

# FULL SCALE EXPERIMENTAL CHARACTERISATION AND NON-LINEAR FINITE ELEMENT MODELING OF LOAD RESPONSE OF A COMPOSITE WIND TURBINE BLADE

S. Laustsen<sup>1,2\*</sup>, E. Lund<sup>1</sup>, O.T. Thomsen<sup>1</sup> and L. Kühlmeier<sup>2</sup>

<sup>1</sup> Department of Mechanical and Manufacturing Engineering, Aalborg University, Aalborg, Denmark, <sup>2</sup>Suzlon Blade Technology B.V., Aarhus, Denmark, \* Corresponding author ([steffen.laustsen@suzlon.com](mailto:steffen.laustsen@suzlon.com))

**Keywords:** *Wind turbine blade, Sandwich structures, Full Scale Measurements, FEM*

## Abstract

The current study involves a full scale test of a wind turbine blade (see [1] for similar studies), which has been monitored in terms of induced global loads and displacement responses, and further more closely monitored in terms of full field displacement measurements on a specific substructure of interest. The experimental results are compared and used to correlate a non-linear FEM model intended as a tool for calculation of local load/stress responses based on the globally induced loads. The methods and assumptions adopted to develop the FEM tool are explained and the result outcome is discussed.

## 1 Introduction

To characterize the detailed stress and strain distribution in a local part of a complex composite structure, a feasible approach is to use numerical methods, such as the Finite Element Method (FEM), to develop a model capable of describing how externally applied global loads are converted into internal forces in the substructure of interest.

To validate the accuracy of the modeling results, experimental methods are normally used, with the objective of correlating the model predictions in terms of displacement and strain fields with the experimental observations.

Based on this, the framework for further and more detailed analyses of the substructure can be developed taking additional local parameters into account that cannot be included by the global computational model.

## 2 Motivation

Numerous structural details exist on modern wind turbine blades and in most cases these are well investigated numerically. Experimentally, however, in most cases only coupon test specimens subjected to simplified one-dimensional loading conditions have been investigated in terms of failure and

fatigue analyses. These cases rarely agree with the actual loading conditions, which are usually multidimensional. Superposing the one-dimensional cases do in some cases correspond well to the simulated response of a multidimensional case, but in many structural details this is not the case.

Thus, the motivation behind obtaining information on displacement, strain and/or stress boundary conditions for a chosen local detail/zone is to use this information as the basis for developing further and more detailed experimental investigations on the substructure level, which then can be conducted in a multi-axial test rig designed specifically to take the actual loading conditions into account.

## 3 Blade Substructure of interest

In the present study a full scale test of a 42 m wind turbine blade has been conducted to determine the local displacement and strain fields in a selected substructure of the blade, see Fig. 1. The substructure or local zone constitutes a part of the aerodynamic shell structure of the blade on the suction side near the leading edge, and it has been chosen due to the complex interactions between the external loads applied to the blade and the stress/strain distribution induced locally that occurs at this location.

Modern wind turbine blades are typically manufactured using a combination of monolithic and sandwich composite materials. Thus, the (outer) aerodynamic shells and the internal stiffeners (shear webs) are typically made as lightweight composite sandwich structures, whereas the root end and the central blade main laminates (girders) on both the pressure and suction sides are thick-walled monolithic composite laminates. The considered substructure, besides being a composite sandwich structure, is single-curved, which complicates the determination of the structural response further.

It is well known that (localized) stress concentrations are induced in the vicinity of structural details in sandwich panels such as joints, core junctions, inserts or production defects. These may initiate local failure (crack initiation and propagation) which lead to global failure of the whole sandwich structure [2]. These “very” local quantities compared to the size of a wind turbine blade are the principal interest of this study.

#### 4 Experimental setup

The test setup of the blade is shown in Fig. 2. The external loads on the blade are introduced at two locations, which give a good representation of the state of strain appearing in an operating blade in the region of the local zone. As shown in Fig. 2, the outer load introduction is controlled by two actuators; one in the edgewise, and one in the flapwise direction, respectively. The inner load introduction only consists of an actuator in the flapwise direction. The displacements of each load introduction point have further been monitored.

