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Composite Materials and Renewables: Wind Energy

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In the aerospace industry the benefits of exploiting the excellent specific strength and stiffness properties of composites in terms of lightweight structural design are immediately apparent. Other advantages of fibre reinforced plastics, such as the relative ease to manufacture complex shapes, and their excellent fatigue and corrosion resistance, have made FRP composites increasingly attractive in the renewable energy sector. Considering the predicted growth of production in wind turbines, accounting for nearly 60% of the entire advanced composites market by 2020 [1], a wide variety of scientific material has been published in recent years regarding the optimisation of advanced composites usage in wind turbines. Furthermore, considerable "blue-sky" research is being conducted that aims to take advantage of the multifunctional capabilities of advanced composites in order to extend their integration in less obvious applications such as tidal turbines and solar panels. The objective of this post is to give a general overview of the novel research conducted to facilitate these new technologies, while giving a more detailed insight into the challenges that engineers face in designing the new generation of 100m wind turbine blades.

Overview

In the last 25-30 years the use of wind turbines for electricity generation has grown from a grass-root "green" initiative to a financially sustainable

primary energy resource [2]. The increasing maturity of the industry can be traced from the small 100-150 kW turbines constructed throughout the 1980s to the large 2-5 MW projects installed both on- and offshore today. This growth can largely be attributed to innovations in the integration of lightweight fibre-reinforced plastics (FRPs), which have facilitated increasingly larger blade lengths as shown in Figure 1. Fibre-reinforced plastics represent a prime material choice for wind turbine blades in terms of structural efficiency since the high specific stiffness limits tip deflections, reduces gravity-induced loading and decreases rotor inertia. Furthermore, the excellent fatigue resistance of FRPs helps to minimise material degradation and maintenance costs over the 20-year design lifespan [4]. A few of the currently largest wind turbines including their blade materials are summarised in Table 1.

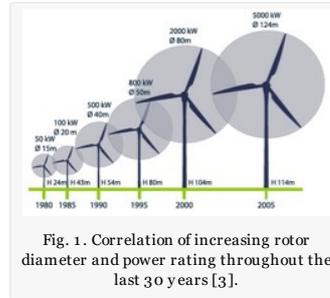


Fig. 1. Correlation of increasing rotor diameter and power rating throughout the last 30 years [3].

Table 1: Summary of various Megawatt wind turbines with defining characteristics and blade material choices [5] – [9].

Company	Model	Blade Length (m)	Rotor ø (m)	Power (MW)	Blade Materials
Vestas	V120-3MW	54.65	NA	3	glassfiber/carbon spars with glassfiber airfoil shells
Enercon	E-126	NA	127	7.5	glassfiber/epoxy with steel mesh for lightning strike
Siemens	SWT-3.6-120	58.5	120	3.6	glassfiber/epoxy composite
Gamesa	G136-4.5 MW	66.5	136	4.5	Organic matrix composite reinforced with fiber glass or carbon fiber
Suzlon	CGP 2.1 MW	NA	99	2.1	glassfiber/epoxy composite

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However, as governmental subsidies run out the long-term growth of wind technology depends on increasing the energy capture efficiency and therefore turbine sizes. This will require further innovation in lightweight structural design by means of multi-functional and stronger materials, as well as cost-effective manufacturing and installation. A current base model wind turbine section is shown in Figure 2.

The Challenge of Designing a 100m Blade

Glassfibre reinforced plastics (GFRPs) were selected in the early wind turbine days because of good material availability and well-documented processing technology. The weight of a turbine blade can statistically been shown to increase with the cubic of the length as shown in Figure 3, resulting in a gravity-induced bending moment that varies with the *fourth* power of the blade length. To improve on this exponential trend carbon fibre reinforced plastics (CFRPs) are now replacing GFRPs in large turbine blades due to their superior specific stiffness and strength properties. To date a hybrid CFRP-spar/GFRP-skin design is the most widely established solution (Table 1), since this presents the best compromise between improved performance and the higher cost of carbon fibre [11].

