Improved design for large wind turbine blades of fibre composites (Phase 3)

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Improved design for large wind turbine blades of fibre composites (Phase 3) - Summary report

Risø-R-Report

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June 2009

Risø DTU
National Laboratory for Sustainable Energy

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Abstract (max. 2000 char.):

An overview is given of the activities of the project "Improved design for large wind turbine blades (Phase 3)", partially supported by the Danish Energy Agency under the Ministry of Climate and Energy through the EFP-grant no. 33031-0078. The project was focussed at the development of new design methods for wind turbine blades, so that uncertainties associated with damage and defects can be reduced. The following topics with respect to failure modes were covered: Buckling-driven delamination of load-carrying laminates, cracking along interfaces in material joints, implementation of cohesive laws in finite element programmes and hierarchical finite element models. Methods and major research results of the project are summarised. Some future goals for future research activities are briefly discussed.

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Preface

This summary-report contains an overview of the activities of the project "Improved design for large wind turbine blades (Phase 3)", partially supported by the Danish Energy Agency under the Ministry of Climate and Energy through the EFP-grant no. 33031-0078. The project ran from 2005 to 2008. The participants in the project were: The Materials Research Division, Risø DTU (project leader), The Wind Energy Division, Risø DTU, The Department of Mechanical Engineering, Aalborg University, LM Glasfiber A/S and Vestas Wind Systems A/S. The project was a continuation of the project "Improved design for large wind turbine blades, based on studies of scale-effects (Phase 1)" (J. no. 1363/01-01-0007) and the project "Improved design for large wind turbine blades, based on studies of scale-effects (Phase 2)" (J. no. 1363/03-0006).

1 Introduction

1.1 Background

The amount of electricity produced by wind turbines increases year by year. Large wind turbines are placed in off-shore parks, projected to be in used for a long time. Due to their size, wind turbines are costly to manufacture and since they should have a long life-time (wind turbines are usually projected for 20 years), it is of paramount importance that the wind turbines are well designed and their behaviour is well understood so that they can be properly repaired if damage should develop.

The largest rotating components of a wind turbine are the turbine blades. They are large structures manufactured from strong, fatigue resistant composite materials (e.g. glass fibre and carbon fibre composites), low-weight core materials (e.g. balsa wood or polymer foam), bonded together by polymer adhesives. Wind turbine blades can develop various different types of damage and failure modes, such as (buckling-driven) delamination and failure of adhesive joints (Sørensen *et al*., 2004). Such damage can result from processing-induced flaws. In order to avoid development of significant damage in a wind turbine blade, the damage evolution of each material and the interfaces between the materials must be understood and properly characterised in terms of mechanical properties that can be used for assessing the damage evolution by the use of reliable models. Such tools will allow the blade designer/manufacturer to set up scientific-based criteria for maximum allowable defect and damage sizes and thus provide criteria for quality control for new-manufactured blades. Furthermore, such tools can be used for evaluating the effect of damage found in a blade in service, on the residual life of the blade.

Fracture mechanics is the mechanics discipline of predicting the strength behaviour of components accounting for cracks. The fracture mechanics approach differentiates between various failure modes and requires the measurements of the fracture parameters of materials and interfaces. Potentially, the approach should also consider the interaction (and possible transition between) different damage/fracture modes. However, a complete set of such tools does not exist today for composite materials for wind turbine blades.

The tools that we aim to develop are based on fracture mechanics. The scientific aims are to develop general tools for analysing the various failure modes by the following approach:

1) developing *new characterisation methods* for the measurement of "new" (fracture mechanics) parameters

2) developing *new modelling tools* for predicting the load-carrying capabilities of structures

3) experimental *verification* of the characterisation methods and modelling tools by case studies where the capability of the tools are examined. In this step, we investigate whether the model are capable of predicting the behaviour of real components. This is done by testing generic specimens that are also modelled.

