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Published in:
Scientific Proceedings

Publication date:
2011

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Jensen, F. M., Nielsen, P. H., Roczek-Sieradzan, A., Sieradzan, T., Branner, K., & Bitsche, R. (2011). On innovative concepts of wind turbine blade design. In Scientific Proceedings (pp. 275-279). European Wind Energy Association (EWEA).

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ON INNOVATIVE CONCEPTS OF WIND TURBINE BLADE DESIGN

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Abstract

Recent work at Risø DTU on wind turbine blades has shown that more failure mechanisms need to be taken into account, than the classical ones such as buckling, material failure, etc. One of the failure modes, which were demonstrated in full-scale tests and are not part of a commercial certification test, is transverse shear distortion of the cross section. Another failure mechanism is the non-linear out-of-plane deformation of the load carrying cap laminate, which could be the reason for some failure of today's wind turbine blades. These two potential failure mechanisms are taken into account in the design of a new innovative 40m load carrying box girder presented in this paper. Also buckling and inplane material failure in the longitudinal direction is considered in the design. The box girder has been designed by Risø DTU and manufactured by SSP Technology A/S and makes use of 3 patented reinforcements in order to prevent interlaminar failure in the caps and transverse shear distortion. The material savings in the cap is up to 40% compared to the traditional SSP Technology design. This suggests that substantial weight savings can be obtained, at least when the failure criteria mentioned above are considered alone. Furthermore, sub-component testing has been performed to support the numerical analysis and the coming full-scale test. The current work seems to confirm that significant improvement in the structural components of wind turbine blade can be obtained by utilization of the invented structural solutions.

Keywords: wind turbine blade, box girder, numerical simulation, combined load, interlaminar failure, shear distortion, full scale test, sub-component test.

1 Introduction

An extensive wind turbine blade testing program at Risø DTU has led to numerous conclusions regarding the structural design of wind turbine blades and has drawn attention to failure mechanisms and loading configurations that often are not required in design and certification tests, see ref. [1].

The aim of this work is to provide a blade design that can address the failure mechanisms observed recently, see [1], [2] and [3]. The recently observed failure modes are the non-linear out-of-plane deformations of the load carrying cap laminate and transverse shear distortion of the cross section. Also, the two classical failure criteria, buckling and in-plane material failure (static only) in longitudinal direction, are considered in this work. Designing a wind turbine blade is a trade-off between improving the performance and reducing the weight, see [2]. Thus, it is necessary to address the occurring failure modes by means of solutions that will not increase the weight.

The concept blade represents significant structural improvement with regards to the design criteria established in ref. [2] and [3]. The first design criterion only allows a certain (e.g. 4-6mm for a 34m blade) out-of-plane deformation of the load carrying cap laminate in order not to have too high interlaminar stresses and/or too high transverse tension stresses in the unidirectional layers.

The second design criterion is to prevent the cross section from distorting sideward in an unstable manner, meaning that the deflection increase considerably only by applying a little bit more load. One way to examine this is to measure the deformation in the diagonals of the corner in the box girder. If the deformation starts to increase (or decrease) significantly in a nonlinear manner it illustrates that the blade has started to distort in a non-linear manner. This failure mode has not received much attention in the exciting certification rules, probably mainly due to the fact that combined flap- and edgewise loads are not taken into account in a certification process, see ref. [1]. A 40m load carrying box girder has been designed and manufactured using these new considerations together with the classical criteria such as buckling and maximum allowable strains.

The design only takes static criteria into account and does not consider any kind of fatigue related issues. Furthermore, the tip deflection is increased considerably and without compensating for that either by prebending, coning or tilting the blade, tower clearance will be a problem. A study of how much tip deflection can be allowed is not part of this study, only the potential in weight saving of the load carrying laminates using static criteria is taken into account. As a Proof of Concept, a load carrying box girder has been designed and manufactured. The box girder includes 3 structural solutions patented at Risø DTU, see ref. [4],[5] and [6]. Two of the reinforcements reduce the inward out-of-plane deformation of the load carrying laminate and the third reduces the transverse shear distortion by inserting a diagonal between two opposite box corners. By use of these inventions the thickness of the load carrying laminates was decreased by 40% and the box was prevented from distorting in the transverse direction. The shear webs and the root section (0-10m) remain unchanged from the original design from SSP Technology A/S. The weight of the new introduced reinforcements (diagonals, longitudinal and transverse cap stiffener), has also been taken into account if the total weight reduction of the box girder has to be decided.