Currently the design of wind turbine blades is based around placing unidirectional fibres along the spar axis to provide bending stiffness, while $\pm 45^\circ$ layers in the skins and webs are used to resist twisting and shearing [12]. Sandia National Laboratories performed a trade-off study concerning innovations in materials and manufacturing processes to ascertain an improved, cost-effective blade design for the next multi-megawatt turbine generation [11]. The researchers conducted finite-element analyses of a baseline fully E-glass/epoxy blade under extreme gust conditions, which showed that the increasing gravity-induced bending loads called for structural reinforcement at the blade root if the blade length was to be scaled up to 60m. Rather than reinforcing the existing design with more E-Glass, replacing the outer half of the spar cap (50% span) with a stitched CFRP laminate was found to result in 32% and 16% reductions in total blade mass and manufacturing cost respectively. The researchers based their decision of the span-wise extent of replacing GFRP with CFRP on a parametric assessment aimed at finding the best compromise in terms of manufacturing cost and increased structural rigidity.

In the future full-span CFRP spars will lead to further reductions in weight and tip deflection with a direct effect on the rotational inertia, aerodynamic performance and energy capture efficiency of the blade. Furthermore, it is estimated that full GFRP rotor blades of 120m in diameter will require 2.5 tons of resin [3] such that through-thickness dissipation of exothermic heat at the thick root sections during cure will become increasingly problematic. In terms of cost, it is currently unclear if the increased demand in carbon fibre by the aerospace, energy and automotive sectors will drive prices up or lead to economies of scale that will further reduce CFRP costs [11]. In the future carbon nanofibre-GFRP hybrid materials may be potential candidates for use in future turbine blades as they combine high strengthening and stiffening potential of carbon nanofibres with relatively cheaper GFRP [13]. The use of carbon fibre for wind turbine blades is further discussed in [14] – [16].

Manufacturing of Turbine Blades

Wet hand lay-up in open moulds has naturally developed as the traditional manufacturing technique for GFRP wind rotor blades due to its process maturity and cost-effectiveness compared to other techniques [2]. In 2008 a survey of wind turbine operators revealed that 7% of all wind turbines blades have to be replaced as a result of failure induced by manufacturing defects [17]. Furthermore, with the expected doubling of production volume in the next 5 years [1], there has been a natural drive towards faster yet more consistent manufacturing processes that facilitate superior material properties. Toward this end pre-preg technology and vacuum-assisted resin transfer moulding (VARTM) have emerged to be promising replacement techniques [11].

VARTM is currently the industrial norm since combining and curing the resin and fibres in one step significantly lowers manufacturing costs. Nevertheless, two of the largest manufacturers in the world, VESTAS and GAMESA, use pre-preg technology to guarantee more repeatable material properties, higher fibre-volume fractions and reduce the degree of fibre-waviness [17]. The main reductions in cost of the VARTM process can be attributed to the use of thicker ply lamina and the elimination of high-temperature and pressure autoclave curing [11]. However, the use of thicker plies exacerbates the magnitude of ply drops in a tapered blade and increases the likelihood of hidden flaws, which may result in the development of delaminations and a shorter fatigue life compared to pre-preg laminates [19] – [20]. Quite recently VARTM has been proven to lend itself to process automation with a subsequent scope for further reductions in cost, and improvement in the aforementioned mechanical shortcomings. MAG Industrial Automation Systems have developed the Rapid Material Placement System (RPMPS), which is an automated blade moulding facility that is capable of laying-up glass and carbon fibre on moulds, cutting the manufacturing time of a 4.5m blade by 85% [21]. Grande (2008) outlines the Siemens' innovative IntegralBlade technology that makes blades in one piece, unlike the typical blade that is made in two shells and glued together [22]. The process is based on vacuum infusion with a closed outer mould and an expanding, flexible inner bladder. The IntegralBlade system reportedly offers several advantages, including shorter cycles and more efficient

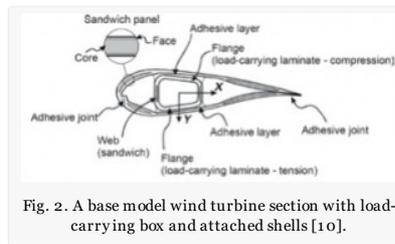


Fig. 2. A base model wind turbine section with load-carrying box and attached shells [10].

