

Innovative design procedures for large-scale wind turbine blades

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Developing a large-scale blade is a key issue in the current competitive wind turbine market simply because a wind turbine with large-scale blades provides the most effective way of reducing the cost of energy (COE). Rotor blades up to 128 m in diameter for wind turbines with power ratings up to 2.5-6.15 MW are already available in the market, and are expected to grow more in future thanks to the development of innovative blade designs.

One of the critical issues associated with large-scale blades is weight. According to the square/cubic law, weight grows as the cubic power of blade length while energy extracted increases as the square power. Over the years, the weight growth exponent has been lowered from 3 to 2.3 due to advanced composite materials and design improvements. However, there are still many potential weight-reduction opportunities related to large-scale blade technology development. In fact, a weight reduction in the blade becomes possible not only when using a low-density material such as carbon fibres but also with an innovative design using new lay-ups and new blade geometry, eventually reducing the overall cost of energy.

Standard wind turbine blade systems are mainly characterized by a straight main axis with twist and tapered cord and a blade made of E-glass fibres with a fibre angle of 45 degrees. Innovation is required to reach more cost-effective large blades. New composite materials, new lay-ups and new blade geometry are three innovative approaches to building

cost-effective, lightweight, large-scale wind turbine blades. Material costs are continuously changing, and the use of glass fibres (E-, S- and R-glass) and carbon fibre should be explored considering density/cost, specific stiffness and strength. The various fibre angles should also be used to best meet the design requirements. Rather than just a straight blade, various blade geometries should be investigated to increase power efficiency and to alleviate aerodynamic loads and increase fatigue life. Pre-bending will certainly alleviate the use of expensive high-stiffness materials.

A fully-coupled aerodynamic-structural iterative analysis can be useful for adaptive wind blade designs. Several iterations of the aerodynamic analysis followed by structural analyses are performed until a blade design is finalized. More particularly, this process is needed to include the bend-twist and/or sweep-twisting coupling behaviour in order to alleviate passively the aerodynamic loads. The computational fluid mechanical analysis mainly aims to increase aerodynamic efficiency through lift and drag forces. The structural analysis includes a prediction of deflection, ultimate strength, buckling load and fatigue life. However, full three-dimensional modelling does

not always lead to a better design. In order to effectively explore a new and different design realm, designers need a flexible, user-friendly design tool, providing an insight into the behaviour of blades. The tool should be flexible enough to easily perform coupled aerodynamic-structural iterative analyses as well as manual iterations between analyses. It also needs an optimization module or the capability to perform a parametric study, leading to a high-performance blade complying with the design requirements imposed by industrial standards. The effects of each design variable or parameter (materials, fibre angles and shape) on blade loads and strength need to be visualized.

A lightweight blade would, in most cases, require high-specific-stiffness and strength materials, which generally increases material costs. However, such high performance should offset the cost increase: the overall system cost can be reduced by using a lightweight blade since this reduces the costs incurred in the tower and nacelle. Cost increases related to the use of diverse fabrics and innovative design can also be lowered by a business alliance between material suppliers, non-crimp fabric (NCF) and blade manufacturers, resulting in lower total material and manufacturing costs.

Innovative blade design

Blades are only 10% of the total system cost while blades generate all the energy, and an innovative blade design is an effective way of reducing the overall cost of energy. A substantial part of the laminate is built-up by UD, biaxial and triaxial NCF. The UD NCF is about 50% of the NCF fabrics, usually for spar caps and trailing and leading edges. The triaxial NCF is for root build-up and internal and external skins. Hybrid composite materials, new lay-ups with optimized ply angles, and new blade geometry (new shape, SWEPT, FlexSys, etc.) are three essential factors for accomplishing light weight, large-scale wind turbine blades.

Material selection: hybrid composite materials

Hybridization of composite materials can certainly provide blade designers with more design freedom, enabling lower weight while meeting the strength and stiffness requirements at acceptable costs. In addition to conventional E-glass fibres, advanced glass fibres (R- and S-), carbon fibres and their hybridization are certainly strong candidates for the skin as well as the shear web and spar caps. Figure 1 shows that self-weight tip deflection decreases from E-glass to carbon fibre, and the associated material cost increases. The wind industry is already familiar with the use of hybrid fibres. Global manufacturers like Vestas Wind Systems (Randers, Denmark) and Gamesa (Zamudio, Spain) have been using carbon fibres as the primary reinforcement in the spar caps for large-scale blades. Similarly, LM Glasfiber (Lunderskov, Denmark), the world's lea-

ding manufacturer of wind turbine blades, has also used carbon as reinforcement in the shell laminate on the trailing edge. Siemens (Aalborg, Denmark) is leading the development of a new type of blade made of E-glass fibre using an innovative manufacturing process called integral blade vacuum infusion, eliminating adhesives and increasing blade integrity.

