(\theta, -\theta)_{10}]_S$ and with equal ply thickness at the starting edge of the winding which is the small radius edge. It should be noted that since the present study does not include the structural design of the tower, in order to make comparative study with the Glass/Epoxy and steel tower, thickness of the tower at the hub height is selected to be 2.4 cm for the Graphite/Epoxy case. This value is similar to the tower top wall thickness used for steel tower structures [9]. For the analysis in this section friction coefficient is selected as *fst=0.007* and initial winding angle is taken as 70^o using the geometrical properties of tower *type 5*.

Table 2. Material properties

	E-Glass	S-Glass	Graphite	Steel
E_1 [GPa]	39	43	213.74	210
E_2 [GPa]	8.6	8.9	18.62	
ν_{12}	0.28	0.27	0.28	0.3
G_{12}=G_{13} [GPa]	3.8	4.5	5.171	
G_{23} [GPa]	3.8	4.5	4.137	
ρ [kg/m^3]	2100	2000	2051.88	7850

Natural frequencies of the tower associated with the low meridional and the low circumferential vibration modes are primarily governed by the bending stiffness coefficient along the shell axis (D_{11}) [7]. Therefore, for the structural response of the tower bending stiffness along the tower axis, D_{11} stands out as the most important stiffness coefficient. In the present study, in order to create a basis for the comparison, high modulus graphite/epoxy stiffness in the bending mode (D_{11}) is considered as the most critical parameter and set as a reference. Then, initial layer thicknesses are determined for the E-glass/epoxy, S-glass/epoxy laminates and steel tower such that meridional bending stiffness coefficient of the E-glass/epoxy, S-glass/epoxy and steel towers matched the corresponding stiffness of the graphite/epoxy tower along the whole axis of the tower. Initial wall thicknesses for the E-glass/epoxy, S-glass/epoxy laminates and the steel tower are normalized with respect to the initial wall thickness of graphite/epoxy laminate, and normalized values are presented in Table 3.

Table 3. Initial wall thickness ratios normalized with respect to the initial layer thickness of Graphite/Epoxy

E-Glass/epoxy	1.3
S-Glass/epoxy	1.275
Graphite/epoxy	1
Steel	0.45

Note that above thickness values result in a similar stiffness variation for D_{11} for all materials; however other stiffness terms, such as bending stiffness coefficient in the circumferential direction or axial stiffness coefficients, are still considerably different. One can tailor materials according to the intended application and for wind turbine tower structures investigated in this paper, only the most critical mode is analyzed.

Figure 8 shows the thickness variation in the axial direction which results in the same meridional bending stiffness (D_{11}) characteristics.

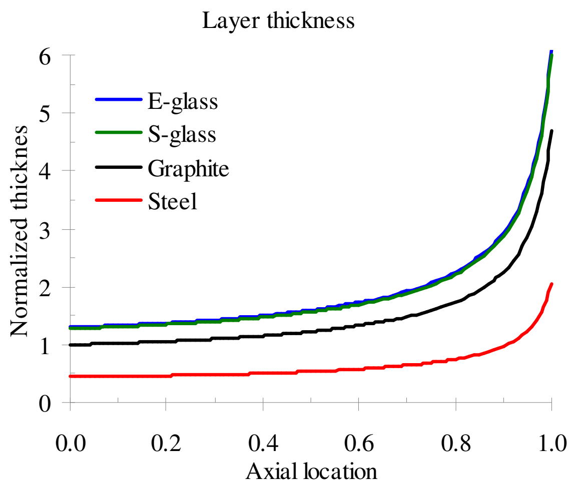

Figure 8. Layer thickness variation along the tower length normalized with respect to the initial thickness of graphite tower

From Figure 8, it can be concluded that, fitting to the initial expectations, glass materials require larger thickness values to achieve the meridional bending stiffness of carbon as a result of their mechanical properties. On the other hand, steel tower requires lower thickness over the whole span of the tower. Figure 9 which shows the cumulative tower masses in metric tons calculated using four different tower materials. The values shown in Figure 9 are the total masses of the tower. Figure 9 shows that although the steel tower requires lower thickness to match the bending stiffness coefficient of graphite-epoxy tower over the complete span of the tower, total weight of the steel tower is %66 higher than the graphite-epoxy tower because of higher mass density of steel. It can also be concluded that, fitting to the initial expectations, glass materials require larger thickness values to achieve the meridional bending stiffness of carbon as a result of their mechanical properties. In conclusion, tower mass can increase remarkably up to 33.5% if E-glass is used instead of graphite, and 24.6% if S-glass is selected as the tower material.

