York, C. (2008) High Specification Offshore Blades. Work Package: 1C – Blade Materials. Technical Report. University of Glasgow.

# HIGH SPECIFICATION OFFSHORE BLADES

# Phase 1 Report for ITI Energy

## Work Package: 1C – Blade Materials

**Issue Date: 6/06/2008**

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**Number: 48276/1-2**

## Academic Perspective

**Blades are regarded as the only component unique to wind turbine blades. They represent only 10 – 15% of the total system cost so the perception is that a reduction in the cost of energy through blade cost improvements is constrained. However, the use of novel materials technologies is predicted to reduce design loading by 10 – 20%, which may indirectly lead to substantial cost savings. The aim of this report is therefore to identify materials technologies offering potential for improved blade performance and their potential for (patentable) intellectual property exploitation.**

## I. Background

Blades are regarded as the only component unique to wind-turbines: they capture all of the energy and produce all of the system loads . Blades themselves represent only 10% – 15% of the total system cost, hence the ability to reduce the cost of energy (COE) through blade cost improvements are constrained. However, studies on innovative blade design, particularly through the use of novel structures and materials technologies, predict a 10% – 20% decrease in design loading, which may translate into substantial savings for major components such as the tower, drive train and blades themselves, or offset the effect of increased blade size. It has been suggested that a modest cost premium in the blades may still result in improved cost of energy through other system economies. The challenge therefore lies in the identification of novel materials technologies, which will most readily translate to a reduction in COE.

## II. Introduction

Veers et al.[1] present one of the relatively few peer reviewed archive journal papers addressing current and future trends in state of the art technologies for design, materials and manufacturing of wind turbine blades. This is an important review article, providing a comprehensive overview of the substantial resource archives of notably the Sandia National Laboratory, National Renewable Energy Laboratory (NREL), Energy Research Foundation (ECN) and others, together with AIAA/ASME wind energy symposia and general literature, spanning between 1994 and 2003.

It is clear from this article and the supporting literature that commercial wind turbines have grown to the point where blade weight increase is now a critical design concern. Current efforts to address this issue include the incorporation of new materials together with efficient manufacturing processes through which new and innovative structural design concepts may be realised. Research in the area of structural materials now focuses on the optimal use of commercial carbon fibres and glass/carbon fibre hybrids, which includes composite laminate tailoring for load alleviation; often coupled with innovative blade geometries. Low-cost commercial-grade advanced materials, such

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[1] Veers PS, Ashwill TD, Sutherland HJ, Laird DL, Lobitz DW, Griffin DA, Mandell JF, Musial WD, Jackson K, Zuteck M, Miravete A, Tsai SW, Richmond JL. Trends in the Design, Manufacture and Evaluation of Wind Turbine Blades. *Wind Energy* 2003; **6**: 245-259

as carbon fibre, are seen as enabling materials which will permit a step change in blade design from heavy blades using tradition low-cost glass to lightweight blades using higher-cost carbon.

## III. Glass-fibre Materials for Wind turbine application

Two major databases have come from the study of glass-fibre composites: the European FACT database[1,2] and the US DOE/MSU composite material fatigue database[3,4]. The EU database is regarded as being more comprehensive than the US database, but covers fewer materials; both are continuously updated[5]. Extensive testing has demonstrated that fibre architecture and fibre content are fatigue life design drivers, e.g. a dramatic reduction occurs when fibre volume exceeds a critical level. A recent review of materials degradation in utility scale offshore wind turbines[6] concludes that fatigue is the most significant degradation mechanism in current wind turbines: limiting life, reliability and performance.

Similar fatigue life reductions occur due to ply drops in tapered laminates, bonded stiffeners and sandwich panel terminations[7,8]. However, data suggests that large (safety factor) knockdowns can be avoided by dropping one ply at a time and/or at a particular location or by surrounding ply drops with continuous plies; *rules which incidentally have been understood by the aerospace community for many years. Indeed, it would seem that this applies to much of the new technology reported in the turbine blade literature.* To stress this point still further, it is also been reported that testing under spectral loading has demonstrated that a linear damage assessment such as Miner's rule is non-conservative (often by a factor of 10 on predicted service lifetime) when based on constant-amplitude coupon data*; a fact that has been taught to aerospace undergraduate students for many years.*

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[1] De Smet BJ, Bach PW. Database FACT: fatigue of composites for wind turbines. *ECN-C-94-045*, ECN, Petten, 1994.