An example of (1) is the development of a new fracture mechanics testing method, the double cantilever beam specimen loaded with uneven bending moments (DCB-UBM), which was developed and refined in Phase 1 and Phase 2. This fracture mechanics testing method enables mixed mode fracture testing, measurement of fracture energy of adhesive joints, and bridging laws and cohesive law for describing delamination of fibre composites.

An example of (2) is the modelling approach for refining the level of details in areas developing damage in a full 3D blade model; the finite element mesh is refined in areas where damage and cracking was to be modelled (this is called hierarchical modelling).

An example of (3) is the strength prediction of medium size adhesive joints, subjected to four point flexure; this generic problem was studied in Phase 1 and Phase 2. The strengths of the specimens were successfully predicted from fracture mechanics data obtained by testing of DCB-UBM specimens (Sørensen *et al.*, 2006).

If the experimental verification is successful (i.e., with good agreement between predictions and measurements), it can be concluded that the proposed approach works well. Then this approach can be tried in the design office of the wind turbine manufactures. If the experimental validation is not successfully met, it is necessary to reconsider the assumptions and limitation made in the characterisation and modelling formulation, so that it may possible to develop better tools in the future.

In contrast to a so-called probabilistic design approach, fracture mechanics can be used for qualitative prediction of the dependence of strength on specific damages and can thus be used as a tool for predicting whether an observed damage will propagate or not at a given applied load level. It can thus be a very helpful tool in the repair and maintenance of wind turbine blades, which, as mentioned above, are designed to last for 20 years.

Fracture mechanics is the core concept of this research project. A design approach that uses fracture mechanics and accounts for the presence of damage and cracks is called a damage tolerant approach.

1.2 Purpose

The long-term goal of this project is to develop *general characterisation and modelling tools* for each possible failure mode, so that the mechanical properties of the materials can be fully utilised and the structural design can be optimised. The new design methods will enable the wind turbine industry to improve their design details and their choice of materials.

The specific problems investigated in this project (Phase 3) are failure of materials joints (cracking along the interface between dissimilar materials), failure of composite panels subjected to compressive loads (buckling-driven delamination) and modelling of damage in a global model of a wind turbine blade.

This report is a summary report and thus contains only a brief presentation of the research topics and the major results. More details can be found in the publications that are listed in the end of this report.

2 Buckling and compressive strength

2.1 Introduction

Delaminations can be defined as areas with poor or no bonding between adjacent layers. They are typical in layered composite structures and can be considered as a type of interlaminar cracks that reduce the strength of the structure. Delamination normally originates from either flaws origination from the manufacturing process or from impact damage during production, transport or service. In the manufacturing process, instabilities and imperfections of various types may result in delamination. The thermal and chemical shrinkage of composite components may also lead to delamination (Bolotin 1996). Impact damage may lead to multiple delamination, which can result in a significant reduction in strength. In addition, stress concentrations around structural discontinuities such as holes, notches, ply-drops and connections may cause the initiation and growth of delamination.

Delamination is usually the most critical type of damage that a composite and sandwich structure experiences under compressive loading (Abrate 1991, Pavier & Clarke 1995).

When a panel with a delamination is subjected to compressive loading, the plies on one side of the delamination may buckle. This buckling will then introduce bending in the plies on the other side of the delamination. Hence, these remaining plies will be subjected to both bending and compressive loading, resulting in higher stresses than observed without the delamination and therefore reduced failure load (Peck & Springer 1991; Pavier & Clarke 1995). This type of buckling is known as the *local buckling* mode and typically occurs when the delamination is large and close to one of the surfaces. In general, however, compression-loaded panels are subjected to two buckling modes. The other mode is known as the *global buckling* mode, wherein both sub-laminates buckle toward the same side of the panel. This type of buckling typically occurs when the delamination is small and deep in the laminate, as shown in Figure 1.