It should be noted that in the sample analysis presented, all towers have the same tower top/root radii and the cone angle. Since the present study is not intended to give a complete tower design, tower radius and cone angle are kept fixed for all material systems. It is considered that with full composite or hybrid composite towers, the tower radius can be decreased with proper selection of the filament winding parameters. Thus, transportation of composite towers can be easier compared to complete steel towers.

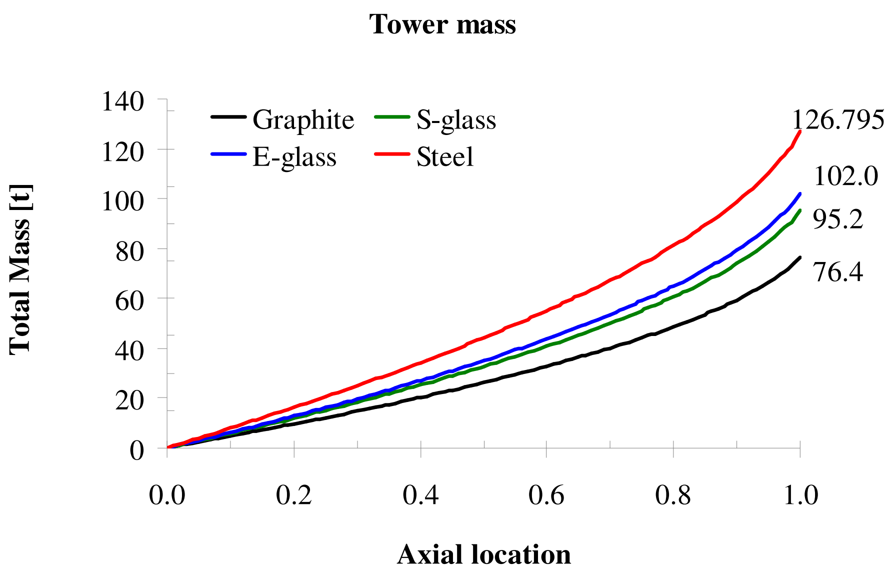

Figure 9. Cumulative tower mass in metric tons calculated using three different tower materials

8. Conclusion

Traditional geodesic path dependency of the filament winding method defined by the winding laws limited the options of the designer compared to other manufacturing techniques. In the present study, the effect of semi-geodesic winding on the variation of the winding angle, the thickness and the natural frequencies of composite shells of revolution is investigated for the purpose of improved tailorability during the design process. Filament winding manufacturing technique is intended to be used on new generation composite wind turbine towers which are a priori lighter, more corrosion resistant, and easier to manufacture and transport. Sample calculations presented in this article show that the use of higher friction coefficient during the winding process results in higher winding angle and thickness along the whole meridian of the shell of revolution. Winding angle and thickness are two important parameters which affect the stiffness coefficients and natural frequencies of the composite tower. Present study showed that the preset friction applied during semi-geodesic winding is an important design parameter which can be controlled to obtain gradually increasing thickness from tower top to the base of the tower, and favourably alter the dynamic characteristics of the composite towers. One drawback addressed in the article with regard to the filament winding of towers utilizing semi-geodesic fiber paths is that to achieve increasing thickness towards the larger radius edge, the range of friction coefficient that can be utilized is rather limited if the winding of the complete tower is performed in one shot. It is obvious that winding of wind turbine towers in one shot is not practical, and more logical manufacturing would be to divide the tower into sections and wind the shorter tower sections separately. It is noted that if the winding operation is intercepted at intervals and winding is repeated in sections, gradually increasing thickness can be achieved with a wider range of friction coefficient. A major advantage of semi-geodesic winding is that manufacturing of the composite tower by semi-geodesic winding automatically produces tapered wall thickness. If the winding starts at the lower radius end of the tower, gradual increase of the thickness towards the larger radius end is possible. Thus, wall thickness of the tower can be adjusted automatically in tapered form which is very desirable to achieve optimum tower structures.

Although the comparison of the towers made from graphite/epoxy, glass/epoxy and steel materials shows the definite advantage of the graphite/epoxy tower over the glass/epoxy and steel towers in terms of stiffness and total mass, the cost of the carbon material precludes its use as the tower material. However, it is considered that full glass/epoxy towers or hybrid glass/epoxy-steel towers can be an alternative to the current steel towers of wind turbine systems if the cost issue is studied well. Semi-geodesic winding offers advantages in manufacturing variable thickness, thus variable stiffness, composite towers, and variable stiffness concept stands out as an important structural aspect to exploit for optimization purposes. It should also be noted that with the use of full composite or hybrid composite-steel towers, the tower radius can be decreased with proper selection of the filament winding parameters. Thus, transportation of composite towers can be easier compared to complete steel towers both in terms of weight and size.

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