SSP TECHNOLOGY

Catching the winds of Tomorrow

Copenhagen Class™

Taking world class blade design into new unexplored territories

AWEA 2011
New Technology in Blade Design – 5/25/2011

COPENHAGEN CLASS

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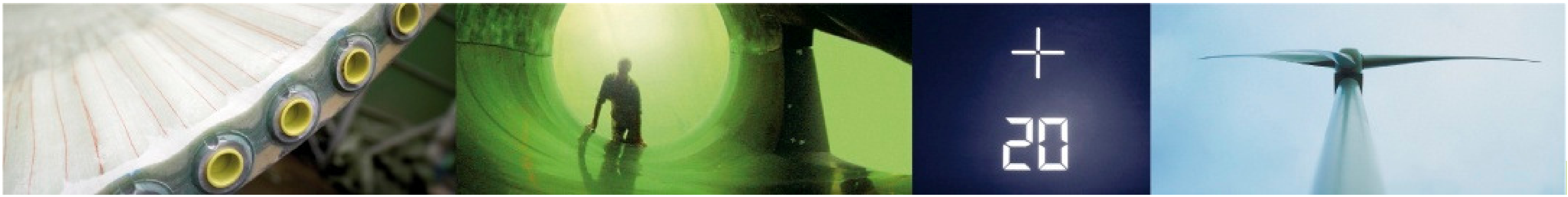

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Exploring....

Copenhagen Class™ has been developed as a new design class for blades supplementing the current design and certification criteria given by the certifying bodies because:

- The rated power of the turbines steadily increases and the design of blades are getting rapidly more challenging and is breaking into new territories (loading, weight, length) literally every day.
- Although the business is maturing, we are still experiencing systematic failures on smaller blades. Carrying the technology used for those unchallenged into very long blades represents huge risk for turbine suppliers and wind park owners.
- Entering into no-man land as regards to blade length, weight, tip-speed and loadings using current software, knowledge and design principles drives the risk, cost and safety margins up.
- Risk for failure is increasing and traditional way of designing blades does not necessarily counter this. The cost of failure can be disastrous, both for the design project, the design company and the ultimate customer.
- The wise blade designer accepts the fact, that in reality, we have no real operating experience with very long blades, and although we keep pushing the size, we do not know, whether we are doing the right thing.

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Systematic Risk Management

The Copenhagen Class™ design concept is based on a systematic risk analysis for all risk related to blade design, key risk being identified as:

- Blade solution design phases are often separated and do not interact. Hence, the blades are not optimised and risk is not handled based on a holistic design overview, and interactions between different disciplines within blade design (aerodynamic, structural, aeroelastic, interaction with turbine, materials, production processes, QA management, tooling and production design) are not always fully considered.

- The existing recommendations for blade design and the corresponding test requirements are developed at a time when blade dimensions were approximately half of the size of the present design. Failure modes previously either covered by safety margins, taking in account based on experience or not considered relevant, now can be design and risk drivers.

- The present design standards do not, therefore, full fill the needs for design of larger wind turbine blades of today. Blind trust in these can lead to increases failures.

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The Concept

The Copenhagen Class™ design concept has 4 key components

- Explorative and holistic design process including all aspects of design under one management and one delivery and performed in open dialogue with turbine designers and blade manufacturers.
- Systematic and research based failure mode analysis and risk management performed by Risø DTU, Denmark and SSP Technology in conjunction. For each design project a specific risk analysis will be performed and a specific set of design principles will be given by Risø DTU to handle the identified risk.
- Peer review done by Risø DTU of the design prior to finalising to evaluate the successful implementation of the specific design principles in the blade design.
- Extended number of full scale test to verify design criteria specified by Risø DTU.

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The Research

The Copenhagen Class™ failure mode analysis has been performed by Risø DTU, a leading research and educational Danish institution within blade design and other key disciplines with wind turbines, and is based on extensive research performed over the last decade.

- The extensive wind turbine blade testing program carried out by Risø DTU has lead to numerous conclusions regarding structural design of blades, the correlation with other design disciplines and the relevance of several failure mechanisms and loading configuration, that most often is not considered in blade designs.
- The blade testing program at Risø DTU is predominantly performed on a SSP 3-component blade loaded in edgewise, flapwise and combined directions. Further, at large number of sub-components test has been performed as either experimental work or to calibrate the very complex and unique FE software developed by Risø DTU.
- All testing and research performed by Risø DTU are publicised either via their web page www.risoe.dk/research/sustainable_energy/wind_energy.aspx , papers or reports.

