York, C. (2008) High Specification Offshore Blades Work Package: 1D: Blade Manufacturing. Technical Report. Department of Aerospace Engineering, University of Glasgow.

HIGH SPECIFICATION OFFSHORE BLADES

Phase 1 Report for ITI Energy

Work Package: 1D – Blade Manufacturing

Issue Date: 6/06/2008

Prepared by:
Department of Aerospace Engineering
University of Glasgow

Number: 48276/1-3

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 advance manufacturing technologies is expected to directly reduce cost savings. The aim of this report is therefore to identify manufacturing technologies offering potential for facilitate the construction of very large offshore blades and their potential for (patentable) intellectual property exploitation. This report should be read in conjunction with Package 1C.

I. Background

Blades of up to 50m length have been built by both Nordex and GE Wind using hand lay-up of primarily glass structure with open-mould, wet processes; 40 m blades with carbon augmented wood-epoxy have been built by NEG Micon; Vestas has a long history of manufacturing with pre-preg glass and; TPI Composites is manufacturing 30 m blades using specialised vacuum-assisted resin transfer moulding (VARTM) process. More novel approaches include the use of a dry pre-form with a single-shot infusion, eliminating the need for secondary bonding.

II. Introduction

Although several manufacturers are still using open-mould, wet lay-up processes, increasingly stringent environmental restrictions will likely result in a move toward processes with lower emissions. In current production, two methods are emerging as the most common replacement for traditional methods. These are the use of pre-impregnated materials and resin infusion, with VARTM being the most common infusion method. Both VARTM and pre-preg materials have particular design challenges for manufacturing the relatively thick laminate typical of large wind turbine blades. For VARTM processes, the permeability of the dry pre-form determines the rate of resin penetration through the material thickness. For pre-preg material, sufficient bleeding is required to avoid resin-rich areas and eliminate voids from trapped gasses. An elevated temperature post-cure is desirable for both pre-preg and VARTM processes. Current commercial pre-preg materials generally require higher cure temperatures (90° - 110°) than epoxies used in VARTM processes (60° - 65°). Heating and temperature-control/monitoring becomes increasingly difficult as laminate thickness is increased. Mould and tooling costs are also strongly affected by the heat requirements of the cure cycle. The use of automated pre-forming and automated lay-up technologies are also potential alternatives to hand layup in the blade moulds. Benefits could include improved quality control in fibre/fabric placement and a decrease in both hand labour and production cycle times.

It is expected that for a given fibre, laminate manufactured with pre-preg resin will have the best static and fatigue strength. As a result of induced waviness and other details, dry fabrics that are then infused by VARTM are expected to have lower strength performance. However, pre- preg materials have historically been more expensive and require higher cure temperatures than liquid epoxy resin systems. Currently, the majority of turbine blade manufacturers use a “wet” process, either VARTM or a open mould layup and impregnation. Dry layup of preforms and subsequent infusion therefore remains as a process of high interest for the wind industry.

It is clear from the current literature that uncertainties remain regarding: the optimum strength performance of commercial carbon fibres in a low-cost fabric/pre-form process with VARTM infusion; the strength and production cost comparisons of pre-preg forms and; the performance/cost ratio comparison between large and moderate tow fibres.

III. Manufacturing alternatives

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.

---

[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.

IV. Aerospace perspectives on the manufacturing of wind-turbine blades

The DTI have recently produced a number of related documents[1,2,3], which have been summarised and augmented in the following subsections in the context of technologies which are directly transferable.

Cost-effective composites

Aerospace industry composite materials have been specifically developed to increase structural efficiency, particularly in stiffness critical applications. However, weight savings have to be balanced against material and manufacturing costs. The acquisition and through-life costs of composite components can be considerably more expensive than heavier metallic components. More than half the cost of a composite structure is associated with lay-up, cure and assembly. Acquisition and through-life costs can be significantly reduced by low-cost manufacturing and reliable condition monitoring. Recent reviews of the composites industry have highlighted the need for more cost-effective manufacturing processes for high-performance composites: the emphasis now being on consistency, longevity and cost-effectiveness, rather than minor increases in mechanical performance.