The stress analysis of multi-directional NCF requires special attention. Homogenized stiffness can be calculated for each NCF laminate and used to perform the overall structural analysis. But designers often make mistakes when determining the ultimate strength of the multi-directional NCF (biaxial or tri-axial) by treating it as a building block with anisotropic stiffness and strength. Failure criteria such as Puck and Tsai-Wu should be applied to each ply, not to a multi-directional NCF as a whole. So each ply (either a glass or carbon layer) characterized by one ply angle should be treated as a building block even for multidirectional NCF. Micromechanics-based multi-scale approaches prove much more versatile not only when determining the effective stiffness but also when performing strength and fatigue life predictions.

The durability of materials is the most difficult and important property to characterise. It varies depending on the material (fibres and resin) system, lay-up sequence with different fibre angles and curing process. The Goodman fatigue approach is the most popular method for durability analysis, and its use is recommended by industrial standards such as IEC and GL

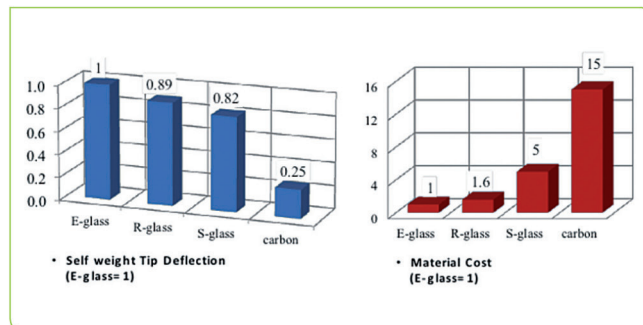
to ensure a 20-year fatigue life simply because there is no alternative so far. But the Goodman approach is simply far from experimental test results and lacks a physical basis. A fatigue life prediction method based on micro-mechanics of failure (MMF) recently became available, providing the most powerful method to analyze the durability of composite blades. This way, only the constituents (fibre and resin) and interface need to be characterized, and other factors such as fibre architecture, material hybridization and different angles are analyzed using a computational representative element model.

New laminates: shallow fibre angles

Current composite design practices are in most cases limited to conventional rules and lay-up sequences: unidirectional laminates (UD), bi-axial (± 45) and triaxial $[0_2/\pm 45]_s$ laminates, allowing only thickness variation. The highest strength and stiffness in the longitudinal direction are reduced as the off-axis angle increases. But the in-plane shear strength increases as the off-axis angle increases. Therefore, the optimal selection of proper fibre angles requires an accurate estimation of normal and shear stresses. The transverse normal resultant (not the transverse stain) is negligible because of the geometric slenderness of the blade. As depicted in Figure 2, if the conventional fibre angle 45 degrees is changed to a 25-degree fibre angle, the effective stiffness and strength of a triaxial NCF laminate are 25% and 233% higher respectively, whereas the shear strength decreases by only 5%. Fatigue durability is also much higher at

Fig. 1: Weight and material cost comparison for different fibre-reinforced composite materials

Fibre types	E-glass	R-glass	S-glass	Carbon
Density [g/cm ³]	2.55-2.64	2.55	2.46-2.49	1.7
Young's modulus [GPa]	70-77	84-86	86-90	220
Pristine strength [MPa]	3450-3790	4400	4590-4830	4500-5500
Failure strain [%]	4.5-4.9	5	5.4-5.8	1.2



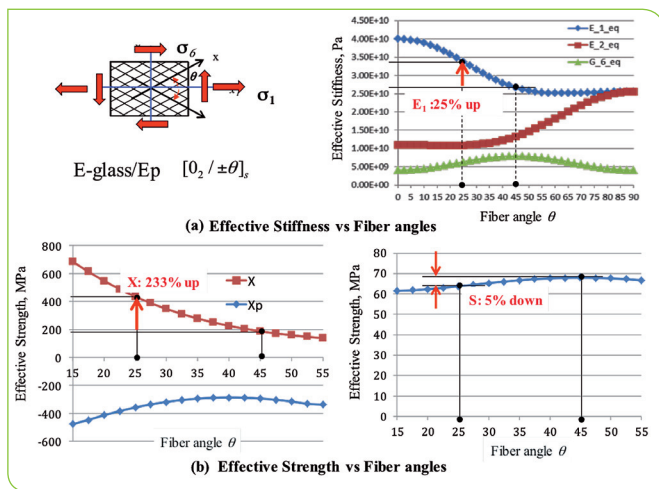


Fig. 2: Variation of the effective (a) stiffness and (b) strength of a triaxial NCF E-glass/epoxy laminate with fibre angles composite materials

25 degrees than at 45 degrees, as demonstrated in a result based on the MMF.