2 Methods and procedure

The present work presents a study of the structural static strength of wind turbine blades loaded in combined flap- and edgewise directions. Both numerical and experimental work have been used to address the most critical failure mechanisms.

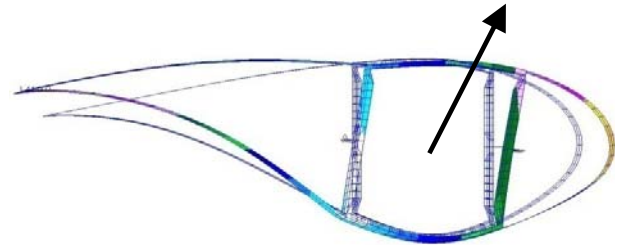


Figure 1. Numerical simulation shows transverse shear distortion of a cross section loaded in a combined edge- and flapwise direction (indicated with the arrow).

A full-scale test performed recently at Risø DTU on a 34m blade from SSP Technology A/S validated the results from the numerical simulations, see ref. [7]. The test was not part of a certification process, but was performed in frame of a research project. The aim was to find out how critical it is to sustain the combined load scenario for present blades.

2.1 Test with combined flap- and edgewise loads

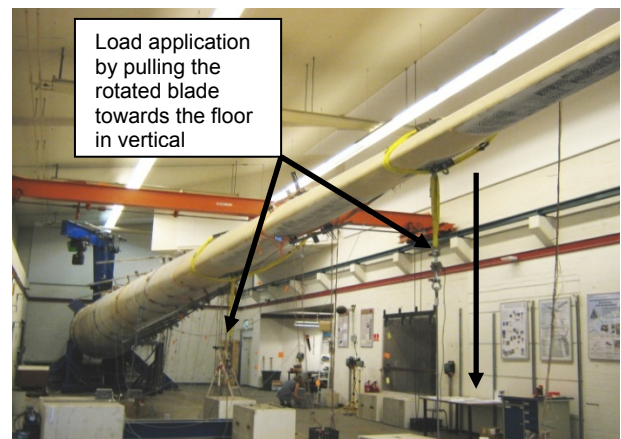


Figure 2. Photo of the blade in a combined flap- and edgewise load situation at Risø DTU's blade test facility.

Tests with combined flap- and edgewise loads have been carried out with the load

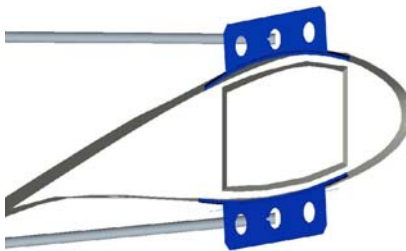
applied on the suction side and with an angle of attack of 30 degrees from the flapwise plane.

Figure 2 shows the blade on the test rig during combined flap- and edgewise loads.

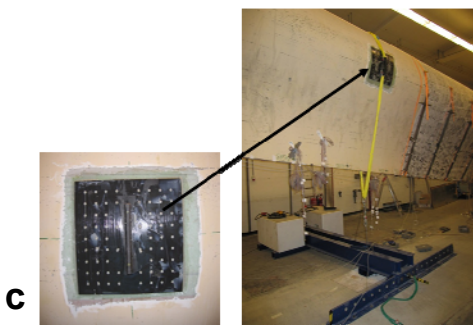
A newly developed load application system, shown in Figure 3b and c, employs anchor plates glued to the airfoil as illustrated in Figure 3c. Traditionally, this would be done with means of a wooden clamp surrounding the blade's cross section and thereby resulting in unrealistic local stiffness, see Figure 3a and ref. [1].



a



b



c

Figure 3. Fig. a. Traditional method for load application often used in commercial tests. Fig. b and c. Novel loading method used at Risø DTU test facility.