[2] Kensche CW (ed). Fatigue of materials and components for wind turbine rotor blades. *EUR 16684*, European Commission, Luxembourg, 1996.

[3] Mandell JF, Samborsky DD. DOE/MSU composite material fatigue database: test methods, materials, and analysis. *SAND97-3002*, Sandia National Laboratories, Albuquerque, NM, 1997.

[4] Mandell JF, Samborsky DD, Cairns DS. Fatigue of composite materials and substructures for wind turbine blade. *Contractor Report SAND2002-0771*, Sandia National Laboratories, Albuquerque, NM, 2002.

[5] Mandell JF, Samborsky DD. DOE/MSU composite material fatigue database, 2003 update, Internal Report, Sandia National Laboratories, Albuquerque, NM, 2003.

[6] McGowan, J.G.; Hyers, R.W.; Sullivan, K.L.; Manwell, J.F.; Nair, S.V.; McNiff, B.; Syrett, B.C. A review of materials degradation in utility scale wind turbines. Energy Materials: Materials Science and Engineering for Energy Systems 2007; **2**, 41-64

[7] Mandell JF, Samborsky DD, Cairns DS. *op. cit.*

[8] Van Leeuwen H, van Delft D, Heijdra J, Braam H, Jorgensen E, Lekou D, Vionis P. Comparing fatigue strength from full scale blade tests with coupon-based predictions. *2002 AIAA/ASME Wind Energy Symposium*, Reno, NV, 2002; 1–9.

Known deficiencies in these composite material fatigue databases have however led to a major new EU funded programme, entitled 'Optimat blades' covering: variable amplitude loading; multiaxial stress states; extreme (environmental) conditions; thick laminates and repair; residual strength and condition assessment; and design recommendations for glass-fibre/polyester composite material. Carbon fibre composites will be addressed at the end of the programme. *This may explain why there is little current cross-fertilisation from the aerospace industry.*

Initial studies on carbon fibre composites indicate that the critical problem, from a fatigue standpoint, is fibre misalignment; the claim being that small misalignments can produce a dramatic reduction in fatigue strength.

## IV. Glass-fibre Materials for Wind turbine application

Three fundamental carbon fibre implementations can be indentified: bulk replacement of load-bearing glass-fibre materials, selective (hybrid) reinforcement; and new, total blade designs. The first two cases prove to be cost-effective in otherwise conventional blades; carbon fibre is generally only placed in the load-bearing spar structure. The third case offers potential for design innovations that can improve the performance and reduce loads. Interestingly, from the aerospace perspective, Airbus, Bombardier and others have only relatively recently begun a collaborative venture to design and manufacture the first all-composite-wing.

Carbon fibres possess higher modulus (by a factor of three), lower density (by a factor of two-thirds), higher tensile strength and reduced fatigue sensitivity[1]. The disadvantage is increased cost; however, this may be mitigated to a certain extent by a reduction in blade weight. Note that strain-related properties of lower-cost varieties of carbon composites, particularly in compression, are significantly poorer than those of aerospace–grade materials; they also show increased sensitivity to reinforcement architecture, manufacturing method etc. Ultimate compressive strains for large-tow carbon-fibre pre-impregnated laminates (pre-pregs), with relatively straight fibres, are quoted as being between 1 – 1.2%. These values fall to around 0.6 – 0.8% for low-cost fibres (larger tow size) and thicker laminates formed using Resin Transfer Moulding (RTM) techniques. Pre-pregs are regarded as being acceptable for blades, but their ultimate strain values provide a relatively small margin when considered together with other factors that affect compressive strength, e.g. fibre misalignment or waviness, etc. RTM techniques have significantly less margin.

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[1] Mandell JF, Samborsky DD. DOE/MSU composite material fatigue database, 2003 update, Internal Report, Sandia National Laboratories, Albuquerque, NM, 2003.

In summary, the limited data available to date for low-cost forms of carbon fibre laminates suggest that the static ultimate compressive strain may limit designs. Furthermore, pre-preg manufacturing techniques are suggested as the most promising, since they provide the greatest control over fibre alignment and straightness.