Optimal fibre angles in $[0_2/\pm\theta]_s$ depend on the normal and shear stress ratio and on the buckling resistance. The normal stresses are caused by flapwise and edgewise bending moments whereas shear stresses (or shear flow) are caused by the twisting moment and shear force. A multi-cell beam theory can be used to calculate the shear flow distribution without resorting to a full three-dimensional shell model. The shear flow and buckling resistance are in favour of 45 degrees. However, the shear resistance difference between 0 degrees and 45 degrees is not significant, say within 10%. In most cases, a 25-degree angle provides enough shear resistance to support the shear flow and buckling resistance. Hence, the entire skin of the blade, except the trailing and leading edges, spar cap and shear web, can consist of $[0_2/\pm 25]_s$ triaxial NCF. The buckling resistance can be further increased by including a thicker core material (such as balsa).

The shear webs are mainly made of 45-degree biaxial fabrics, but shallower angles, e.g. 30-degree biaxial NCF, can be more effective since they better resist longitudinal strains at the top and bottom parts which are attached to the spar caps. A conventional shear web has two legs, but one web is also possible, greatly sim-

plifying the manufacturing process.

Non-crimp fabrics

Non-crimp fabrics (NCF) involve lower material and manufacturing costs than traditional pre-impregnated composites. The stitching machine for NCF is shown in Figure 3. In order to achieve an optimal structural design using NCF, a better

understanding of the effects of fibre architecture on fabric stiffness and strength is needed. Chomarat recently developed thin and thick NCF made of carbon and hybrid fibres with shallow angles up to 20 degrees.

The NCF is modelled at two levels: a local meso-model and global mechanical models. The meso-model includes the stitching patterns and fibre angles, providing homogenized properties that can be fed into the global (macro-mechanical) models. The global macro-level results are fed back to the meso-model to evaluate the strength and fatigue life. These results are used to validate the predictive models. The NCF processability, i.e. permeability and drapeability, applicable to the wind turbine blades has been determined experimentally, focusing on establishing relationships between processing and performance.

Blade geometry: coupling effects and pre-bending

An innovative wind turbine blade needs to be designed to withstand the stochastic nature of wind and to increase power efficiency in normal conditions. For instance, a blade can be designed so that the angle of attack can be better adjusted to external wind velocity. Active pitch control is used to spill wind power above rated wind speeds. However, the control system may not response to sudden changes in wind such as gust loading conditions.

Layered composite materials can be tailored to reach a tension-shear coupling behaviour, i.e. A_{16} term in the in-plane A matrix. For instance, a laminate such as $[0/25]$ exhibits positive shear deformation under a normal tensile load, and shows negative shear under normal compression. So if a box beam with both top and bottom skins of the same laminates $[0/25]$ is subjected to a bending moment which causes, respectively, tensile and compressive normal loads in each skin, the box will exhibit a twisting rotational deformation. The overall behaviour is called a bend-twisting coupling.

Using this bend-twisting coupling feature, a blade can be designed to twist towards feather upon flapwise bending, lowering its angle of attack. The lowered angle of attack will reduce the lift and drag forces along the blade, thereby alleviating the loads and thus increasing fatigue life (Figure 4a). Such unbalanced lay-ups can be introduced in skin or spar cap laminates. However, such bend-twist coupling

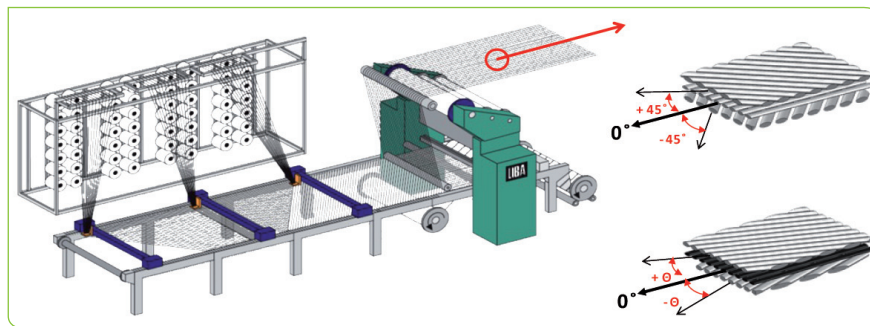


Fig. 3: Computer-controlled NCF manufacturing machine: a shallow angle is possible up to about 25 degrees