The local blade zone was monitored using the full field measuring white light technique, Digital Image Correlation (DIC) [3], from the outside of the blade, while strain gauges were mounted both inside and outside for verification purposes and to give an indication of the through-thickness variation of the in-plane strain components, see Fig. 3. Finally as shown in Fig. 4, linear variable differential transformers (LVDTs) were mounted inside the blade adjacent to the local zone to monitor the progressing cross-section ovalization (Brazier effect [4]) with increasing external loading.

To establish sufficient experimental information concerning the dominant load response parts of the blade substructure, the blade was subjected to six different load cases in different directions. The considered load cases are illustrated in Fig. 5 with respect to the cross-sectional shape of the blade.

Thus, the chosen setup allows for the measurement of four different measurement quantities, all dependent on the applied loads, which can be used to verify the numerical model;

- Global displacements at load introductions
- Relative cross-section deformation (from LVDT) adjacent to the considered blade substructure
- Full field displacement field of the blade substructure (DIC)
- Strain values of blade substructure from strain gauges and DIC

In the presented work, it has been decided not to consider the strain values, due to the extensive data treatment and considerations required compared to the displacement results. This choice is further explained in section 6.

#### 5 Numerical modeling

The explained experimentally obtained full scale deformation and strain maps are used to inform and fine tune a full scale geometrically non-linear FEM model based on layered shell elements.

In terms of full scale modeling of wind turbine blades the typical approach is to use layered shell elements, and this is also adopted in the current work. By having a full geometrical description of the outer blade surface it is relatively simple to build a FEM model of a laminated structure, which yields sufficiently accurate results in terms of displacements and in-plane stress and strain quantities.

In developing such a model, different potential pitfalls have to be considered and taken into account, as these can have considerable impact on the reliability of the obtained results.

Due to the fact that the geometrical description of the blade often conveniently relates to the external surface of the blade, node offset options are normally used to account for this. As explained in [5], node offsets can sometimes lead to erroneous results. This is especially the case when torsional or coupled bending-torsion responses are considered. This has to be taken into account in the current analysis of the blade, where coupling effects between the bending and torsional deformation modes exist due to the geometry and constitution of the blade.

The FEM discretization, as in any other FEM model, also has to be considered. However, in this case as well as in similar cases, the mean discretization is not driven by a demand for model convergence, but rather by the desire to have a good representation of the stiffness variation. The lay-ups do in some cases change down to a length of 10 mm, while the convergence demands in terms of global strain energy on the element size might be one or two decades longer than that. Due to this demand, it has been chosen to use a standard 4 node iso-parametric shell element (CQUAD4 in Nastran)

When modeling laminated structures two different approaches can be taken, when defining the different plies and their stacking sequence, depending on the analysis tool available. The approach can either be zone-based or ply-based modeling, referring to how

the laminate description varies across the structure. In zone-based models the laminate is normally defined for different regions or patches of the blade, while ply-based models allow for a definition of how each ply in production is placed into the mold and how these interact as a laminate across the whole structure. The latter allows for a more thorough description and is often more time consuming to carry out, but this method also allows for a better investigation of the sensitivities of the model results to the adopted modeling assumptions. This is because the parameters for each ply can be changed individually and in close relation to the production tolerances, which might influence the model predictions.

## 6 Discussion and conclusion

To obtain an experimental validated numerical model, the model predictions must be correlated to the experimental results.

Different approaches can be taken to do this, dependent on how closely the model results are to be correlated with the experimental data. In this connection a clear distinction between displacements and strains should be made. In the numerical work the strain field computed based on the displacement field is normally very smooth, while the experimentally obtained strain field can be very erratic due to noise or fine spatial resolution. Although strain gauges can provide an accurate measurement of the surface strains, the strain variation across the blade surface can be obscured due to local geometric imperfections (induced in the manufacturing), which cannot realistically be included in the global FEM model. Effects of such local geometric variations will typically not give rise to equally significant discontinuities in the displacement field.