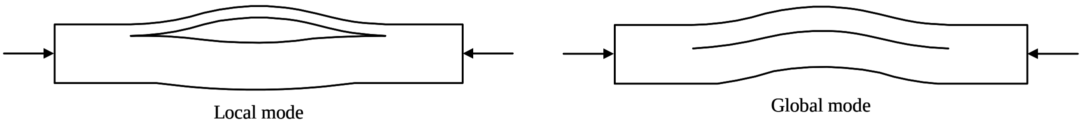


Figure 1 Local and global modes of delamination-induced buckling.

Wind turbine blades are often constructed with a load-carrying box girder (main spar) that supports the outer shell. The purpose of the spar is to give the blade sufficient strength and stiffness, both globally and locally. Globally, the blade should for instance be sufficiently bending stiff so that it does not bend too much and collides with the tower under different types of loading. This requires that the flanges of the spar are rather thick, that the materials used are highly advanced composites that have high strength- and stiffness-to-weight ratios and that most of the fibers are in the longitudinal direction. Delaminations may be found within these load carrying flanges and are therefore critical for the compressive strength of the blade and thereby also for the operation of the wind turbine. The aim of this study is to investigate how much the strength of the panels is reduced due to the delaminations and to study under which conditions a delamination will grow.

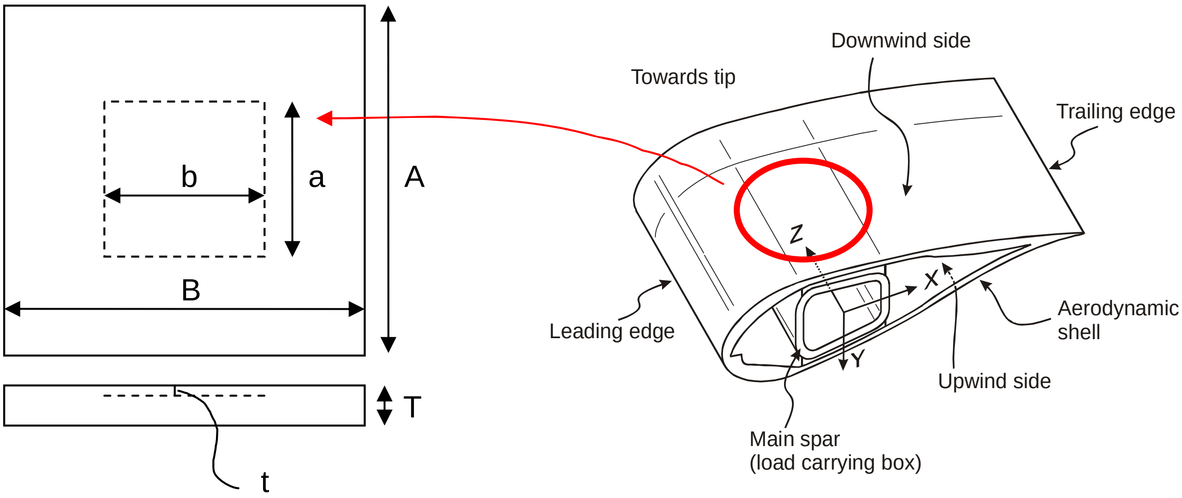


Figure 2 Description of test specimens, which are similar to the load carrying laminate in the main spar of a typical wind turbine blade.

2.2 Experimental work

The panels tested in this study under in-plane compression are similar to the load carrying flange in the main spar of a typical wind turbine blade (see Figure 2). The test specimens are rectangular composite panels made of glass reinforcement and epoxy resin. The lay-up is symmetric with approximately 90% of the reinforcement in the load direction and the remaining reinforcement in the ±45° directions. Two different types of panels were tested, one type was made with prepregs and the other type was made using the vacuum infusion technique. For both types some of the panels were manufactured with no intentional defects or imperfections, while others had Teflon sheets imbedded to simulate delaminated rectangular areas of different size (*b/B*) and depth (*t/T*) as shown in Figure 2. A specially designed test rig was used in a 5 MN Instron testing machine. The rig is designed to limit rotation and out-of-plane deflection of the edges of the panels. The panels were loaded past ultimate failure and an advanced digital image correlation (DIC) measurement system was used in addition to conventional displacement transducers to monitor deflections of the panels under increasing load (see Figure 3).