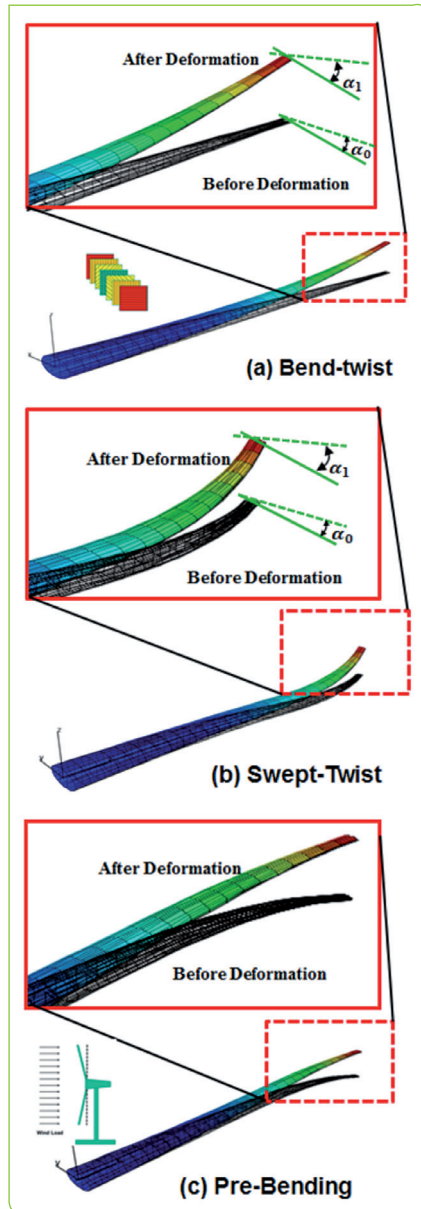


Fig. 4: Blade with (a) bend-twist, (b) swepttwist and (c) pre-bending effects (demonstrated using HyBlade)

cannot be easily achieved by using only unbalanced fibre angles since such an off-axis angled laminate would significantly deteriorate its stiffness and strength in the longitudinal direction.

The twisting moment can also be induced by an outboard blade curved towards the trailing edge direction. The aerodynamic pressure (Figure 4b) causes a twisting moment and rotates the blade, lowering the angle of attack. Such a blade is named

“Sweep-Twist Adaptive Rotor (STAR)”. It was tested by Knight & Carver with the support of Sandia National Laboratories.

Adaptive blade design can also include pre-bending towards aerodynamic pressure to ensure interference margins with the tower (Figure 4c). With this feature, the blade can be less stiff, and less expensive carbon fibres can be used. But such a pre-bent blade would cause transportation problems.

An innovative blade can be designed considering the above-mentioned features all together. The pressure-side skin is mostly subjected to tension-tension fatigue while the suction side is mostly subjected to compression-compression fatigue. Considering such load cycles, more appropriate laminates and materials should be selected to increase the fatigue limit. Hybrid materials, unbalanced laminates and blade shapes are all designed simultaneously to reach a better design. It is surely a complicated design process, especially for a large-scale blade. However, it can be simplified by the fact that the blade is statically determinate, which is often overlooked by structural designers. Namely, the internal moment distribution along the blade (flapwise, edgewise and twisting moments) can be statically determined directly from force equilibrium (neglecting dynamic inertia): considering

aerodynamics, self-weights and centrifugal loads, independently of materials and lay-up sequences.

Multi-disciplinary coupled analysis

The wind turbine generates power by responding to a stochastic wind, which involves several multidisciplinary processes. The wind passing across a blade aerofoil generates drag and lift forces depending on the angle of attack. These forces thrust the blade to rotate, contributing to the power, and at the same time they cause dynamic vibration and structural deformation, stresses and fatigue of the blade.

Multi-disciplinary analysis

A wind turbine blade design process is a multidisciplinary exercise combining aerodynamics, multi-body dynamics and structural analysis. Aerodynamic loads are calculated from external wind conditions together with the aerofoil and angle of attack. The loads are applied to multi-body dynamic (MBD) models, from which internal forces and moments are obtained and used to calculate the blade stress and strains using the material properties. The strains and stresses are then used to predict the ultimate strength and fatigue life. These sequential analyses should proceed for a period of time. Figure 5 schematically shows sequential aerodynamic-MBD-structural steps describing the overall