Risø DTU Failure mode analysis

The failure mode analysis has focused on 3 weak points in the design process:

- Failure Modes

  Not all failure modes are taken into account during "certifiable" design process

- Design tools
  - Geometric non-linear study as opposed to analytical or linear analysis methods
  - More advanced boundaries and FE modeling
  - Calibration of "sensitive" elements to test data
  - "Intelligent"(and relevant) Post processing

- Sensitivity study:
  - Analyse the sensitivity of design features to production tolerances e.g. the transverse shear distortion

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Failure modes for a blade for a 120m rotor, class 3 onshore

Risø DTU and SSP has performed a specific risk analysis for a blade for 120m rotor as per the next slide.

The slides show all key additional risk areas, identified by Risø DTU and the failure modes in bold are those specifically relevant for the given blade design.

The relevant failure modes will be handled by specific design principles given by Risø DTU as a supplement to the certification requirements given by the certifying body.

The ranking indicates the suitability for the various testing methods. 1 is worst, 5 is best.

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Failure modes	FEM + analytical tools	Full-scale test	Discovered at blade test	Discovered on the field
Buckling	4	5	a) Redesign b) Time delays	a) Redesign b) Retrofit c) Failure
Tower Clearance	5	5	a) Redesign	a) Redesign b) Failure
Longitudinal Strain failure in spar caps	4	5	a) Redesign	a) Redesign b) Failure
Fatigue Failure (Longitudinal strain)	4	5	a) Redesign	a) Redesign b) Failure
Mode 1: TE Adhesive joints	**3**	**4**	**a) Repair** **b) Redesign**	**a) Repair** **b) Redesign**
Mode 2: Transverse shear distortion	**4**	**4**	**a) Failure** **b) Redesign**	**a) Failure** **b) Redesign** **c) Retrofit**
Mode 3: Interlaminar/Transverse strain failure in spar cap	**4**	**5**	**a) Failure** **b) Redesign**	**a) Failure** **b) Redesign** **c) Retrofit**
Mode 4: Flutter (Divergence)	**3**	**4**	**a) Not testable**	**a) Failure** **b) Complete redesign**

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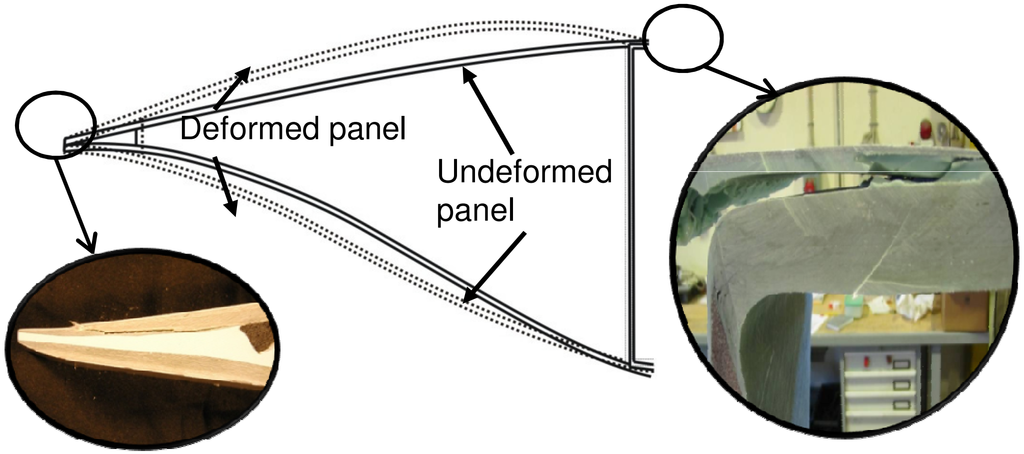
Failure mode: Adhesive joints



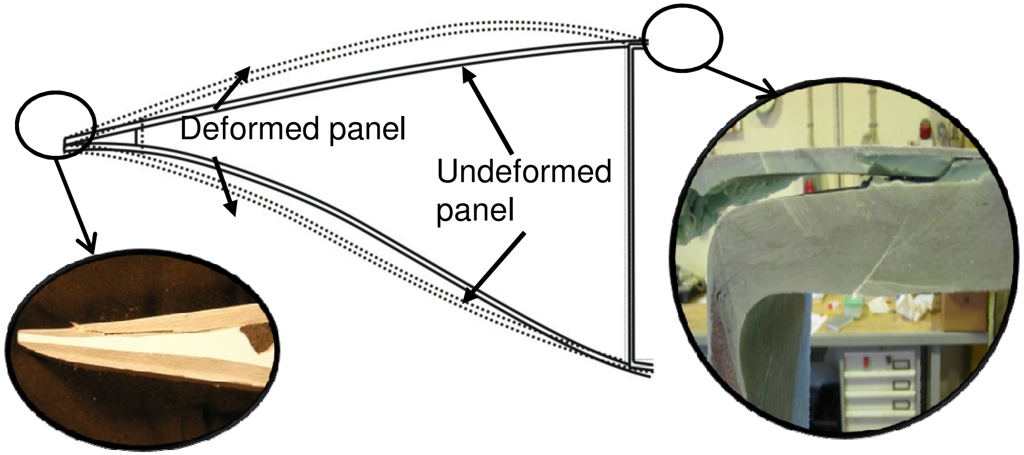
Current design criteria/methods fail to:

- Analyse in detail out of plane bending behaviour resulting in peal on bonded joints
- Over simplistically analyses bond failure by shear allowables
- Two solutions exist for a more holistic analysis:
  - Fracture mechanics
  - Empirical test data

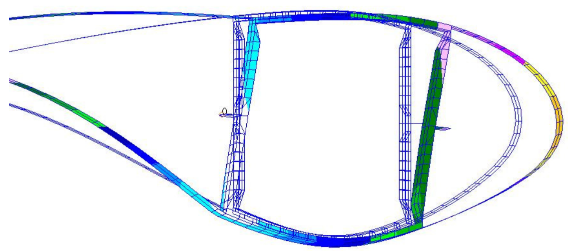
Problems with adhesive joints are expected to be even more dominant in the future wind turbine blades, which will bring along increased edgewise loads, critical for the adhesive bound in the trailing edge.

Failure mode: Adhesive joints – Copenhagen Class evaluation

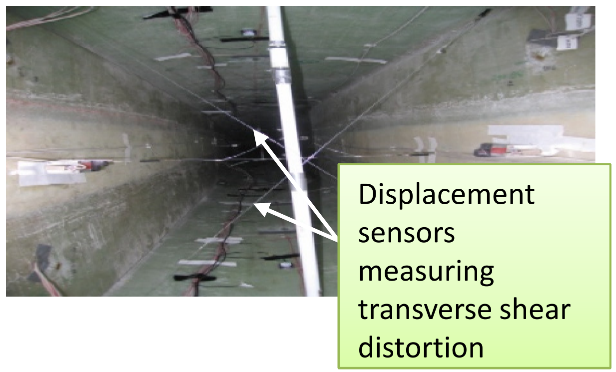
- **Analysis process**
  - Criteria to be finalised in preliminary design phase
  - Non-linear FE to define detailed stresses in bonds
  - Results to be correlated against extensive test database of Risø



Failure mode: Transverse Shear Distortion



- Current design criteria/methods fail to:
  - Analyse the extent of transverse shear distortion
  - Phenomenon is non-linear and as such NL FE is critical
  - Case is highly sensitive to production deviations (as-drawn vs. as-built).
- Tests by Risø DTU to date indicate that:
  - 34m blades are not critical for this failure made
  - Problem will become more critical for larger blades
- Full scale testing is an important input to correlate models (diagonal displacement sensors measure shear distortion)
  - Alternative clamp configurations to be evaluated due to clamps influence



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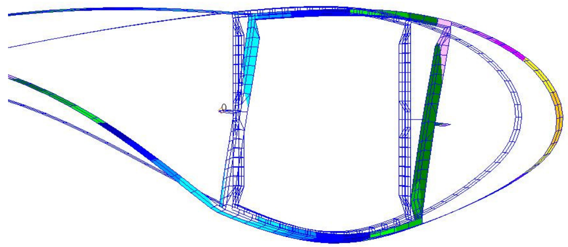
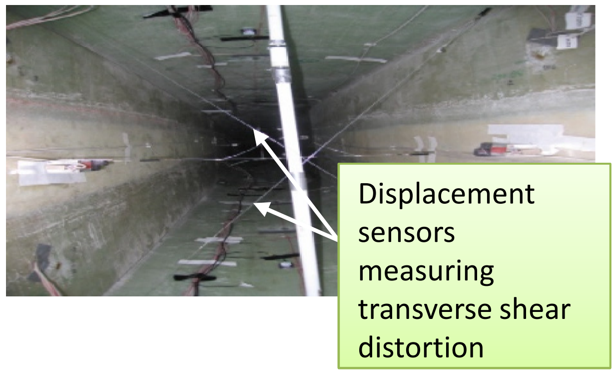
Failure mode: Transverse Shear Distortion – Copenhagen Class eval.