Figure 3 Experimental setup. Deflections were measured by a DIC measurement system on one side of the panel and by conventional displacement transducers on the other side.

As described above, the compressive loaded panels are subjected to the two different buckling modes; the global buckling mode and the local buckling mode. The following buckling responses were observed during the experiments:

a) Global buckling.

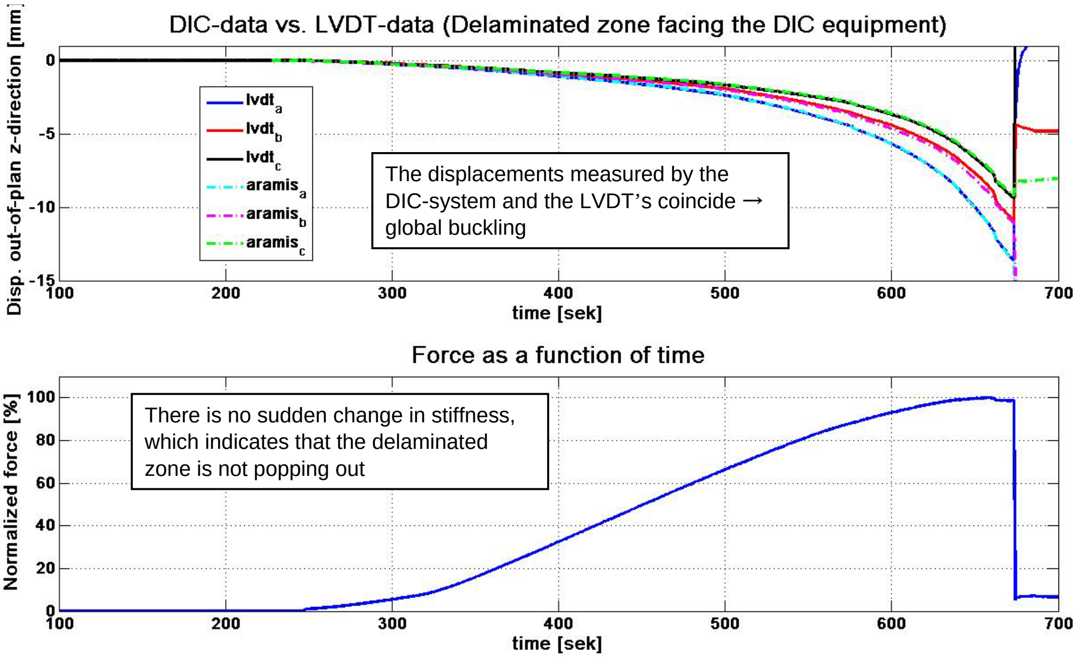
b) Local buckling without growth. The delaminated zone pops out and very little growth of the delaminated zone is observed before ultimate failure.

c) Local buckling with growth. The delaminated zone pops out and substantial growth of the delaminated zone is observed before ultimate failure.

d) Global buckling with mode jump. The buckling begins in the 1. global mode-shape. At failure a mode-jump is observed and the panel fails in an s-shape.

e) Local buckling cause instant failure. The panel fails right after the delaminated zone pops out. This typically occurs at high loading.

An example of a global buckling mode is shown in Figure 4. The out-of-plane deflections measured by the DIC measurement system (Aramis) on one side of the panel and by conventional displacement transducers on the other side coincide. The sub-laminates are therefore moving to the same side and no opening of the delaminated zone is observed.