Thus, experimentally obtained displacements can in many cases prove to be the preferred reference quantity although it is the strains that are really the desired objects for comparative studies and detailed analysis.

To obtain an initial estimate on accuracy of the prediction of the displacements, a comparison is made between the blade deflections at the outer load introduction point, see Fig. 6, the cross sectional deformations, see Fig. 7, and the surface displacement field, see Fig. 8 and Fig. 9.

Because the result comparison of the cross sectional deformation and the full field surface deformation of the substructure is more comprehensive to present, only results for the Combined Compression (CC)

load case is shown. The specifications regarding the camera settings and data processing adopted with the DIC measurements are shown in Table 1.

The result comparison between the FEM model predictions and the experimental results represents a preliminary measure of the correlation. Better correlation between the results can be obtained by changing one or more governing modeling parameters which have to be identified. As shown, the model predictions overall correlate well with the measurements in terms of trends, but it is seen that the model appears to be more compliant for the tip displacements and the cross sectional deformations. Parameters to consider immediately could therefore be the input of elastic properties for the blade materials. The model sensitivities to these parameters are still to be investigated. It is considered rational to look at the material values, because the design values, which often are used, are the most conservative within the production tolerances.

As a conclusive note to the presented work, it should be underlined that the predicted results have been based on a linear FEM analysis. Because laminated composite structures are often very compliant, geometrical non-linear models are generally needed. Besides taken the stress-stiffness effects into account this also allows for an investigation of geometrically non-linear effects, e.g. ovalization or buckling, due to the change in geometry.

Although the experimental setup and the applied loads might not trigger non-linear effects to any significant degree, the non-linear numerical model should still be able to predict the measured response and further be able to predict the response at higher load levels and in this sense exhibit extrapolated experimental validated non-linear effects. These predictions are of interest due to the possible change of boundary conditions on the substructure, which might be very different than the conditions predicted by the linear analysis.

## Acknowledgement

The work presented is part of an Industrial PhD project carried out in collaboration between Suzlon Blade Technology B.V., Denmark and the Department of Mechanical and Manufacturing Engineering, Aalborg University, Denmark. The project has received partial sponsorship from the Danish Agency for Science, Technology and Innovation. The support is gratefully acknowledged.

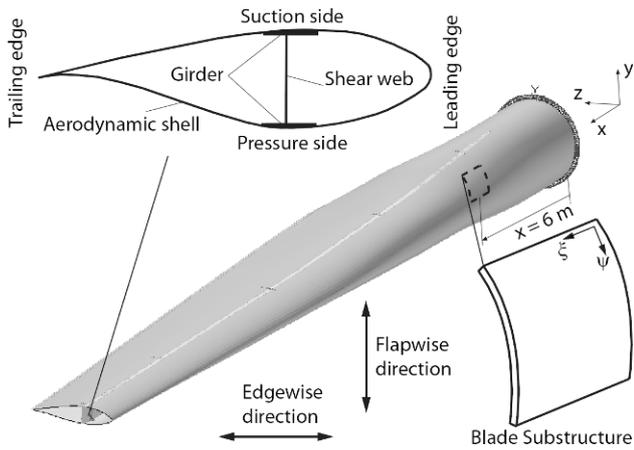


Fig. 1: Blade terminology and location of blade substructure.