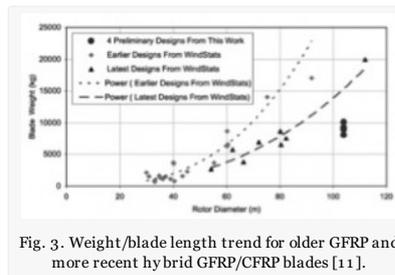


Fig. 3. Weight/blade length trend for older GFRP and more recent hybrid GFRP/CFRP blades [11].



Fig. 4. Siemens IntegralBlade Manufacturing Technology [18]

use of manpower and space. Additionally, there are no tolerance issues between the shells and structural spars. Most importantly the blade is an integral structure with no glued joints that could weaken and potentially expose the structure to cracking, water entry, and lightning strikes.

It is clear that both pre-preg technology and VARTM have merits in terms of their application to large turbine blades but the myriad of design factors and possible volatility of material costs currently prohibits the definition of an optimum solution. To guarantee the financial sustainability of wind power the evolution of current manufacturing technology should be of paramount importance, and automated systems such as RPMPS point in the right direction.

Offshore Wind Turbines

As the power of wind turbines has grown and the blade sizes have increased, there has been an increasing amount of wind turbines installed in

offshore locations; this presents a number of problems in supporting the turbine. In shallow waters up to about 30m in depth, the turbine can be supported with a monopile. Beyond this depth, the monopile must have some other supporting members and beyond 50m the turbine needs to be on a floating platform with cabled supports into the seabed [25]. Floating a wind turbine presents unique challenges as the platform must resist the motion of the sea and minimise pitch, roll and yaw whilst still maintaining the weight of the turbine. However, the wind industry has not converged on a standard design and more research is needed to fully overcome the challenge. Floating wind turbines open the possibility for combining wind and tidal power in one construction site and therefore increase the energy captured per installed structure. This hybrid design may be a solution to offsetting the high initial capital costs of renewable energy systems.

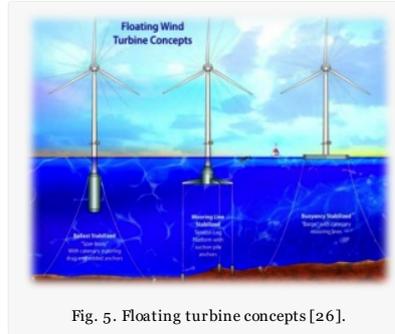


Fig. 5. Floating turbine concepts [26].

Future Developments – Thermoplastics and Morphing

Recently there has been a drive towards using thermoplastic resins in wind turbines in order to take advantage of their higher toughness, faster curing times, unlimited shelf life and the potential for recycling. Although BASF have developed a new acrylonitrile styrene acrylate (ASA) polymer for wind turbine use, the inferior fatigue resistance and high moisture absorption restricts the matrix to being used in small-scale GFRP turbines [27]. However, in the light of the forecasted increase in demand of wind turbines Andersen et al. (2007) make the prediction that by 2040, 380 000 tonnes of FRP will have to be disposed of annually [28]. As around 60% of the scrap created during the incineration of FRP is inorganic ash, and only 30% of FRP waste is currently being recycled, further research into overcoming the structural shortcomings of thermoplastics is essential for a truly eco-friendly use of advanced composite in wind technology. Furthermore, research at TU Delft suggests that the ability to fusion-bond thermoplastics may make it cost-effective to redesign turbine blades with more internal stiffening elements that ultimately facilitate a lighter design solution [29].

In the future the anisotropic behaviour of non-symmetric laminates may be exploited by forcing blades to twist under strong gusts; thereby reducing fatigue loading and allowing the design of longer blades [20]. To improve fatigue life Ong et al. (1999) suggested rotating the primary span-wise fibres by off-axis 20°, which lead to the design of the TX-100 prototype developed by Sandia National Laboratories with 45% volume fraction of carbon fibre at 18° off-axis angle in the spar cap, and 13° for the skins [30] – [31].