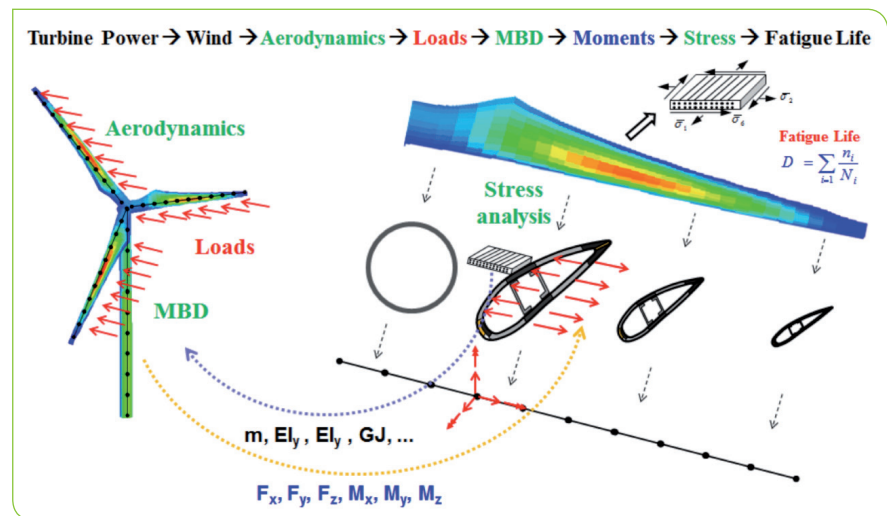


Fig. 5: Wind turbine coupled aero-structural iterative analysis

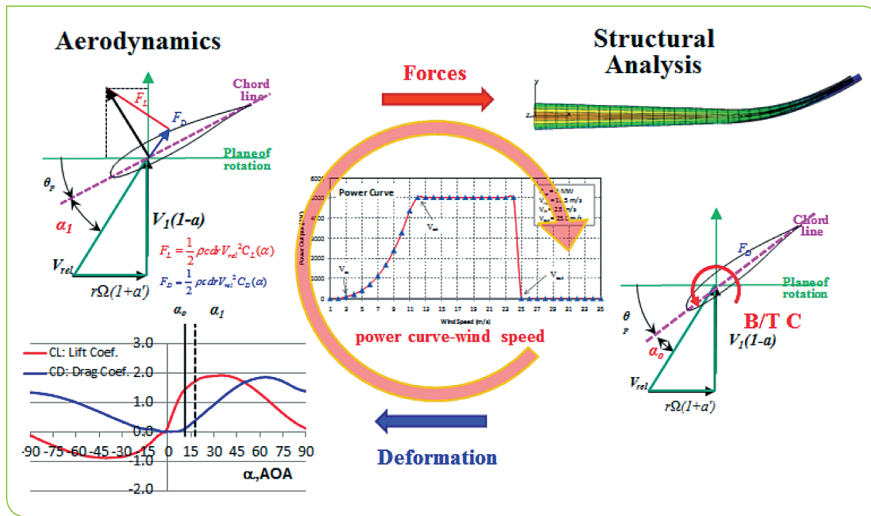


Fig. 6: Coupled aerodynamic-structural iterative analysis for adaptive blade design

response of a wind turbine subjected to aerodynamic loads. The angle of attack changes as a result of the induced twist, which in return affects the aerodynamic load. A coupled aerodynamic-structural iterative analysis will better predict the aerodynamic loading and structural response. Figure 6 illustrates a coupled aerodynamic-structural iterative analysis approach to design large-scale adaptive wind turbine blades.

External loads

Wind turbine blades are designed to meet ultimate and fatigue strength requirements. Ultimate loads arise from extreme wind speeds, extreme wind

direction changes or specific events like start-ups, emergencies, shutdowns, etc. Fatigue load represents normal fluctuating full-load operation, i.e. aerodynamic, gravity, centrifugal and gyroscopic loads over the entire life of the blade. Industrial standards such as IEC 61400-1 provide the requirements of design load cases. For large-scale blades, the effect of gravitational load, in terms of edgewise moment, becomes more dominant due to increased weight.

Most importantly, the aerodynamic and self-weight loads cause internal flapwise and edgewise bending moments and the twisting moment, which cause in-plane

normal and shear loads in the blade cross section, as shown in Figure 7. While the blade is rotating, the self-weight load alternatively changes between the axial and rotational directions, dominantly causing the edgewise moment. Its sign changes as shown in Figure 7. The mass centre and shear centre play important roles in the generation of the twisting moment due to the aerodynamic loads and self-weight. In fact, the twisting moment is caused as a result of the said aerodynamic lift and drag forces multiplied by the distance from the shear centre. The force table in Figure 8 shows the continuation of each external force to shear and normal laminate loads. Eventually, the ratio of the in-plane shear to normal loads affects the optimal fibre angle of the triaxial NCF.