Figure 4 shows measurement equipment installed inside the blade that allows

measuring the transverse shear distortion extent. The diagonal lines crossing inside the box are strings for measuring the deformation between the corners. If one diagonal increases and the other one decreases, it is a sign of transverse shear distortion.

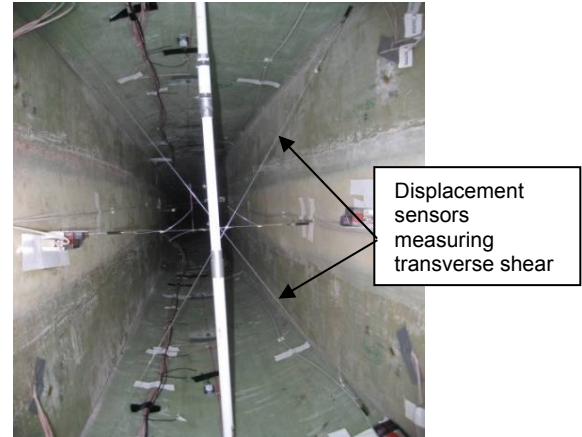


Figure 4. Photo shows measurement equipment installed inside the blade between the two shear webs in order to measure transverse shear distortion of the cross section.

3 Results and discussion

This section presents and shortly discusses the results obtained from the blade full-scale test under combined loading. The main recognised issues are addressed separately.

3.1. Transverse shear distortion

The results from the diagonal displacement sensors indicated a non-stable deformation behaviour, see Figure 5. This behaviour indicates instability similar to results observed in non-linear FE-simulations. If the blade was further loaded, it could be expected that it would collapse in unstable transverse shear distortion, see Figure 5a+b. However, at this stage it is not possible to conclude that the transverse shear distortion would become a serious problem as the unstable behaviour could also change to a stable phase, which seems to be the case at 10m, Figure 5c. In future tests, the load will be increased to allow further investigation into whether this unstable behaviour will continue until failure or if it will stabilize.

