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WIND TURBINE BLADE TESTING
UNDER COMBINED LOADING

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ABSTRACT

The paper presents full-scale blade tests under a combined flap- and edgewise loading. The main aim of this paper is to present the results from testing a wind turbine blade under such conditions and to study the structural behavior of the blade subjected to combined loading. A loading method using anchor plates was applied, allowing transverse shear distortion. The global and local deformation of the blade as well as the reproducibility of the test was studied and the results from the investigations are presented.

1. INTRODUCTION

Today, wind turbine blade certification tests are based on flapwise and edgewise loading only. However, some results have indicated that loads in other directions than pure flap- or edgewise may have major importance and failure mechanisms related to transverse shear distortion discussed in (Jensen 2008) may also be sensitive to this loading direction.

The aim of this study is to investigate how combined loading can be performed on full-scale testing of wind turbine blades without limiting its possibility to deform in shear distortion. The aim is also to investigate how important shear distortion is in blade failure and how it can be prevented.

A thorough analysis of the behavior of wind turbine blades validated by testing is needed in order to improve their structural design and move the design limits. The testing and numerical simulations performed at Risø DTU, see (Berggreen, Branner, Jensen, Schultz 2007; Luczak. Manzato, Peeters, Branner, Berring, Kahsin 2007; Jensen 2008; Jensen Puri, Dear, Branner, Morris 2011) have resulted in a considerable increase in knowledge about the structural response and failure of wind turbine blades.

2. METHODS FOR BLADE TESTING

The tests presented were performed on a 34m long blade from SSP technology A/S. A more detailed description of the loading conditions, measuring methods, test setup and preparation are found in (Nielsen, Jensen et al. 2010) and in (Nielsen, Nielsen et al. 2010) the combined load definition and test methods are described in detail.

2.1 Combined Load Case Background. Under normal operation the blade profile is moving towards the wind at a small angle. The resulting aerodynamic force is therefore mainly pointing flapwise towards the suction side, and slightly angled towards the leading edge. A typical load in the flapwise direction is shown in Fig. 1.

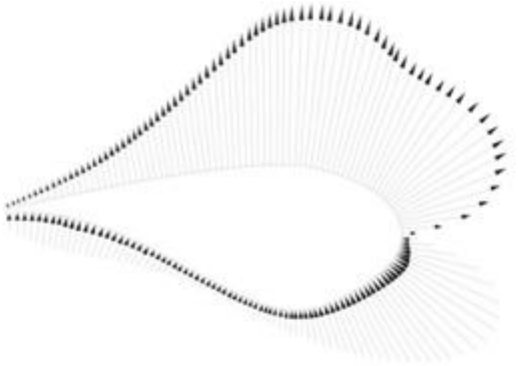

Fig. 1. Pressure distribution on an aerodynamic profile generating the aerodynamic loads.

In the edgewise direction, the main loads are a gravity load and the dynamic loads, which e.g. result from an emergency stop of the turbine.

A part of the present project was to explore which loads and loading directions were appropriate in a combined load case examination of the blade.

For the SSP 34m blade the available loads were the extreme loads in the flap- and edgewise directions. Thus, the determination of the loading on the blade was performed from these and the magnitudes of the loads were made by vector addition of the extreme loads in flap- and edgewise directions. The loads were then applied at an angle of 30°, measured from the flapwise direction towards the leading edge.

2.2 Loading. For the combined load test the blade is mounted on the test rig as shown in Fig. 2. This loading method is based on a new concept and the process of test preparation and load application is described in more details in (Nielsen, Nielsen et al. 2010). The way the blade is positioned allows the force to be applied on the suction side of the blade pulling towards the floor, which creates an angle of 30^o with the flapwise plane.

The loads are defined as % of Risø loads, where 100% Risø loads represent the ultimate load where a similar blade failed in a flapwise test.

Fig. 2. The blade bolted to the test rig. The tip was truncated at 25m. The blade is loaded at a 30^o angle to the flapwise direction, simulating combined flap- and edgewise loads.