Although the TX-100 is less stiff than its non-twisting CX-100 counterpart it increased the fatigue life by 150% [20]. Hulskamp et al. (2011) demonstrated another method of reducing fatigue loads using sensors and actuators to control trailing-edge flaps along the span of the blade. A significant load reduction was found with this small-scale experiment, however issues with scale-up and the integration and reliability of the electronics must still be addressed for this technique to have industrial applications [33]. Continuously cambered morphing trailing edge flaps have significant advantages over hinged flaps as they reduce the complexity of the design leading to a lower part count, simpler manufacturing techniques and increased aerodynamic efficiency [34]. Towards this end Daynes & Weaver (2011) have successfully manufactured a prototype of a continuously cambered morphing trailing edge as shown in Figure 4 [32]. The trailing edge produces the same lift characteristics as a traditional hinged flap with 34.4% less flap tip deflection (13.1 degrees to 20 degrees), thereby reducing the required actuator work by 69.2% under maximum aerodynamic pressure loading. The trailing edge flap is manufactured from a NOMEX honeycomb core sandwiched between woven CFRP upper and silicon lower skins, and actuated by a CFRP push-pull linkage as schematically depicted in Figure 9.

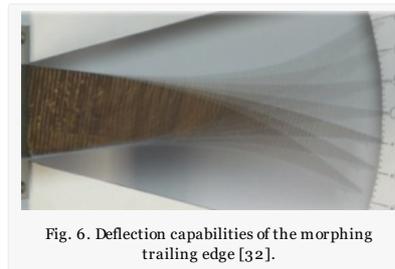


Fig. 6. Deflection capabilities of the morphing trailing edge [32].

Corrosion and erosion of FRP blades are substantial problems for offshore wind turbines. Offshore turbines suffer from increased wind, UV and high salinity with wetting-drying cycles that have been found to increase corrosion. Erosion may also occur in a number of environments due to ice formation on the blades and the impact of sand, earth and insects. An exhaustive review of wear in FRP materials is presented in [35]. Surface coatings have been considered in order to reduce the effects of corrosion and erosion. Non-stick coatings may be used to resist insect-impact and tapes have been applied to the leading edge of blades in order to protect this erosion-prone area [36]. Coating GFRP with electroless Ni-P has also been found to increase resistance to NaCl corrosion [37] and superhydrophobic coating has proved very successful at preventing water and UVC damage, although more work is needed

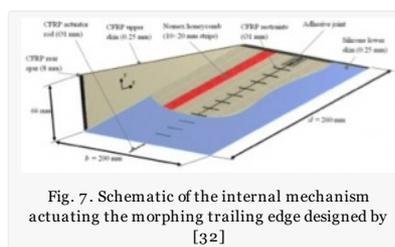


Fig. 7. Schematic of the internal mechanism actuating the morphing trailing edge designed by [32]

to prevent icing [38]. Lightning protection is also an issue, with taller blades and carbon reinforcements making turbines increasingly attractive to lightning strikes. One suggestion is to use two down conductors instead of one, which protect the turbine by connecting it to the ground [39].

Conclusions

As the demand for renewable wind energy will continue to increase in the coming years there is a real incentive to build considerably larger wind turbines in order to improve the overall energy capture efficiency. Carbon fibre reinforced plastics will play an essential role in facilitating longer turbine blades but certain reluctance prevails in the industry regarding the higher material costs compared to glass fibre reinforced plastics. For this reason, improvements in component quality produced by out-of-autoclave processes such as VARTM and the development of cost-effective pre-preg materials is of paramount importance. Another promising alternative to reducing blade weight and manufacturing cost is the integration of multifunctional composites, where embedded technologies such as SHM or self-healing will enable the reduction of safety factors and therefore decrease material usage. As the use of advanced composites continues to grow a major research effort will have to focus on developing new resin systems that lend themselves to ecological recycling.

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