Proceedings of 9th PhD Seminar on Wind Energy in Europe
September 18-20, 2013, Uppsala University Campus Gotland, Sweden

ULTIMATE STRENGTH OF WIND TURBINE BLADE STRUCTURES UNDER MULTI AXIAL LOADING

P. Haselbach*, K. Branner
Department of Wind Energy, Technical University of Denmark
Roskilde, Denmark
*e-mail: phih@dtu.dk

ABSTRACT

Wind turbines must endure a variety of weather conditions including uncontrollable, extreme winds without developing damage and fracture during a lifetime of minimum 20 years. The variety of loading leads to multi axial loading resulting in complex states of stress. The prediction of the effects of the complex states of stress with existing failure criteria can be uncertain and damages and failures often occur earlier than expected. In order to increase reliably and robustly operating wind turbine systems it is of great importance to predict damage initiation and growth accurately. Therefore a profound understanding of the mechanical behaviour of composite materials and structures for wind turbine blades is necessary.

The purpose of this PhD project is to investigate how multi axial loading effects influence the ultimate strength of typical composite structures in wind turbine blades and to develop methods to perform reliable prediction of failure. The complex loading of wind turbine blade structures subjected to different realistic load case will be investigated in order to determine most critical multi axial loading spots in the structure. Damage detection, modelling and prediction of damage evolution under multi axial loading will be carried out based on accurate physics-based failure criteria that have been developed and are preferred to curve-fitting-based criteria. The main limitation associated with latter criteria is that their applicability is restricted to load combinations corresponding to those from which the fitted curves originate. The ability of different criteria to predict failure under multi axial loading conditions will be investigated and methods to account for imperfections will be developed.

NOMENCLATURE

σ	normal stress = force/area
τ	shear stress = force/area
θ	angle
Sub-, Superscripts	
x_1, x_2, x_3	direction indices, direction 1, 2, 3-coordinates
σ_1, σ_2, σ_3	principal stress directions (1,2,3)
τ_{12}, τ_{13}, τ_{23}	shear stress directions (12,13,31)
Abbreviations	
$WWFE-II$	World-Wide Failure Exercise II
FEA	Finite Element Analysis
$HAWC2$	Horizontal Axis Wind turbine simulation Code 2^{nd} generation, aeroelastic code intended for calculating wind turbine response in time domain
ICE	International Electrotechnical Commission international standards organization

INTRODUCTION

Renewable energy is gaining ground, but like other sustainable technologies wind turbine systems show a deficit regarding technological maturity and relative cost competitiveness. In order to decrease the cost of energy, the overall performance of each individual component is developed towards higher efficiency. Improved reliability is considered to minimize down time, maintenance, logistic and manufacturing costs. The structural and aerodynamic design of wind turbine rotor blades play a decisive role in the cost-effective considerations because improved aerodynamic profiles harvest more energy and well-engineered blades have less vulnerability and reduce the loads of the subsequently load-bearing primary structures.

Hahn et al. [1] showed in a study on reliability of wind turbines experiences of 15 years with 1,500wts that the structural failures of rotor blades contribute with approximately seven percent to the overall failure for mechanical and electrical components of wind turbines. Another study dealing with component reliability done by Khan et al. [2] concludes a failure rate of 9.776% per year for rotor blades. Even so rotor blade damages do not occur disproportionally compared to other defects, their impact on stand-still periods is of high relevance due to long downtimes of about four days an average (see Figure 1) [1].

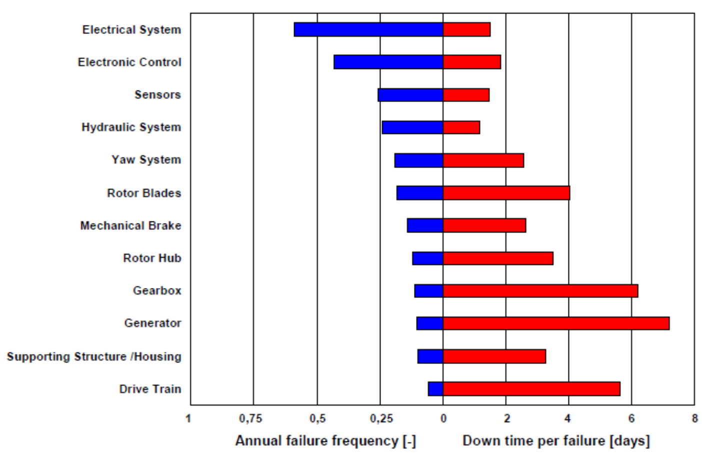

FIGURE 1. Failure Frequency and downtimes of components [1].