A load application method using anchor plates was applied as presented in Fig. 3. The anchor plates are specially shaped steel fittings attached to the blade with an epoxy adhesive.

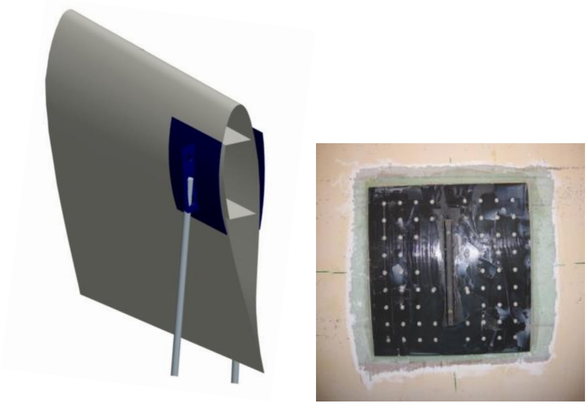

Fig. 3. Load application using anchor plates. In the performed test the anchorplates glued to the blade had a surface area of 500x500mm.

Several possibilities for the load introduction were investigated in order to allow the blade to deform freely. Considering all aspects, as presented in (Nielsen, Nielsen et al. 2010), it was decided to only use one anchor plate at each of the three loaded sections.

3 RESULTS

The results of full-scale blade testing under combined loading are presented in this section.

3.1Global Behavior. Before testing the combined load case, finite element analysis (FEA) was performed in order to predict the possible failure of the blade. It indicated buckling of the cap at approximately 8.5m from the root at a load of approximately 111% of the Risø load.

The measurement of the global displacement of the blade in the horizontal direction (parallel to the floor is presented in Fig. 4. It can be observed that the blade deflects towards the pressure side and the leading edge in the region close to the root, but towards the suction side and the trailing edge in the region close to the tip.

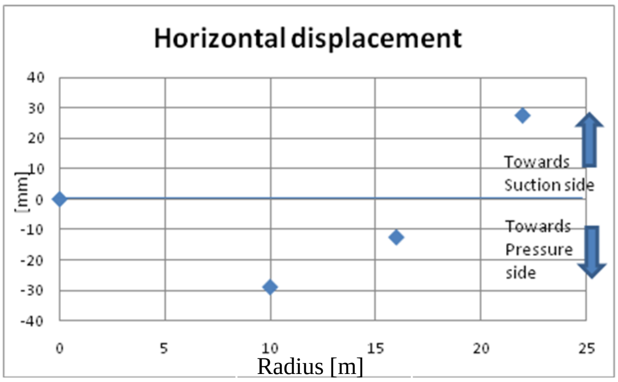

Fig. 4. Horizontal displacement measured at 55% of the Risø combined load.

The deformations at different sections were studied at 4m, 7m and 10m from the root. Fig. 5 presents the results for the 10m section. At small loads the blade section is twisting counter-clockwise as seen from the root, while it starts to twist clockwise as the load is increased. This behavior is sketched for the same section in Fig. 6.

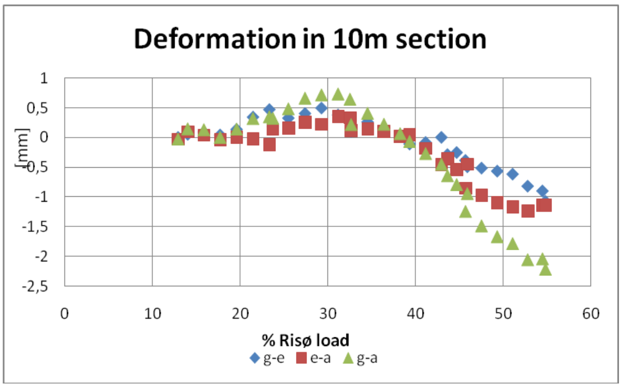

Fig. 5. Deformation of the 10m section: Difference in vertical displacement between the points *g*, *e* and *a* (location indicated in Fig. 6).