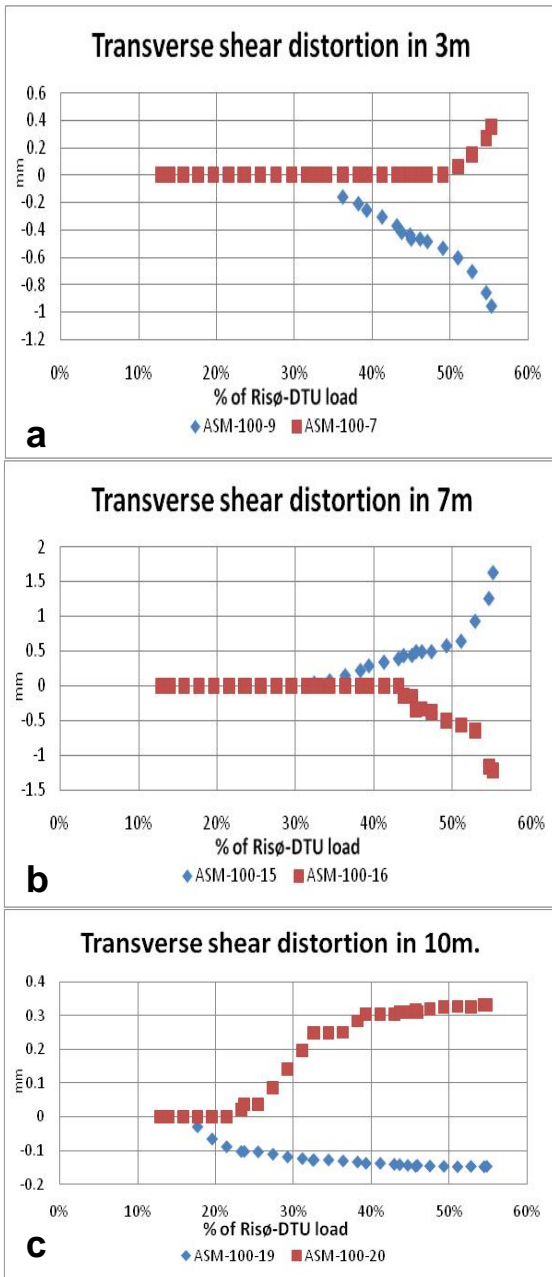


Figure 5. Results from full-scale tests with combined load. 100% refers to ultimate failure load predicted on basis of a similar blade Fig. a and b. Steep nonlinear trend of the transverse shear distortion measure is indicated. Fig. c. The steep behaviour levels out at approx. 35% of the predefined Risø DTU load.

Transverse shear distortion resulting from insufficient corner stiffness of the box girder was prevented by implementing the cross (or diagonal) invention, presented in detail in ref. [1] and [4]. The idea is to stiffen the structure prone to distortion with light and efficient connection of opposite corners. As

presented in the following, the transverse shear distortion can be efficiently diminished with this invention presented in Figure 6.

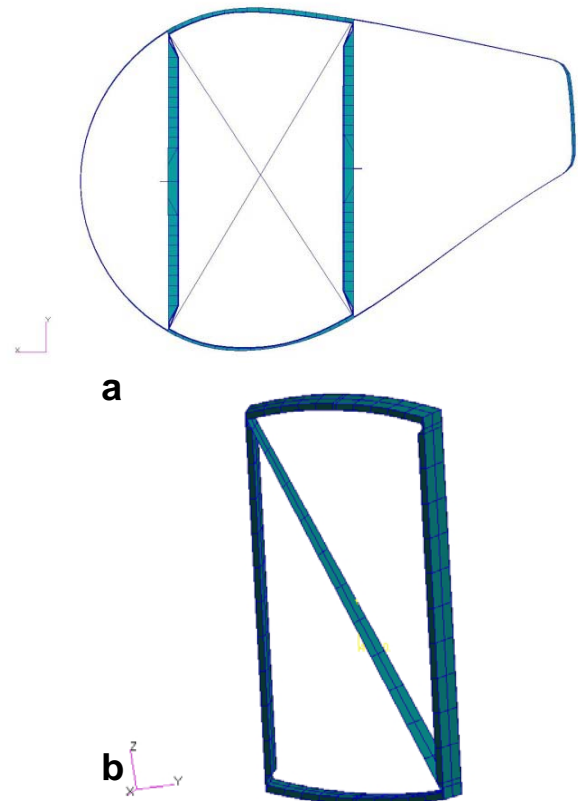


Figure 6. Cross sections of two finite element models of a wind turbine blade (Fig. a) and a load carrying box girder (Fig. b). Also, two different embodiments of a patent(ref. [4]) are presented, which solve the transverse distortion problem. Fig. a. Blade section with the cross reinforcement, which is able to carry only tension. Fig. b. Box with one diagonal reinforcement. The diagonal can carry both tension and compression. It is manufactured as a sandwich panel.

The design only takes static criteria into account and does not consider potential fatigue failures in the diagonal or in the joints. This has to be investigated in the future.

3.2. Cap deformation

Another important failure mechanism addressed in the work at Risø DTU is ovalisation of the box girder, see ref. [1]. In this phenomenon, the caps reveal inward out-of-plane deformations which decreases load carrying capacity of the structure, see Figure 7.

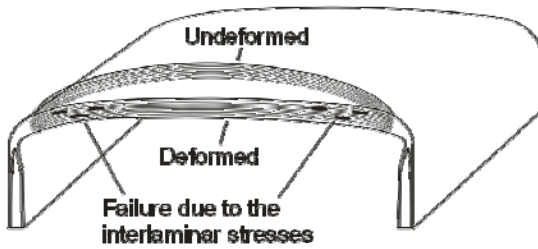


Figure 7. Interlaminar shear failure resulting from deformation of the cap. After ref. [1].