TABLE 1. Typical damage of wind turbine rotor blades [3]

Type	Description
Type 1	Damage formation and growth in the adhesive layer joining skin and main spar flanges (skin/**adhesive debonding** and/or main spar/adhesive layer debonding)
Type 2	Damage formation and growth in the adhesive layer joining the up- and downwind skins along leading and/or trailing edges **adhesive joint failure** between skins)
Type 3	Damage formation and growth at the interface between dace and core in sandwich panels in skins and main spar web (**sandwich panel** face/core **debonding**)
Type 4	Internal damage formation and growth in laminates in skin and/or main spar flanges, under a tensile or compression load (**delamination** driven by a tensional or a buckling load)
Type 5	**Splitting and fracture** of separate fibres in laminates of the skin and main spar (fibre failure in tension; laminate failure in compression)
Type 6	Buckling of the skin due to damage formation and growth in the bond between skin and main spar under compressive load (skin/adhesive **debonding induced by buckling**, a specific type 1 case)
Type 7	Formation and growth of cracks in the gel-coat; debonding of the gel-coat from the skin (**gel-coat cracking** and gel-coat/skin debonding)

Damages in rotor blades can occur in various ways. B. F. Sørensen et. al. listed seven different failure types (given in Table 1) of observed damages in their study [3].

A sketch of typical damage types is given in Figure 2. Blade failures often are multi-directional due to multi-axial loadings. Ultimate damages are often triggered by combinations of material damages and nonlinear instabilities like 2^{nd} deformations of the hollow shell structures. According to simulations and experimental methods hot spot, where damages are most likely to occur, are $30-35\%$ and 70% in length from the blade root [4] [5]. In longer and more flexible blades the transition zone from oval to more flat aerodynamically formed cross section seems to be prone for damage initiation and damage propagation [5] [6].

Designing more flexible, lighter and thinner rotor blades requires a profound understanding of the mechanical behaviour of composite materials and rotor blade structures.

Wind turbine rotor blades usually consists of outer aerodynamical shells and and inner load carrying substructure, like box girders or shear webs connected to reinforced caps. Figure 3 shows the main components of a rotor blade. The joints are usually glued together by adhesives.

Nearby the shear webs the outer aerodynamic shell of the rotor blade structure usually consist of strong glass fibre or glass fibre/carbon fibre mix laminates to carry the huge bending moments. The shear webs facing towards the leading or trailing edge are laminate/core/laminate sandwich structures. For the blade structure towards leading and trailing edge light and stiff laminate/core/laminate sandwich structures are mainly used to avoid buckling of the aerodynamic shells. Figure 4 shows the nomenclature and used materials in a conventional blade structure.

Even so numerical prediction methods for single loaded unidirectional composite materials perform well, reliable universally performing numerical prediction methods for bi-axial or multi-axial loading (see Figure 5) do not exist. Results and recommendations based on the benchmarking of failure criteria under triaxial stresses for fibre-reinforced polymer composites

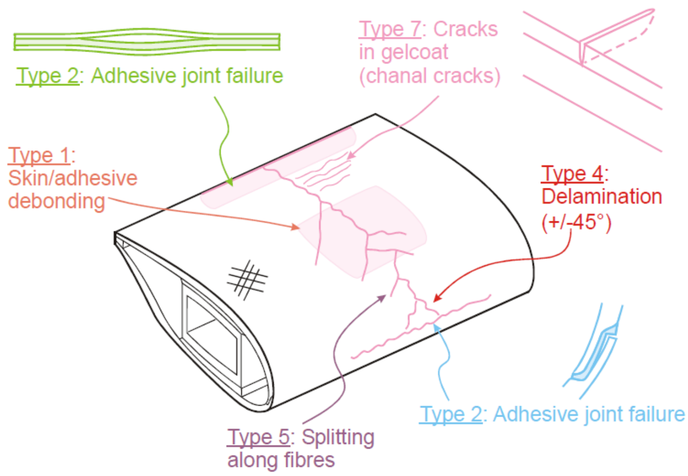

FIGURE 2. Sketch of common damage types found on a wind turbine blade [3].

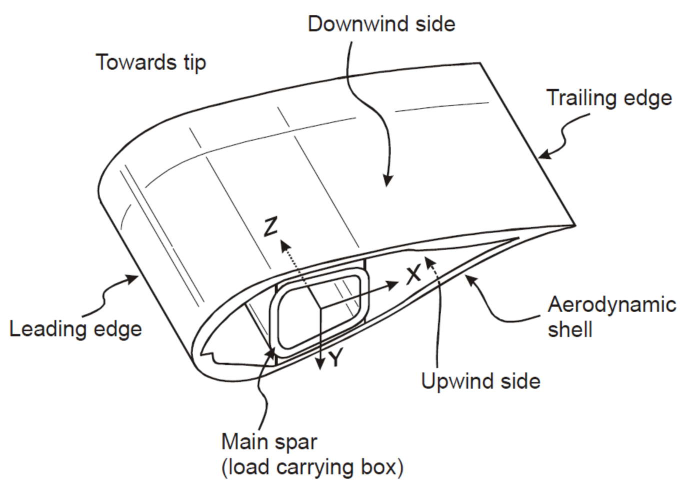

FIGURE 3. Main components of a rotor blade [3].

(know as World-Wide Failure Exercise II (WWFE-II)) [7] have shown this detailed. The applicability of existing methods is often based on curve-fitting based criteria, which are restricted to load combinations corresponding to those from which the fitted curve originate.