Fig. 2: The setup of the full scale test

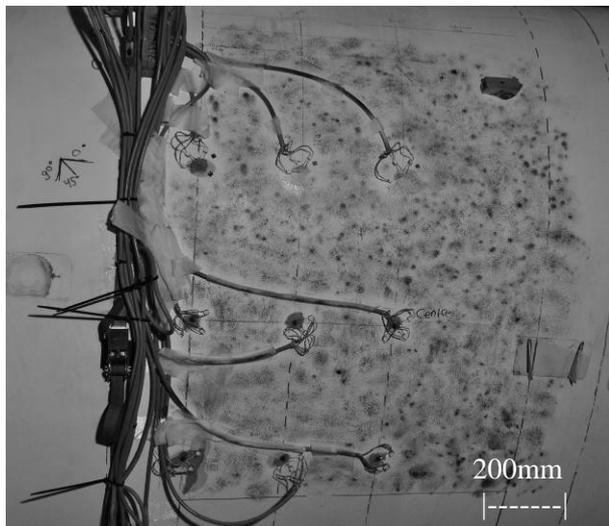


Fig. 3: The strain gauge instrumented panel, which is also coated in preparation for DIC measurements

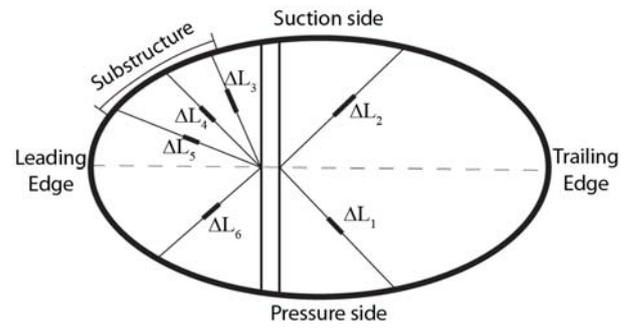


Fig. 4: Location of LVDTs for ovalization measurements

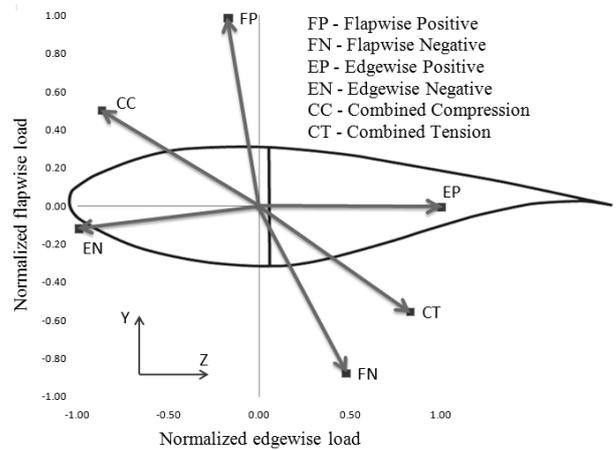


Fig. 5: Loading directions and annotations of the different load cases

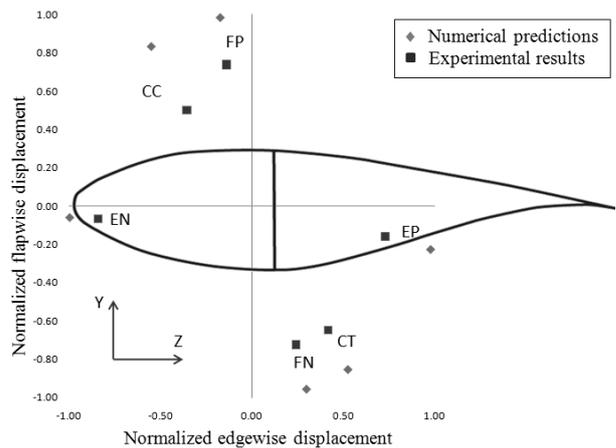


Fig. 6: The predicted tip displacements compared to the experimental results

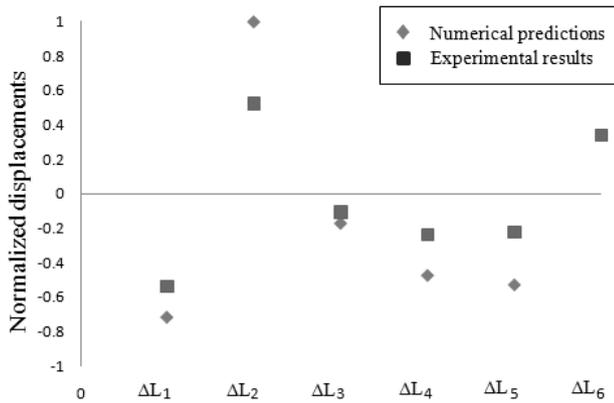


Fig. 7: The predicted cross section deformation compared to the experimental results for the Combined Compression (CC) load case