The out-of-plane deformation could also cause tension failure in the UniDirectional (UD) layers which dominate in the load carrying laminate. In Figure 8, the transverse strains were measured back-to-back in a 34m wind turbine blade tested in flapwise loading direction.

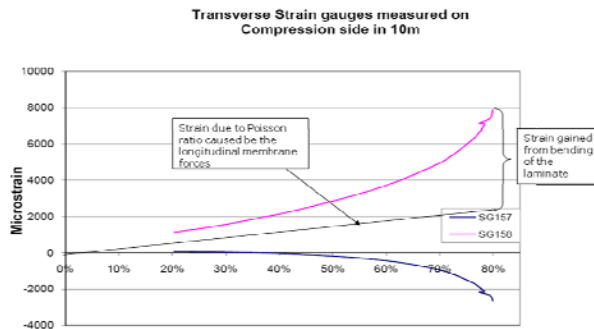


Figure 8. Transverse strains measured in a full-scale test of a 34m wind turbine blade. The two strain gauges measured on the inner side (pink-SG158) of the load carrying laminate and on the outer side (blue-SG157). 100% refers to ultimate failure load predicted on basis of a similar blade. The reason why this blade failed at 80% was that only the load carrying box girder was tested, see ref. [1]

The strain measured in transverse direction is approximately twice as high as in the longitudinal direction (not shown here). This is mainly due to the fact that the flexural lateral stiffness is very low. This is because there are no fibres in transverse direction here and the epoxy resin needs to transfer the out-of-plane loads. These are the non-linear Brazier loads caused by the longitudinal curvature. Explanation of this issue and its relevance for wind turbine blades can be found in ref. [1], [2] and [3].

The strain measured in full-scale test and test on coupon level cannot be compared directly since part of the strain is related to the Poissons ratio. To extract the strain which generates stresses, the membrane strains need to be subtracted in order to show the bending contribution. The membrane strain, caused by the global bending and the related Poisson transverse contraction can be found by taking the average strain, see straight line in Figure 8. Subtracting the membrane strain results in a bending strain level of $6000\mu\text{S}$ ($= 8000-2000\mu\text{S}$) at 80% load.

In Figure 9, an example from the literature [8] shows how the critical strains were found for a UD glass fibre laminate.

Figure 9 shows the maximum allowable strains for a UD glass fibre laminate. Figure 9a and b show tension perpendicular and parallel to the fibre direction respectively. An outstanding difference of a factor 4 can be noticed between the maximum strain level in longitudinal and transverse direction. When comparing the measured transverse strains compensated for the membrane contribution (Figure 8) with the maximum allowable strain from ref. [8], it can be observed that the blade has exceeded the maximum strain level by approximately $1000\mu\text{S}$ ($=6000- 5000 \mu\text{S}$). The design only takes static criteria into account and does not consider any kind of fatigue relates issues at the moment.