Automated processes help to reduce cost, although scale-up may impact on what is achievable. Studies in civil aircraft show a weight saving of up to 25% but with a cost penalty in the region of 30%. Manufacturing processes for composites do however tend to require a long cure cycle, reducing the achievable parts/hour. For example, a typical aircraft component manufactured by RTM may have a three-hour cycle time.

Although cost reduction and light weight are still the main drivers, the rapid development of structures required for the Boeing 787 has meant the continued use of pre-pregs in the short term. Research and development funding has

---

[1] Department of Trade and Industry. HYBRIDMAT 2: Strategies in the joining of hybrid materials in automotive structures – a mission to France and Germany. *Global Watch Mission Report*. 2004.

[2] Department of Trade and Industry. HYBRIDMAT 3: Advances in the manufacture of advanced structural composites in aerospace – a mission to the USA. *Global Watch Mission Report*. 2006.

[3] Department of Trade and Industry. HYBRIDMAT 4: Advances in the manufacture of 3-D pre-form reinforcement for advanced structural composites in aerospace – a mission to the USA. *Global Watch Mission Report*. 2006.

been directed towards development of out-of-autoclave curing processes, resin infusion processes, and integrated stiffened structures with one-stage cure. The emphasis for future programmes is very much on major capital investment in facilities and process development.

Composites offer potential weight and cost saving advantages for small, thin section wing structures. For larger wing sections, composites tend to be weight neutral. Cost savings have been achieved mainly by improvements in automated lay-up equipment, used mainly for large flat or shallow curvature components, which are now capable of laying 50-150 mm wide tapes at speeds of 15-20 m/min with minimum wastage. Automated tow placement machines, used for surfaces with complex curvature, are now also reaching maturity and can place up to thirty 3 mm wide tapes in one pass at speeds of 5-10 m/min. Such machines represent high capital investment cost but are justified by labour savings approaching 90% and time saving approaching 80% compared to hand lay-up. The material formats required to feed these machines currently are 5-15% more expensive than hand-lay material. Invar remains the material of choice for any mould tool used for lay-up. Even very large tools, such as the tool for the Boeing 787 cockpit section, involve Invar sections supported by a frame. As component size increases, however, metal tooling has increasing disadvantages in respect of: physical mass, particularly for rotating tools used with automated tape lay-up machines and; high thermal mass which lengthens process times and curing costs. The challenge is therefore to develop either a damage resistant composite material for tool surfaces, or a highly toughened primary structure resin matrix capable of low-temperature cure.

Woven cloth and pre-forms

Two significant advantages of a woven pre-form over the traditional fabric cutting and layering fabrication are a net shape perform that can be woven to a high fibre volume, reducing the de-bulking required in the moulding tool and improving inter-laminar properties. Complex shapes can be woven with multidirectional fibre orientation in-plane, 0º/90º, ±45º, quasi isotropic, XY, orientations and through-thickness, Z fibres at 90º or some other angle to the in-plane fibres. The Z fibres can be positioned in localised areas of the component or throughout the perform structure to enhance inter-laminar properties. Other advantages that 3-D woven performs the high conformability of thick fabric, the option of using different fibre types in the weaving process, and the ability to vary Z-fibre volume content in the fabric from 1% to over 30%. Composite structures with integral 3-D woven reinforcement are less susceptible to delamination, more damage tolerant and impact resistant than non-crimp fabric (NCF), but with lower strength and stiffness.

Thick pre-forming technologies

Many parts are now starting to utilise dry fabric materials as the cost saving is around two thirds of the price of standard pre-impregnated materials. Parts are generally made using non-crimp fabric (NCF), assembled using stitching and then manufactured using resin transfer moulding (RTM). The pre-forming techniques (covering 2-D and 3-D reinforcements) can provide a staggeringly wide range of geometric shapes and fibre architectures but little is understood about the sensitivity of composite structures to the pre-form architecture and variability. Exploitation of the current technology is much more advanced in the USA than in the UK.