## V. Other Materials for Wind turbine applications

S-glass is the stronger, more expensive cousin of E-glass, which is used in the majority of current turbine blade designs. However, the enhanced properties of S-glass offer an alternative to the yet more expensive carbon fibre. Griffin and Ashwill[1],[2] present preliminary structural designs for hybrid carbon/glass-fibre blades for turbine system ratings up to 5 megawatts. This work is complementary to scaling studies[3,4] for the identification of sizing limits in critical components and technologies, e.g. alternative composite materials, manufacturing processes and structural designs. These studies suggest that are very few fundamental barriers to the cost-effective scaling of current commercial blade designs and manufacturing methods for sizes up to 120m diameter. The most substantial constraint appears to transportation costs, which are said to rise sharply for lengths above 46 m; more recent studies suggest that this restriction may be less relevant to offshore installation.

Hybrid materials have been suggested as a mid-span transition from a glass-fibre (inboard) to a carbon/glass hybrid spar cap (outboard). However, after consideration of structural issues concerning ply splicing and ply drops, in addition to the manufacturing complexity of such a transition, a preferable option would be to extend the load-bearing carbon inboard to the blade root. The concept of hybrid materials is currently being exploited in the aerospace industry, the most notable material being Glare$^{TM}$, which through the interleaving of aluminium and glass-fibre layers is claimed to possess enhanced damage tolerance and fatigue properties. The concept of terminating the metallic layers in a similar way to that proposed in the hybrid carbon/glass mid-span transition has not previously been proposed. Introducing metallic materials may also mitigate the problems associated with lightening strike. Another aerospace application which may be applicable to wind-turbine construction is the use of a lightweight

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[1] Griffin DA, Ashwill TA. Alternative Composite Materials for Megawatt-Scale Wind Turbine Blades. *2003 AIAA/ASME Wind Energy Symposium*, Reno, NV, 2003, 191-201.

[2] Griffin DA, Berry D, Zuteck MD, Ashwill TA. Development of prototype carbon-fiberglass wind turbine blades: conventional and twist-coupled designs. *2004 AIAA/ASME Wind Energy Symposium*, Reno, NV, 2004, 1-12.

[3] Griffin DA. Blade system design studies Volume I: Composite technologies for large wind turbine blades. *SAND2002-1879*, Sandia National Laboratories, Albuquerque, NM, 2002.

[4] Griffin DA. Blade system design studies Volume II: Preliminary Blade Designs and Recommended Test Matrix. *SAND2004-0073*, Sandia National Laboratories, Albuquerque, NM, June 2004.

syntactic film core (SynCore™) as a partial replacement for carbon fibre material; this is similar in concept to a thin sandwich structure. However, special attention needs to be given to the balance between the overall laminate buckling strength and the limiting strain constraints of the two materials; an issue affecting any hybrid material. This strategy was found to be more suited to deep, two spar wing-box configurations rather than slender multi-spar wing-boxes[1].

Materials and structural designs that reduce blade weight are of benefit for megawatt-scale blades, as this would reduce the need for additional reinforcement in the regions of the trailing edge and blade root transition to accommodate the gravity induced edgewise fatigue loads; although gravity loading is a design consideration, it is not regarded as an absolute constraint to scaling of conventional materials. For cost-effective blade design at this scale, however, consideration of blade stiffness and the associated tip deflections become of paramount important. Current strategies for addressing these issues involve composite material tailoring.

## VI. Composite material tailoring

Blade twist has a direct influence on the angle of attack of the aerofoil section, which translates to a change in aerodynamic loading, affecting power output of the turbine. Hence, the notion of blades that twist as they bend (and/or extend), provide additional opportunities for enhanced energy capture or load alleviation[2]. Coupling behaviour can of course be achieved in either an active or a passive manner, but the passive approach seems to be gaining momentum due to merits of simplicity and economy. Recent blade designs with curved (spar) plan-form introduce similar coupling characteristics but without the requirement for exotic composite tailoring; coupled together these features may lead to further augmentation in the overall design characteristics.

Laminate coupling can be introduced using biased lay-ups in the blade skins and/or spars if the bias on the upper surface is mirrored by that on the lower one. *Simulations* predict a substantial increase in fatigue damage for twist/coupling towards stall. However, by contrast, fatigue damage is reduced when blades twist towards feather; and without reducing average power.

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[1] York CB. Buckling analysis and minimum mass design procedures for composite wing box structures. *AIAA J. Aircraft* 2006; **43**, 528-536.

[2] Lobitz DW, Veers PS. Load Mitigation with Bending/Twist-coupled Blades on Rotors Using Modern Control Strategies. Wind Engineering 2003; **6**, 106-117

Veers and Lobitz have patented[1] a laminate system in which a substantial majority of fibres in the blade skin are inclined at angles of between 15 and 30 degrees to the axis of the blade, to produces passive adaptive aeroelastic tailoring (bend-twist coupling) to alleviate loading; all this they claim, without unduly jeopardizing performance. However, this is far from the truth when wing-box simulations using laminates with different coupling characteristics, but otherwise possessing identical stiffness properties, are compared.