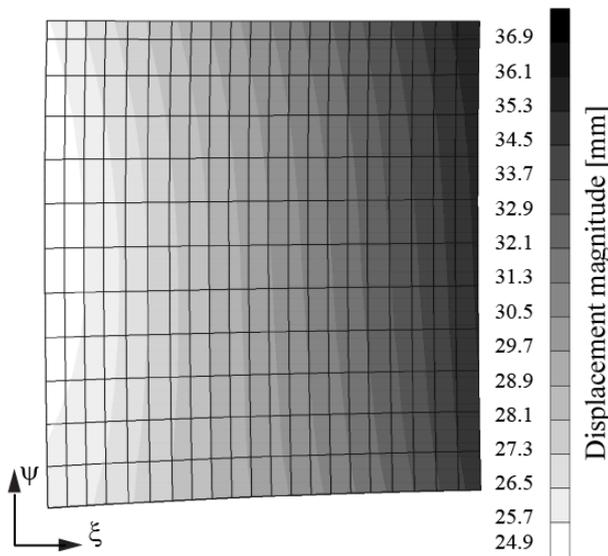


Fig. 8: The numerical predicted full field deformation for the Combined Compression (CC) load case

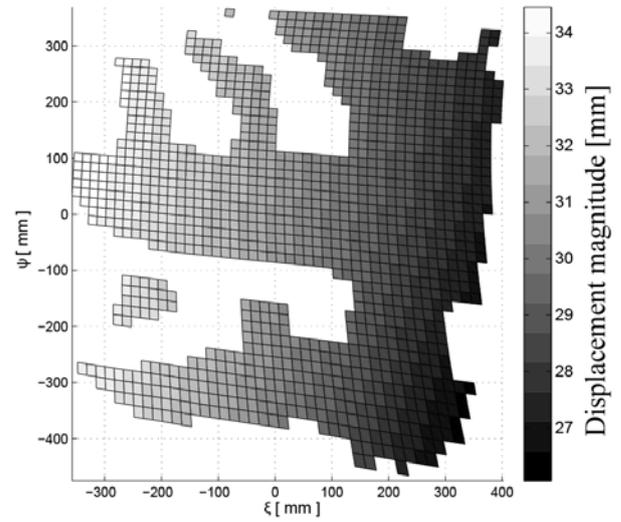


Fig. 9: The experimental full field deformation (DIC) results for the Combined Compression (CC) load case

Technique Used	Stereo Image Correlation
Subset size	40 x 40 Pixel
Shift	40 pixel (0% overlap)
Camera	8 bit, 2048 x 2048 ARAMIS 4M system
Field of view	750 mm x 750 mm
Measurement points	1485
Displacement	
Spatial resolution	21 mm
Resolution	5 $\mu$ m

Table 1: Performance specification of DIC results shown in Fig. 9

## References

- [1] LCT. Overgaard, E. Lund, OT. Thomsen “Structural collapse of a wind turbine blade. Part A: Static test and equivalent single layered models”. *Compos Part A: Appl Sci Manuf* 2010;41:257–7
- [2] D. Zenkert (1995). “An Introduction to Sandwich Construction”, EMAS Publishing, London
- [3] TC. Chu, WF. Rason, MA. Sutton and WH. Peters “Applications of digital image correlation techniques to experimental mechanics”. *Exper. Mechanics*, 25:232-244, 1985.
- [4] L.G. Brazier “On the flexure of thin cylindrical shells and other "thin" sections”. *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*, 116:104–114, 1927.
- [5] D. Laird, FC. Montoya, DJ. Malcom “Finite Element Modeling of Wind Turbine Blades” AIAA-2005-0195