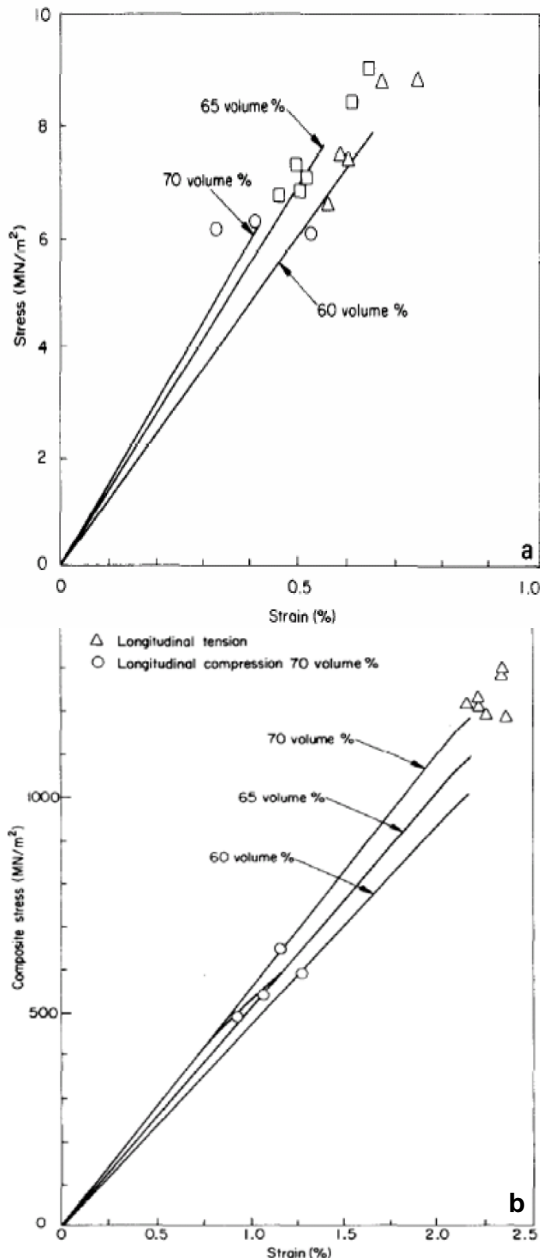


Figure 9. Stress-Strain curves from a UniDirectional glass fibre laminate, from ref.[8]. Fig. a. Tension perpendicular to the fibre direction. Fig. b. Tension in the fibre direction.

Based on this observation, a structural solution that could prevent the inwards cap deformations was invented, see Figure 10. The corners are coupled which limits their relative displacement in the transverse direction of the profile. Again, the reinforcement is to carry only tension. Fixing the corners prevents curved panels from flattening, decreases transverse strains and increases flexural stiffness of the cap. Consequently, the interlaminar shear failure is prevented and the buckling

load is increased. The proof for this solution is presented in ref. [3].

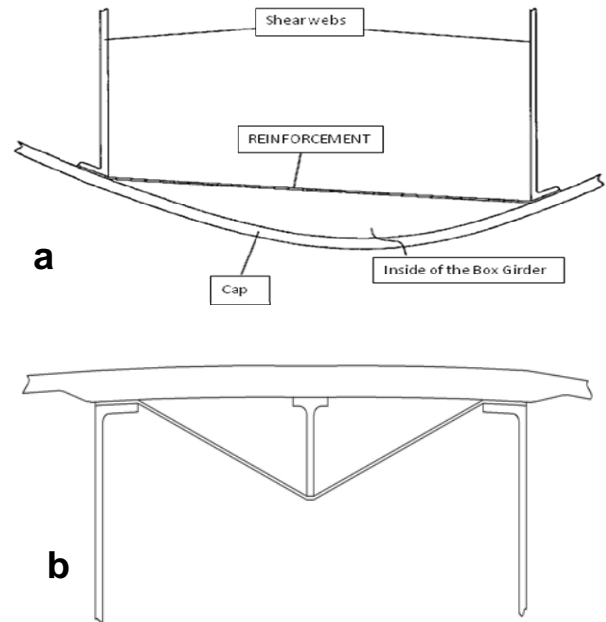


Figure 10. Two embodiments of the cap reinforcement preventing inwards deformations. Fig. a and b present solutions suitable for curved and flat caps respectively. Figures from patent application see ref. [5] and [6].

3.3. Demonstration in full-scale

As Proof of Concept, a load carrying box girder has been designed and manufactured. The box girder includes three out of seven patented structural solutions: two cap reinforcement and one diagonal reinforcement. By means of these inventions the thickness of the load carrying laminates was decreased by 40% and the box was prevented from distorting in the transverse direction.

The primary conclusion drawn from this study confirms significant improvement in the structural response of the blade obtained by utilization of the structural solutions invented. In Figure 11, the influence of implementation of the cross reinforcement is presented. Numerical results of the relative displacement of a selected blade section with respect to a box girder corner are shown. The results confirm that the invention significantly diminishes the transverse shear distortion problem.