- Analysis process
    - Criteria defined in the preliminary design phase
    - Distortion to be extracted from Non-linear FE analysis
    - Sensitivity study to be executed with respect to influence of production tolerances
    - Results compared to criteria
    - Models correlated against test data and results re-evaluated





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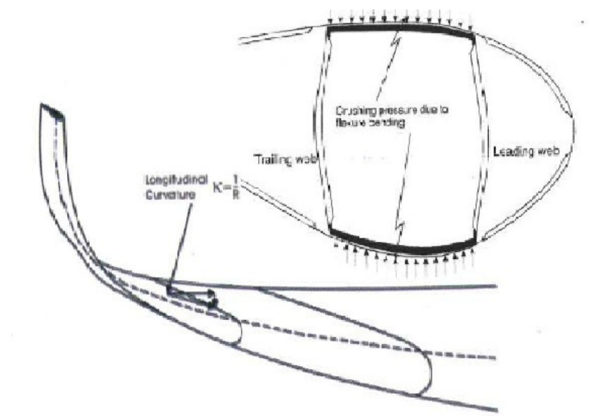
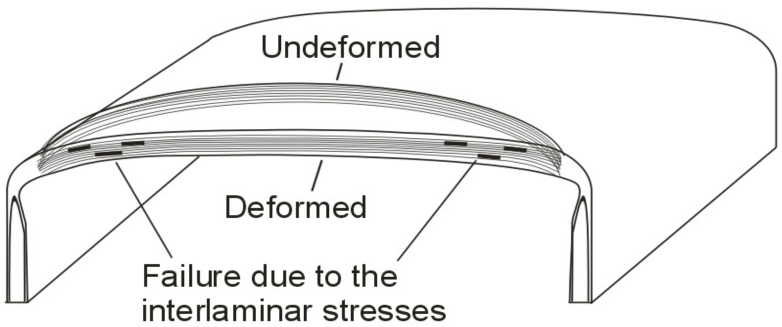
Failure mode: Interlaminar failure/Transverse strain failure in spar cap

The Brazier effect is a nonlinear effect resulting from the longitudinal curvature when bending a beam or a slender structure. Because of the curvature the longitudinal compressive and tensile stresses result in ovalization of cross section.

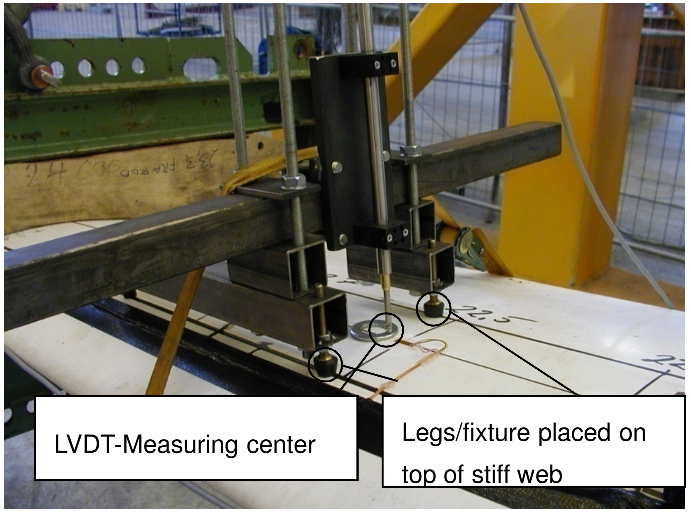
Flattening of the curved cap results in high stresses in the transverse direction. The high stresses cause both interlaminar and tension in the UD-laminates (transverse to the fiber direction).





Failure mode: Interlaminar failure/Transverse strain failure in spar cap

- Analysis process
  - Criteria defined in the preliminary design phase
  - Table of spar width to thickness produced by Risø DTU using Non-linear FE in preliminary design phase for use by the blade designer (defined strain level)
  - Evaluation of detailed design solution by Risø DTU using non-linear FE
  - Evaluation against criteria and full scale test correlation



Failure mode: Flutter

- Flutter is a aeroelastic instability that may result in large amplitude vibrations of a blade, and possible in its failure. Flutter vibrations consists of a coupling of flapwise and torsional blade vibrations, which are sustained by the airflow around the blade.
- FEA-Flutter study for large flexible blades together with other codes e.g. Hawk (not Flex5 since it do not take the rotational degree into account)
- Risø DTU will perform a flutter check using the HAWCStab2 calculations to establish the critical tip speed for which flutter occurs, called the flutter limit. The flutter limit is very dependent on several parameters of which two associated with some uncertainties. These are mass centre position and torsional stiffness. There will be made a sensitivity study of these two parameters to establish the flutter limit in regards to the parameters in question. The result will be presented in a small report and will be based upon mass and stiffness properties provided by SSP.

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Copenhagen Class ™ - bankable advantages

A more competitive blade design due to detailed optimization and understanding/management of risk.

Systematic risk management and substantiated risk handling based on open source experiences and top notch and unique research improves market acceptance for introduction of new technologies in larger blades.

Less failures and higher quality blades.

A significant differentiator.