The coupling behaviour due to off-axis rotation is readily achieved even with an initially uncoupled laminate: following the off-axis rotation however, both extension-shear and bend-twist coupling are introduced, together with degradation in primary-axis stiffness. This is in stark contrast to other methods of developing coupled laminates, many of which require special algorithms to derive the competing configurations, but which do not suffer the same degradation in primary-axis stiffness.

A recent proof of concept study compared bend-twist coupling in wing-box structures possessing top and bottom skin panels with either extension-shear coupling only or both extension-shear and bend-twist coupling. The first laminate is a non-symmetric ply configuration and is of a laminate form only recently identified[2]. The second laminate form can be produced by an unbalanced symmetric ply configuration[3]. These two laminates were carefully chosen to isolate the effects of bend-twist coupling; this was achieved by selecting laminates which had identical stiffness terms, except for the additional terms producing bend-twist coupling in the second laminate. Results revealed negligible difference in the static response, suggesting that only laminates with extension-shear coupling are necessary in producing bend-twist coupling in wing-box structures. The effect of bend-twist coupling at the laminate level is therefore not only undesirable with respect to static instability, since it gives rise to a reduction in compression buckling strength, but that it is unnecessary in terms of achieving the required compliant static deflection response.

Extending this study to incorporate a 20° off-axis laminate reveals a favourable twist rotation, see Table 1, however it does so at the expense of substantial tip deflection and reduced buckling strength.

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[1] Veers PS, Lobitz DW. Load attenuating passively adaptive wind turbine blade. *US Patent No. H2,057*, 2003

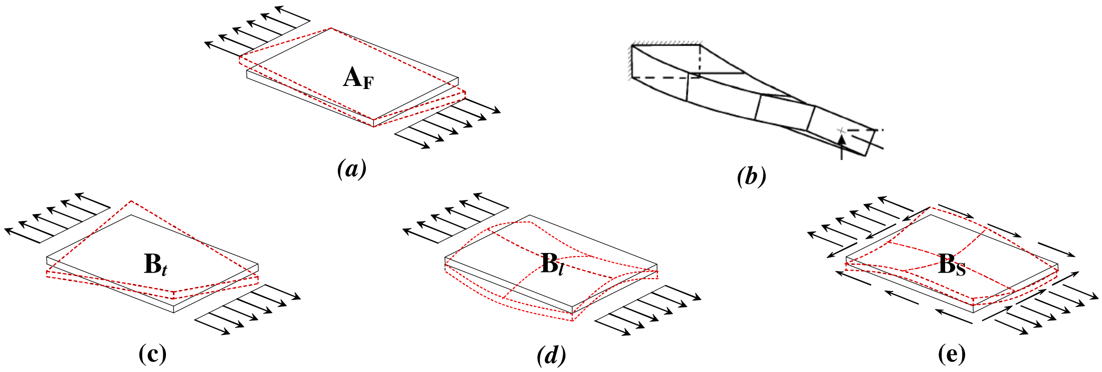
[2] York CB. On composite laminates with extensional-anisotropy. *49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Schaumburg, Illinois, AIAA-2008-1752, 2008.

[3] Baker D. Response of Damaged and Undamaged Tailored Extension-Shear-Coupled Composite Panels. *AIAA J. Aircraft* 2006; **43**, 517-527.

**Table 1 – Comparison of coupled laminate responses**

| Laminate orientation/behaviour | Tip Deflection/Rotation | Plate buckling load |
|---|---|---|
| Axis-aligned/Uncoupled | Datum: 0%/0° | Datum: 0% |
| 20° Off-axis/Uncoupled | 32.5% / 0.42° | -10.4% |
| Axis-aligned/Extension-Shear | 14.1% / -0.26° | +0.0% |
| Axis-aligned/Extension-Shear & Bend-Twist | 39.1% / -0.22° | -1.5% |

Passive load shedding in very large wind-turbine blades, see Fig. 1(b), requires coupled laminates, see Fig. 1(a), as an enabling technology. It is clear that the extensional and bending stiffness matrices possess one of two forms: either fully uncoupled or fully coupled; the isotropic form is excluded in this characterisation because they have been shown[1] to represent subsets of the fully uncoupled form. By contrast, the coupling stiffness behaviour has several complex forms, see Fig. 1(c) – (e), and laminate configurations have yet to be derived, characterised and catalogued. These new laminate forms offer potential for augmentation of bend-twist and axial-twist coupling. Patents relating to bend twist coupling of wind-turbine blades are listing in the appendix.