Failure-moment envelope

During a typical blade design process, the failure indices or material resistance of each laminate are calculated under six resultant sectional loads along the blade. The major forces are the flapwise and edgewise moments. The buckling analysis should be performed to meet all the design load cases. A blade comprises varying cross sections with different geometrical properties and composite lay-up sequences, and each cross section needs to be analyzed separately. This is a long-term process for designers.

A failure-moment envelope has been proposed to help designers grasp how each design variable affects the failure envelope and easily select the materials and lay-up-sequence with visual aid. The envelope represents a relationship of maximum flapwise and edgewise failure moments: the moment load cases inside the envelope will be safer while the moments beyond the envelope would cause material failure. Therefore, the moment loads, which are calculated from design loads provided, e.g., by IEC standards, should be enclosed by the envelope. The moment loads are not affected by the material properties and lay-up sequences. The moment envelopes depend on the selected materials and lay-up sequences, which designers should determine to

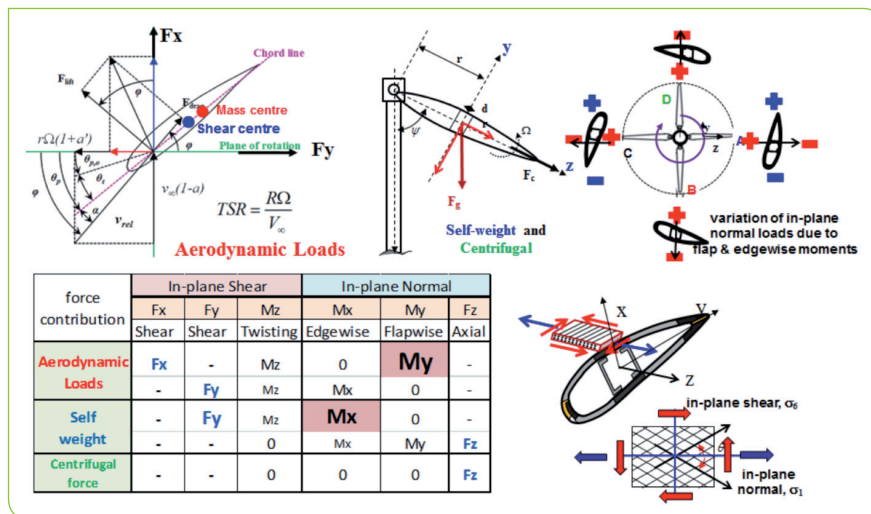


Fig. 7: Relationship between the in-plane shear and normal loads and the external aerodynamic loads, self-weight and centrifugal forces

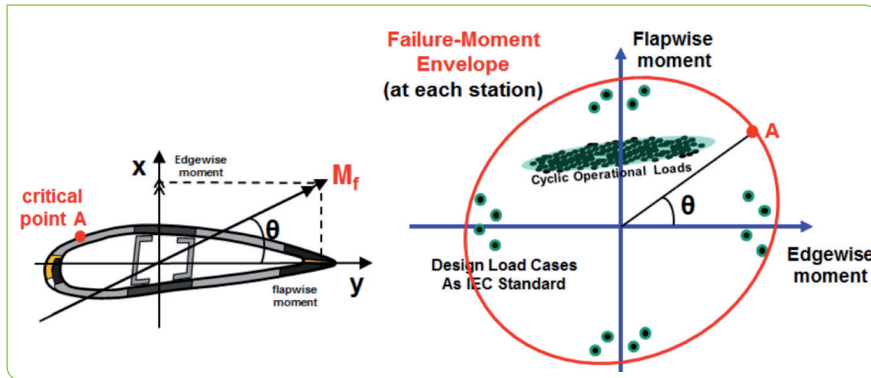


Fig. 8: Failure at point A (using the Puck failure criterion) caused by the failure moment acting at certain cross sections at angle θ ; and a failure-moment envelope enclosing all types of operation and extreme loads for safer operation

meet design requirements while minimizing material costs and weight.

Designers can easily generate the failure-moment envelopes at all blade sections by applying a unit moment resultant at angle θ with respect to the cord line at the end of blade. The moment will be equally applied to each cross section all along the blade. The damage failure indices are calculated based on a failure criterion (Puck or Tsai-Wu) at each section. The critical point at each section can be obtained as

denoted by a point A. The failure moment is then simply calculated by dividing the unit moment by the failure index (see Figure 8), and this moment will denote the point of the envelope at the angle θ . The same procedure is iterated over the angles ranging from 0 to 360 degrees, plotting failure-moment envelopes at all cross sections.