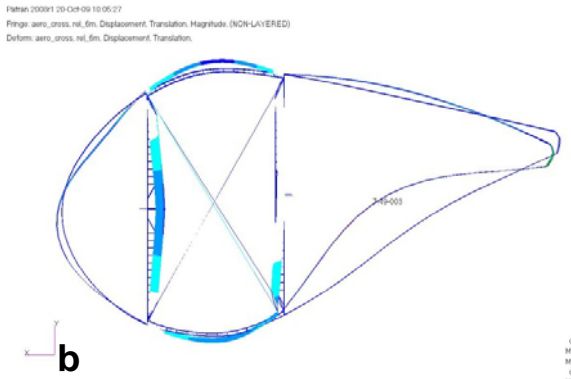
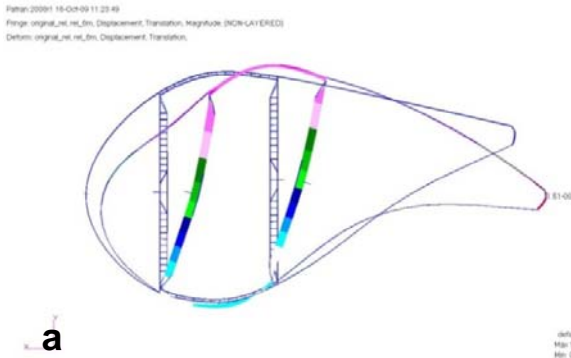


Figure 11. FEA comparison of the deformation of the original blade (Fig. a) and the design utilizing the cross invention (Fig. b). In the reinforced section (6m), the transverse shear distortion is prevented by the reinforcement. The results are scaled by a factor of 30 for visualisation.

4 Manufacturing

The cap reinforcement and a diagonal stiffener were introduced in the concept blade designed and manufactured in frame of the current project. The box girder was manufactured by SSP Technology A/S. The company has developed a patented spar solution which uses resin infusion in female moulds. The female mould technique employed has the advantage of a defined outer geometry, which is beneficial when the box girder is going to be assembled with the aerodynamic shells. The female mould also makes it easier to implement the reinforcements into the box girder, because of better access to the inside of the girder, see Figure 12.



Figure 12. The assembled box girder with cap reinforcement in both upper and lower part and cross reinforcement between the corners.

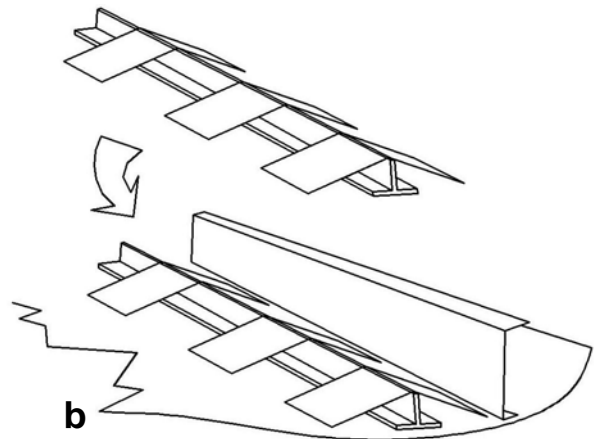


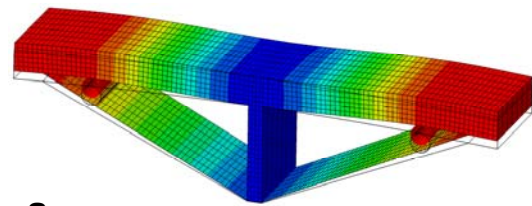
Figure 13. Box girder manufacturing using technology from SSP-Technology A/S. Fig. a. Photo of the lower half of the box girder. Fig. b. A technique which is expected to be used for serial production. The idea is to “collect” the sub-components (longitudinal and transverse stiffener) at a table in order to reduce mould time for the box girder.