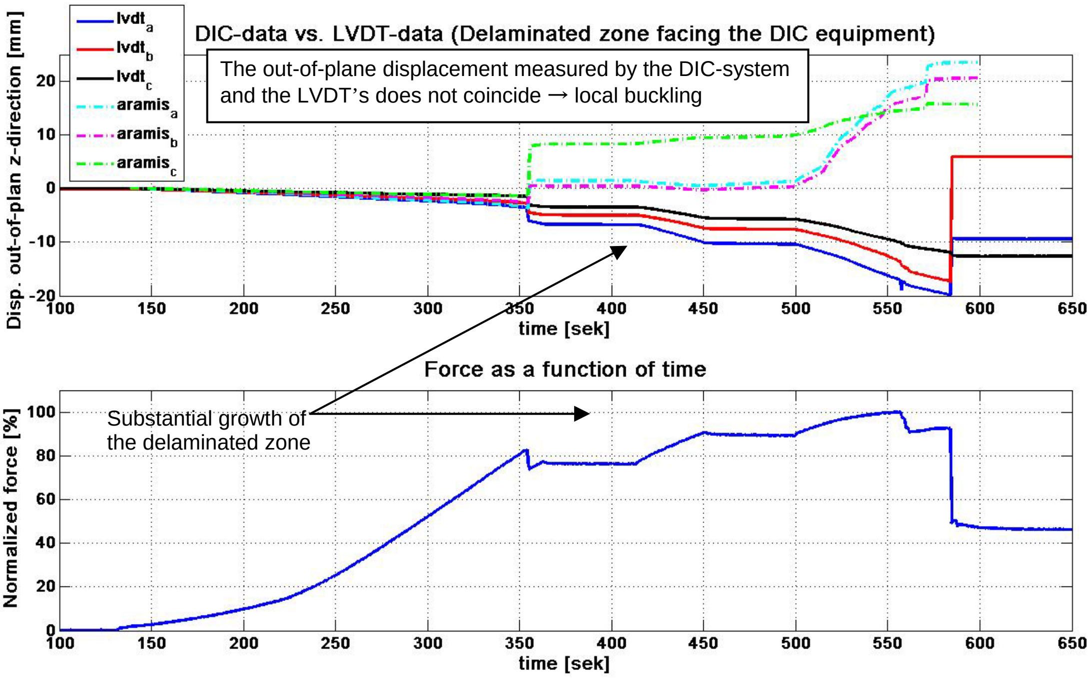


The displacements measured by the DIC-system and the LVDT's coincide → global buckling

There is no sudden change in stiffness, which indicates that the delaminated zone is not popping out

Figure 4 Example of experimental results from a global buckling case.

An example of a local buckling mode is shown in Figure 5. The measured out-of-plane deflections now show that the two sub-laminates move in different directions and an increasing opening of the delaminated zone is observed. The sudden change in stiffness and stipwise change in slope indicate that the delaminated zone is growing. Local buckling was observed with both negligible and substantial growth of the delaminated zone before ultimate failure and in some cases local buckling caused instant failure.



DIC-data vs. LVDT-data (Delaminated zone facing the DIC equipment)

The out-of-plane displacement measured by the DIC-system and the LVDT's does not coincide → local buckling