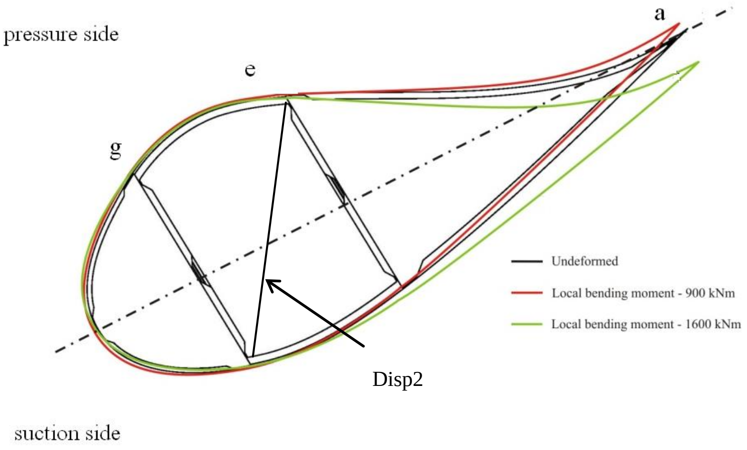

Fig. 6. Sketch of the10m section showing the blade behavior during loading. Black line: undeformed configuration, red line: local bending moment 30% Risø load, green line: local bending moment 55% Risø load.

The FEM calculations showing the change of the length of a box girder diagonal along the blade radius is confirming this observation. Fig. 7 shows the relative length change of a box girder diagonal for different load levels as predicted by the FE model. It can be observed that the radial position where the deformation of the diagonal switches sign moves outward with increasing load. At the 10m section the length of the diagonal first increases, and then decreases as the load is increased. The switch from one side to the other at the 10m section happens at approximately 40% loads, which is in agreement with the measured results presented in Fig. 5.

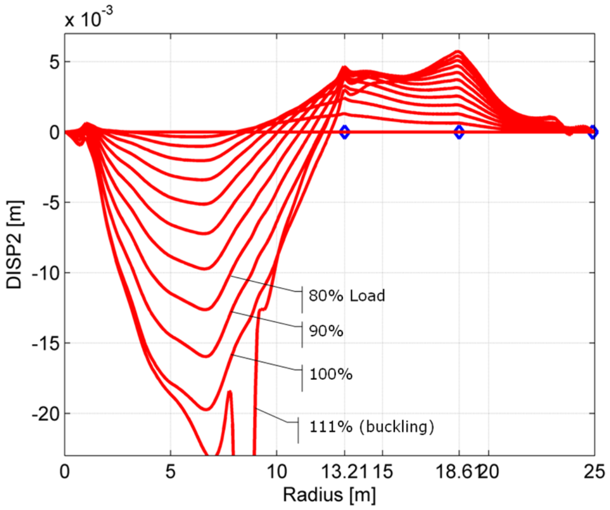

Fig. 7. Relative length change of a diagonal of the box girder for different load levels (0%, 10%, ... , 90%, 100%, 111%) as predicted by the FE model. (Buckling of the suction side cap can be observed at r=8.5m and 111% load.)

3.2 Transverse Shear Distortion. One of the focus areas of the combined load test was investigating the “transverse shear distortion”, as it may be an important failure mechanism for this loading case. The phenomenon of transverse shear distortion is presented schematically in Fig. 8.

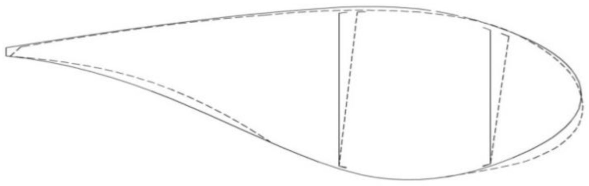

Fig. 8. Schematic presenting transverse shear distortion behavior.