The reinforcements were implemented in the blade using pre-manufactured parts ready to install in the box girder as soon as the curing was completed and before the box girder was assembled. Some of the parts were manufactured using the pultrusion process, which is very efficient and delivers specimens of high quality. The project demonstrated only one technique for implementing the reinforcement, but the experience gained has already resulted in new suggestions to reduce production time and costs, see Figure 13. Also, the decrease in the material thickness obtained by the new design is beneficial for the manufacturing process, because it is less time consuming and prevents defects in the finished laminate. Moreover, the curing process is easier to control since thin laminates reach lower temperatures during the exotherm.

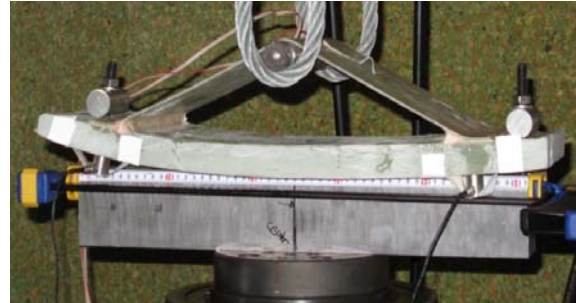
5 Sub-component structural analysis and testing

The numerical study of the cap reinforcement showed high stresses in the transverse direction. The main concern was the strength of the joint between the box girder and cap reinforcement. Numerical studies of complex composite structure are not sufficiently reliable for failure analysis, especially for a bonded joint. As a consequence, it was decided to perform a sub-component test to determine the strength of the joint. The selected test specimen was a part of the cap with the reinforcement attached to it. In an effort to simplify the test setup, the loading of the transverse reinforcement was applied directly to the reinforcement in contrast to the box girder, where the loading is transferred via the distance member. The numerical study was used to secure the behaviour of the test specimen emulate the real loading of the joint.

The properties of an adhesive joint are affected by many factors, such as surface preparation, fillet radius. In the sub-component test, it was possible to test several configurations for the joint and select the solution which showed the best compromise between strength and manufacturing price.



a



b

Figure 14. Analysis and test of sub-component. Fig. a. Finite element model showing deformation expected in the test. Fig. b. Test setup. The sub-component test has proved to be an effective way of establishing important properties of the box girder.

6 Summary

A full-scale test of a 34m wind turbine blade under combined flap- and edgewise load, indicated instability similar to results observed in non-linear FE-simulations. It is plausible that if the blade was further loaded, it would collapse in unstable transverse shear distortion. However, at this stage it is not possible to certainly conclude that since the unstable behaviour is likely to stabilize. In a previous full-scale test it was observed that transverse strain level due to the out-of-plane deformation, caused by the non-linear Brazier effect exceeded the critical level of a UD laminate. Based on the new knowledge, an innovative 40m load carrying box girder was designed and manufactured. The design utilizes 3 patented reinforcements in order to prevent interlaminar failure in the caps and transverse shear distortion of the blade. The patented reinforcement allowed material savings in the cap of up to 40% when only the two new failure criteria together with the two classical ones (buckling and in-plane material failure in longitudinal direction) are considered alone.

Furthermore, sub-component testing was performed to support the numerical analysis and increase the possibility of success for the coming full-scale test.

7 Future work

The 40m load carrying box girder will be tested in Risø DTU's full-scale test facility in order to demonstrate the effect of the new innovative design philosophy. The 34m blade will be tested to ultimate failure using the combined load scenario in order to be able to conclude whether the transverse shear distortion observed at the trial testing will result in ultimate failure. Furthermore, other designs and manufacturing techniques should be investigated.

Acknowledgements

The research is conducted within the frame of a project entitled 'Demonstration of new blade design using manufacturing process simulations'. The project is financially supported by the Danish Energy Agency through the Energy Technology Development and Demonstration Programme (EUDP 2009). The support is gratefully acknowledged. Both the research with the 34m blade and the 40m box girder is conducted in cooperation with SSP Technology A/S and work done by SSP-Technology A/S is very much appreciated.

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