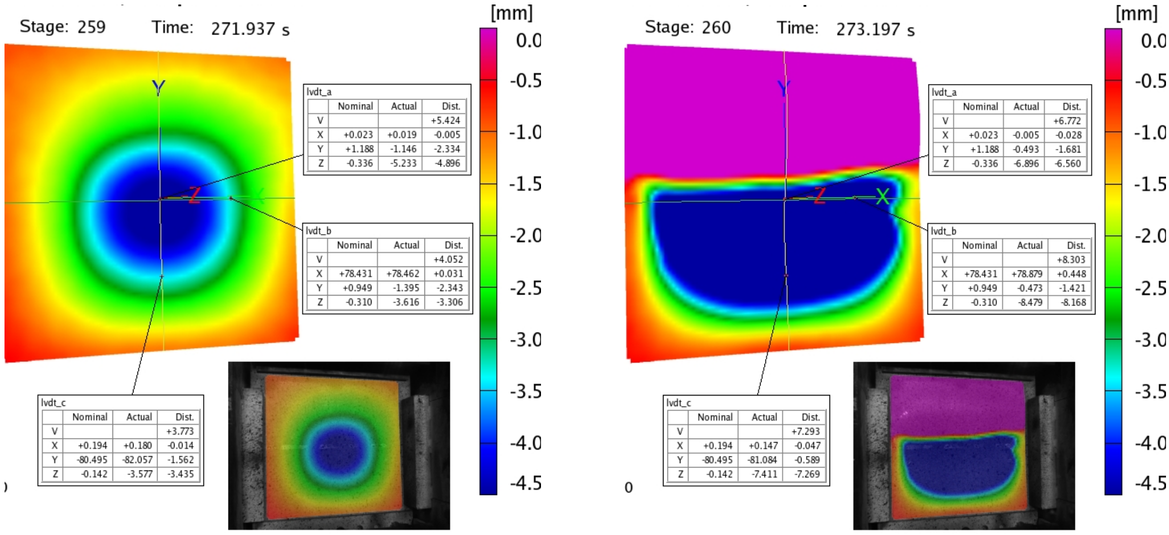
Force as a function of time

Substantial growth of the delaminated zone

Figure 5 Example of experimental results from a local buckling case with growth of the delamination.

Global buckling with a mode jump at failure is shown in Figure 6. The buckling begins in the first global mode-shape and at failure a mode-jump is observed and the panel fails in an s-shape.

It is generally found that large and deep delaminations caused local buckling and instant failure. Smaller delaminations closer to the surface are in some cases found to give stable delamination growth.



lvdt_a

	Nominal	Actual	Dist.
V			+5.424
X	+0.023	+0.019	-0.005
Y	+1.188	-1.146	-2.334
Z	-0.336	-5.233	-4.896

lvdt_b

	Nominal	Actual	Dist.
V			+4.052
X	+78.431	+78.462	+0.031
Y	+0.949	-1.395	-2.343
Z	-0.310	-3.616	-3.306

lvdt_c

	Nominal	Actual	Dist.
V			+3.773
X	+0.194	+0.180	-0.014
Y	-80.495	-82.057	-1.562
Z	-0.142	-3.577	-3.435

lvdt_a

	Nominal	Actual	Dist.
V			+6.772
X	+0.023	-0.005	-0.028
Y	+1.188	-0.493	-1.681
Z	-0.336	-6.896	-6.560

lvdt_b

	Nominal	Actual	Dist.
V			+8.303
X	+78.431	+78.879	+0.448
Y	+0.949	-0.473	-1.421
Z	-0.310	-8.479	-8.168

lvdt_c

	Nominal	Actual	Dist.
V			+7.293
X	+0.194	+0.147	-0.047
Y	-80.495	-81.084	-0.589
Z	-0.142	-7.411	-7.269

Figure 6 Example of global buckling with a mode jump at failure. DIC measurement of out-of-place deflection just before and after ultimate failure is shown.

2.3 Numerical parameter study

Numerical parameter studies have been conducted on both panels with isotropic and orthotropic material properties. The different panels are analyzed with all edges simply supported.

In the isotropic case both the panel and the delaminated sub-part have aspect ratios (*A/B* and *a/b*) equal to 1 – which is quadratic (see Figure 2). In this case the number of half wave buckles (*m* and *n*) is equal to 1.

For the orthotropic cases a more comprehensive study is conducted and different aspect rations of both the panels and the delaminated sub-laminate are analyzed. The primarily study of the orthotropic cases have focused on panels with $m = n = 1$. But as the minimum buckling load depends on both the orthogonal stiffness and the panel ratio A/B, it can be derived that this aspect ratio is different from 1.