The transverse shear distortion was measured for loads up to 90% Risø load. The measurements were performed in steps where the load was increased. The tests were first carried out with the blade reinforced with wires to prevent the transverse shear distortion, see Fig. 9 (red arrows). Then the wires were removed and the test was repeated. Both tests with and without reinforcement were carried out successfully without any damage to the blade.

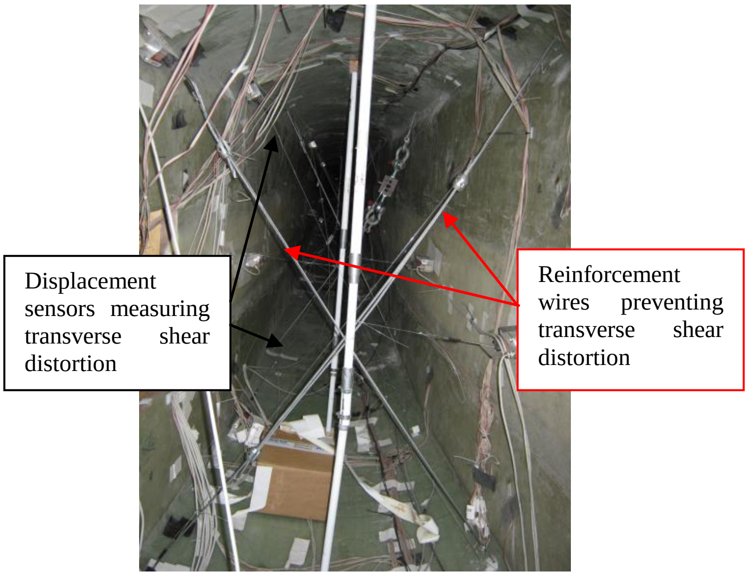

Fig. 9. Photograph taken inside the blade showing the reinforcement wires, and the measurement equipment installed between the two webs. The length of the reinforcement wires in front of the picture are approximately 2m.

Fig. 9 also shows the displacement sensors mounted inside the blade, where the diagonal lines crossing inside of the box are strings that allow measuring the distance between the corners (black arrows).

The comparison of these tests showed a reduction of the transverse shear distortion when the reinforcement was applied, see Fig. 10.

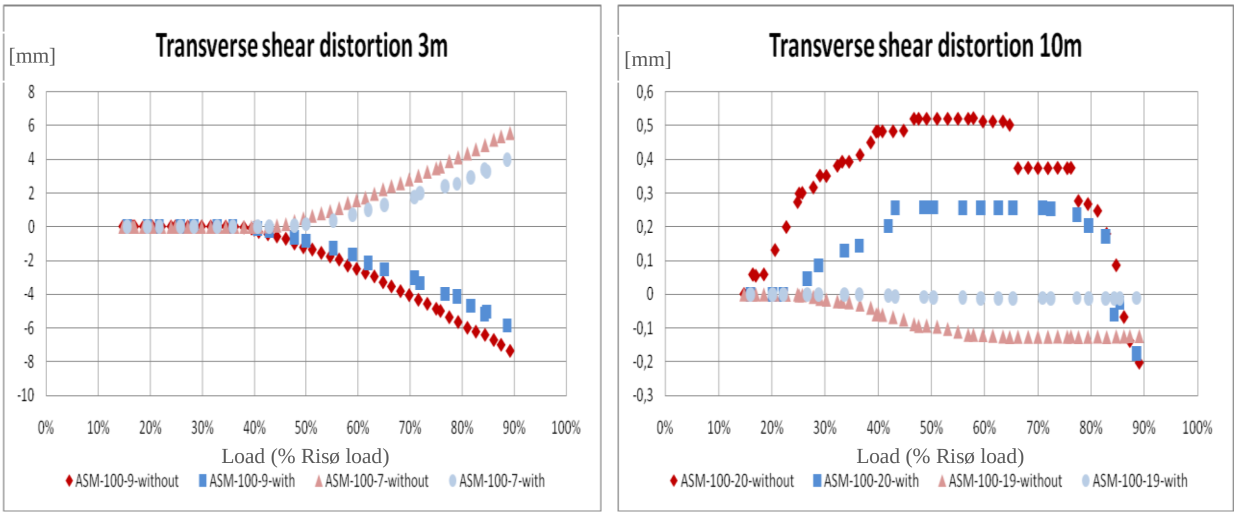

Fig. 10. Transverse shear distortion in 3m and 10m sections with (blue symbols) and without (red symbols) reinforcements.