APPROACH

Hot spots for multi-axial stress locations in blade structures will be analysed on the basis of two different blades structures. A more generic wind turbine blade, the DTU 10 MW Reference Wind Turbine blade [8] and a more specific wind turbine rotor blade (SSP Blade Technology 34m blade) will be used for the analysis. The structural analysis will be performed with a finite element analysis (FEA). The load input for the FEA will be created with the in-house aero-elastic simulation code HAWC2. Different IEC 61400 standard load cases for wind turbine rotor blades provide the basis in order to generate realistic load simulations. Different load combinations and hot spots for multi-axial stresses will be compared and evaluated.

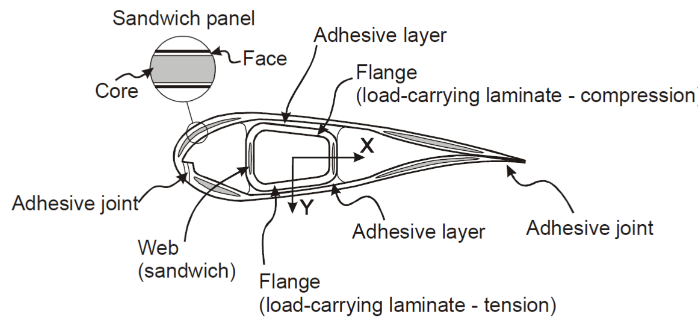

FIGURE 4. Nomenclature and used materials in a conventional blade structure [3].

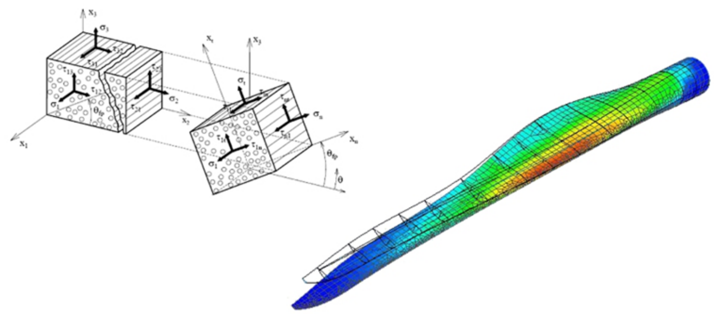

FIGURE 5. Qualitative illustration of multi axial stress states in a wind turbine rotor blade.

On selected areas (hot spots) numerical and experimental investigation will be conducted to clarify how multi-axial loading effects influence the ultimate strength of typical wind turbine structures. Apart from subcomponent tests linear and non-linear simulations will be conducted in order to investigate the ability of different existing criteria to predict failure under multi axial loading conditions.

OUTCOME OF THE PHD PROJECT

The aimed outcome of the conducted PhD project is to contribute to a better understanding of multi axial failures and improving the ability of failure and damage prediction in wind turbine rotor blades.

ACKNOWLEDGEMENTS

The PhD project is part of the new Danish Centre for Composite Structures and Materials for Wind Turbines (DCCSM), grant no. 09-067212 from the Danish Strategic Research Council. The cooperation and the financial support is gratefully appreciated.

REFERENCES

[1] Hahn, B., Durstewitz, M., and Rohrig, K., 2007. Reliability of wind turbines experiences of 15 years with 1,500 wts. Tech. rep., Institut für Solare Energieversorgungstechnik (ISET).

[2] Khan, M. M., Iqbal, M., and Khan, F., 2005. "Reliability and condition monitoring of a wind turbine". *Ann.Canadian Conf. Electrical and Computer Engineering,* ***Volume***(18), pp. 1978 - 1981.

[3] Sørensen, B. F., Jørgensen, E., Debel, C. P., Jensen, F. M., Jensen, H. M., Jacobsen, T. K., and Halling, K. M., 2004. Improved design of large wind turbine blade of fibre composites based on studies of scale effects (phase 1) summary report. Tech. rep., Risø National Laboratory.

[4] Sundaresan, M. J., Schulz, M., and Ghoshal, A., 2002. "Structural health monitoring static test of a wind turbine blade". *National Renewable Energy Laboratory, CO, USA,* ***NREL/SR-500-28719***.

[5] Kong, C., Kim, T., Han, D., and Sugiyama, Y., 2006. "Investigation of fatigue life for a medium scale composite wind turbine blade". *Int. J. Fatigue,* ***Volume***(28), pp. 1382 - 1408.

[6] Laustsen, S., Thomsen, O. T., Lund, E., and Kühlmeier, L., 2012. "Analysis of gird-scored sandwich structures of different curvatures and grid sizes for wind turbine blades". *ECCM* $15 - 15^{th}$ *European Conference on Composite Materials, Venice, Italy*.

[7] Soden, P., Kaddour, A. S., and Hinton, M. J., 2004. "Recommendations for desigerns and researchers resulting from the world-wide failure exercise". *Composites and Technology*(64), pp. 589 - 604.

[8] C. Bak, F. Z., Bitsche, R., Kim, T., Yde, A., Henriksen, L. C., Natarajan, A., and Hansen, M. H., 2013. Description of the dtu 10 mw reference wind turbine, dtu wind energy report-i-0092. Tech. rep., DTU Wind Energy.