*(a)* *(b)*

(c) *(d)* (e)

**Figure 1 – (a) Coupling ($A_F$) between extension and shear, producing (b) bend-twist coupling for passive load shedding in very large wind-turbine blades. Isolating the bending-extension-coupling responses of the laminate forms offer new and as yet unexploited bending-extension-coupling responses: (c) stretching-twisting – $B_t$, (d) stretching-bending – $B_l$ and (e) interlocked shearing- twisting and stretching-bending – $B_S$.**

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[1] York CB. Stacking sequences for Extensionally Isotropic, Fully Isotropic and Quasi-Homogeneous Orthotropic Laminates. *49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Schaumburg, Illinois, AIAA-2008-1940, 2008.

## VII. Conclusions and Recommendations

Passive load alleviation in very large wind-turbine blades requires coupled laminates as an enabling technology and offers great potential for improved blade performance as well as potentially patentable intellectual property.

Current methodologies currently focus on the spar cap components, representing a limited proportion of the extreme fibre material of the blade profile; little attention appears to be given to the composite aerofoil shell.

Off-axis material alignment, currently adopted in twist-coupled blades, can be shown to be far from optimum; algorithmic tailoring must be employed to achieve matched stiffness and coupling enhancements. However, laminate configurations satisfying all of the stiffness and coupling response requirements present major challenges from a reverse engineering perspective, given that a database or expert system of laminate configuration properties is currently unavailable. This extends to the identification of tapered laminates, to facilitate ply drops, which not only maintain similar coupling properties, but offer enhanced fatigue and damage tolerance.

All of the technologies discussed above are thought to lie within Technology Readiness Level 1-2.

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# Appendix – Patents

## Flexure having pitch flap coupling

**United States Patent** **4,037,988**

**Laird** **July 26, 1977**

### Abstract

A flexure for connecting the root end of a rotor end of a rotor blade to a rotor hub in a bearingless rotor assembly. The flexure inherently induces a change in pitch angle in accordance with a change in flap angle. The flexure, which may form an integral portion of the rotor blade, is constructed of a composite material made of fibers secured to one another by a bonding agent. The fibers are arranged in two sets. The variation of the blade pitch angle in accordance with the blade flap angle is accomplished by either varying the number of fibers between the two sets or varying the angle of each set to the longitudinal axis of the flexure, or both.

Inventors: **Laird; George William** (Greenville, DE)

Assignee: **The Boeing Company** (Seattle, WA)

Appl. No.: **05/684,935**

Filed: **May 10, 1976**

## Load attenuating passively adaptive wind turbine blade

**United States Patent** **H2,057**

**Veers , et al.** **January 7, 2003**

### Abstract

A method and apparatus for improving wind turbine performance by alleviating loads and controlling the rotor. The invention employs the use of a passively adaptive blade that senses the wind velocity or rotational speed, and accordingly modifies its aerodynamic configuration. The invention exploits the load mitigation prospects of a blade that twists toward feather as it bends. The invention includes passively adaptive wind turbine rotors or blades with currently preferred power control features. The apparatus is a composite fiber horizontal axis wind-turbine blade, in which a substantial majority of fibers in the blade skin are inclined at angles of between 15 and 30 degrees to the axis of the blade, to produces passive adaptive aeroelastic tailoring (bend-twist coupling) to alleviate loading without unduly jeopardizing performance.

Inventors: **Veers; Paul S.** (Albuquerque, NM)**, Lobitz; Donald W.** (Albuquerque, NM)

Assignee: **Sandia Corporation** (Albuquerque, NM)

Appl. No.: **09/758,166**

Filed: **January 10, 2001**

## Aerodynamically-stable airfoil spar

**United States Patent** **5,269,657**

**Garfinkle** **December 14, 1993**

### Abstract

A structural spar is provided that provides beneficial flexural-torsional coupling to an airfoil so that flexural excursions of the airfoil induces torsion in the spar so as to change the pitch angle of the airfoil in such a manner as to the oppose the flexure, thereby ameliorating the excursion.

Inventors: **Garfinkle; Marvin** (Philadelphia, PA)

Appl. No.: **07/780,807**

Filed: **October 22, 1991**