3.3 Reproducibility of the Measurements. Some of the tests were repeated without making any changes in the measurement procedure. In Fig. 11, the transverse shear distortion (see Section 3.2) in the 3m section is presented. The tests were performed in the following order: a – b – c. The results presented here reveal that the measured deformations did not follow the same path at a lower loading value when the test was repeated.

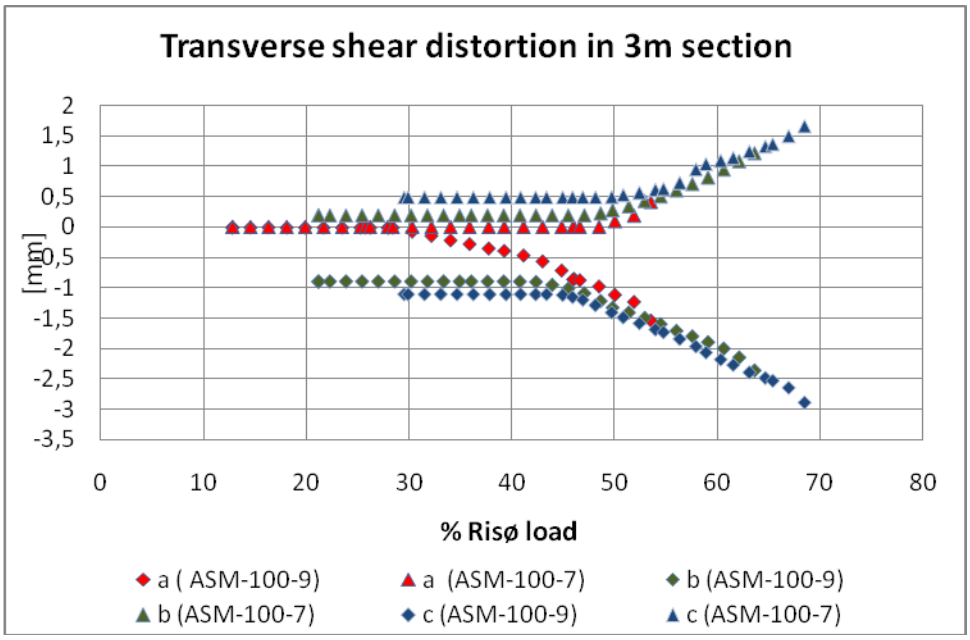

Fig. 11.Data from 3 repeated pulls showing the transverse shear distortion in the 3m section, a (red) the first pull, b (green) the second pull and c (blue) the third pull.

Such behavior was observed at many locations and for different structural components such as panels and webs, see also (Nielsen, Jensen et al. 2010).

4 CONCLUSIONS

This work presents full-scale tests of a wind turbine blade under combined flap and edgewise loading, i.e. at 30° angle from the flapwise plane towards the leading edge.

The global and local deformation of the blade as well as the reproducibility of the tests was studied and some of the results were compared to FE analyses. In this investigation, the FEA closely resembled the behavior of the blade.

Repeated measurements of local deformations indicate that these are only reproducible to some extent. The blade does not behave perfectly elastically, and the results from these measurements depend on the ways in which the blade are loaded and on the previous loading case. Measurements of local deformations has thus to be treated very carefully as the deviation might exceed 50% at a low load level and in the case the load history differs.

The tests presented in this paper provide no indication that transverse shear distortion may result in failure for this particular wind turbine blade in combined loading. It is shown that diagonal steel wire reinforcements can reduce the transverse shear distortion. Such reinforcements may be a reasonable solution, if action should be taken in order to prevent transverse shear distortion.

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