Figure 9 shows failure-moment envelopes and fatigue load cases, plotted at four different cross sections along the blade. The

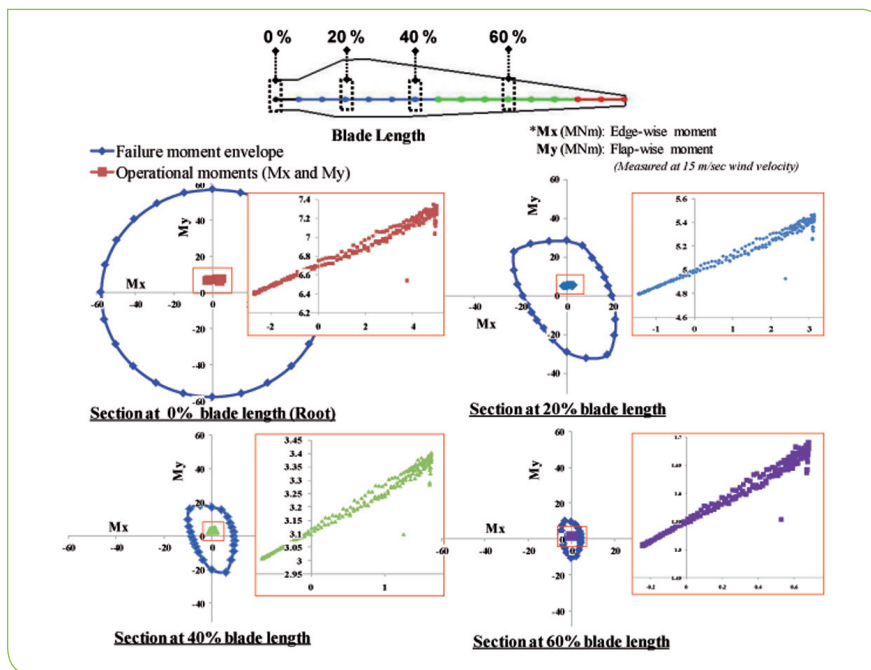


Fig. 9: Operational fatigue load enclosed by the failure-moment envelope at different cross sections of a wind turbine blade

failure envelope is obviously a circle at the blade root since it has axisymmetric lay-ups and a circular cross section. A shortest distance between the moment load and the envelope denotes how safe the load case is. Depending on the lay-up sequence and material properties of a blade cross section, the failure-moment envelope would accordingly vary.

Designers minimize material costs while keeping the envelopes enclosing all the load cases by selecting properly materials, fibre angles and lay-up thickness (excluding the foam material). They can extend the concept to include the effects of the twisting moment. It is recommended to use $[0_2/\pm 25]_s$ as a basis laminate and to determine the laminate thickness to withstand the edgewise and flapwise moments.

The entire design process is greatly simplified by sequentially performing ultimate failure analysis, buckling analysis, stiffness (deflection) analysis and fatigue life durability analysis one by one, without losing analysis accuracy. With the lay-up sequences withstanding the flap and edgewise moments, the foam is now designed to resist buckling loads. The local buckling resistance can be easily enhanced by thickening the foam inside the laminates and increasing the local bending stiffness. The deflection is calculated to ensure tower gap requirements. In order to determine the pre-bent blade geometry, the ultimate loads are applied to the straight blade and the deflection is calculated. Then the blade is bent as much as the calculated deflection in the reverse direction. Finally, the fatigue life prediction is performed using the micromechanics approach to meet a 20-year operational life.

Design and analysis software tools

Several analysis tools are available and can be used to design larger wind turbine blades, as shown in Figure 10. The National Wind Technology Center (NWTC), a division of the U.S. National Renewable Energy Laboratory (NREL), has deve-