The composite manufacturing sector is reaching a level of maturity in aerospace, leading to the acceptance of these materials in primary structures. These 3-D preforms, along with more conventional fabric forms and direct fibre deposition techniques, will need to demonstrate levels of repeatability and process control comparable to metallic materials and solutions in order to design structures with narrower safety margins and extract the maximum value from the materials.

The more advanced net shape performing process, 3-D weaving and 3-D braiding are not yet production processes; whilst they do deliver performance improvements, how cost effective these processes are is still not clear.

Damage tolerance

Damage tolerance in aircraft design is critical. Bird strike is unlikely in wind turbine blade, but severe hail storms are. After impact the surface can show no indentation but delamination may have occurred within the laminate.

The leading and trailing edges of a wing, often manufactured separately, use a variety of materials, from thermosets to thermoplastics, and sandwich structures using honeycomb cores. The centre wing-box is generally carbon fibre composite with spars and spar caps up to 50 mm thick at the root. Thermoset resins are the preferred composite matrix, and are chosen for their good thermal and mechanical properties.

Materials now being proposed for the ‘all’ composite Boeing 787 aircraft, are mostly pre-pregs cured at 180°C in an autoclave. The pre-pregs being used are tough, high glass transition temperature epoxies with good damage tolerance.

Joining of materials

Research work has shown that bonding can form a good joint, with most of the tests failing in the laminate rather than the adhesive. However, issues relating to the joining of carbon fibre composites and metallic materials in aircraft design include: differences in thermal expansion and addressing lightning strike, when using non-conductive materials. However, solutions have been developed in aerospace for mechanically bonding and over-curing composite to metal and composite to composite. The differences in thermal expansion of hybrid structures are important, however, the aerospace industry tends to design thicker structures to handle any increased stresses.

V. Novel manufacturing solutions for wind-turbine blades

Filament winding is an obvious solution for introducing helically would filaments onto a blade mandrel. However this procedure cannot produce bend-twist coupling material properties in the finished blade. Furthermore, the weight of a rotating mandrel for very large offshore blade applications is likely to be impractical. Axial-twist coupling may be achieved using this method, but this coupling mechanism seems unlikely to be of great benefit in axially stiff composite blades. A solution is therefore to use a stationary mandrel with a revolving carousel of tow filament dispensers which travels along the axis of the mandrel. To achieve the desired ply orientations for a bend-twist coupled blade, i.e. angle-plies that are mirrored on the top and bottom surfaces of the finished blade, the carousel must be able to slew between an angle normal to the axis (90° plies) of the mandrel and an acute angle sufficient to satisfy the angle-ply orientation requirements. It is conceivable that Automatic Tow and/or Automatic Tape Laying devices may be employed on such a carousel.

VI. Recommendations

Filament winding is considered to the most cost-effective solution for manufacturing very large wing turbine blades and one which offers a potential for intellectual property development. This is a concept that was discussed between ITI Energy, DCS and Glasgow University two years ago. However a recommendation here is that a slewing mechanism is a necessary addition to the technology to permit the winding of skewed axis filaments, necessary to facilitate the correct alignment for the introduction of bend-twist coupling. All of the technologies discussed above are thought to lie within Technology Readiness Level 1-2.

Bibliography

Department of Trade and Industry. HYBRIDMAT 2: Strategies in the joining of hybrid materials in automotive structures – a mission to France and Germany. *Global Watch Mission Report*. 2004.

Department of Trade and Industry. HYBRIDMAT 3: Advances in the manufacture of advanced structural composites in aerospace – a mission to the USA. *Global Watch Mission Report*. 2006.

Department of Trade and Industry. HYBRIDMAT 4: Advances in the manufacture of 3-D pre-form reinforcement for advanced structural composites in aerospace – a mission to the USA. *Global Watch Mission Report*. 2006.

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