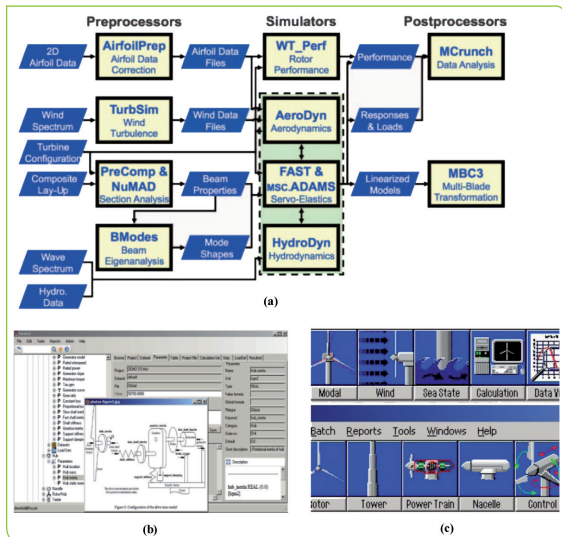


Fig. 10: Wind turbine design tools: (a) NWTC, (b) FOCUS 6.0 and (c) GH-Bladed

veloped a series of design tools including pre- and post-processors to provide the wind industry with state-of-art analysis capabilities. These tools can perform comprehensive “aero-hydro-servo-elastic” analyses. The NWTC design tools were recently accepted by certifying agencies in Europe. The FOCUS tool was developed by the Knowledge Centre Wind turbine Materials and Constructions (WMC) and the Energy Research Centre of the Netherlands (ECN). This integrated modular tool is used to design and analyze wind turbines and wind turbine components such as rotor blades. GH Bladed is an industry standard integrated software package for the design and certification of onshore and offshore turbines.

For sequential blade design, Hanyang Structures and Composites Lab (HSCL, Hanyang University, Korea) is developing a series of MS Excel-VBA integrated user-friendly tools: HyWind, HyBlade and HyFatigue. Fulfilling the design requirements imposed by industrial standards such as IEC and GL, these tools aim to perform coupled aerodynamic-structural analyses, especially focusing on easy-to-use composite lamination by worksheet data entry. The data and analysis flow is shown in Figure 11.

- **HyWind** generates a wind turbine blade geometry based on the Blade Element

Momentum Theory for horizontal-axis wind turbine blades. Simulating wind speed versus time histories covering various wind sources (i.e. wind shear, tower shadow, transient gusts, wind direction changes, etc.), it calculates the load-time histories by aerodynamic wind as well as by centrifugal and gravitational loads.

- **HyBlade** is a finite element program for analyzing composite beam structures with arbitrary cross sections. It imports the time-varying load histories from HyWind

and then performs various structural analyses and calculates ply-level stresses and strains, deformations, failure index based on maximum stress and strains, Tsai-Wu and Puck failure theories and natural frequency. It also includes the failure-moment envelope analysis, bend-twist and sweep-twist coupling effects and composite ply-angles optimization options.

- **HyFatigue** predicts the fatigue life based on multi-scale approaches, i.e. micro-mechanics of failure (MMF) and the constituent fatigue theory (fibre and matrix). The main motivation behind its development is to reduce costly and time-consuming fatigue tests of large wind blade structures.

Conclusion

To reach an optimal lightweight, large-scale wind turbine blade design, an innovative design using new composite materials, new lay-ups and new blade geometry needs to be explored with the help of a design tool providing designers physical insights with result visualization. For an aerodynamic-structural coupled analysis, three-dimensional models would yield more accurate results than a simplified model. But for designers, a simplified yet powerful beam model would be more useful to better understand the mechanical behaviour of the blade. The simplified model can also be efficiently used for multidisciplinary design optimization (MDO), which can play a very important role in reaching the global optimal design satisfying all disciplinary conditions. Result visualization such as failure-moment envelopes can also help designers to deeply understand design conditions and effectively tailor blade geometry and composite material properties. Lastly, tests should be absolutely performed to verify the innovative design concepts. A sub-scaled blade test would be useful and provide an efficient and inexpensive solution. In the development of large-scale blades, apart from the weight increase problem, there are certainly other probable challenges related to manufacturing, transportation and installation. ■

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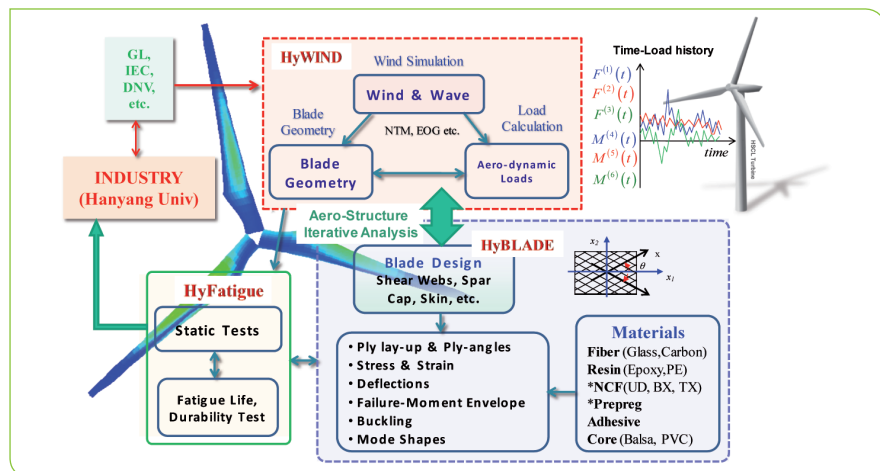


Fig. 7: Coupled aero-structure iterative analysis for adaptive blade design