Uniaxial compression of an orthotropic panel with all edge simply supported leads to the following equation for the critical buckling load N_0:

$$N_0(m,1) = \pi^2\left[D_{11}\left(\frac{m}{A}\right)^2 + 2(D_{12}+2D_{66})\frac{1}{B^2} + D_{22}\left(\frac{1}{B^4}\right)\left(\frac{A}{m}\right)^2\right] \tag{1}$$

where D_{ij} are the elements of the bending-stiffness matrix (from laminate theory) that relates bending and torsion moments with curvatures; $n = 1$ always gives a minimum value. The minimum value of $N_0(m)$ varies depending on m and panel aspect ratio *A/B*. Now let

$$\begin{aligned} k &= D_{11}\left(\frac{m}{A}\right)^2 + 2(D_{12}+2D_{66})\frac{1}{B^2} + D_{22}\left(\frac{1}{B^4}\right)\left(\frac{A}{m}\right)^2 \\ \frac{dk}{dm} &= 2\frac{D_{11}m}{A^2} - 2\frac{D_{22}}{B^4}\frac{A^2}{m^3} = 0 \\ m &= \frac{A}{B}\left(\frac{D_{22}}{D_{11}}\right)^{1/4} \end{aligned} \tag{2}$$

If the value of *m* is set to 1, then the aspect ratio *A/B* can be derived as

$$\frac{A}{B} = \left(\frac{D_{11}}{D_{22}}\right)^{1/4} \tag{3}$$

The orthotropic panels in these studies represent glass fibre reinforced plastic with all the fibers in the load direction. The aspect ratio *A/B* is therefore larger then 1, as D_{11} is considerably larger than D_{22}.

In the studies, the aspect ratio of delaminated sub-laminate *a/b* is equal to the aspect ration of the whole panel *A/B*.

2.3.1 FE-model

The finite-element models were modelled with 20-node orthotropic solid elements. Two or three elements were used through the thickness depending on the through thickness position of the delamination, see Figure 7.

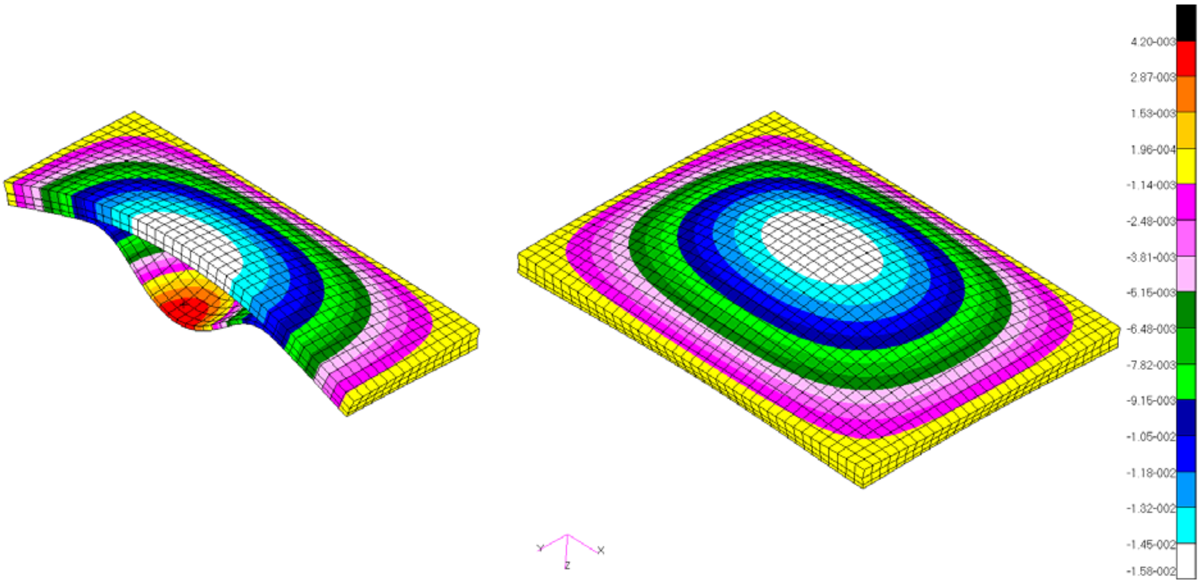


Figure 7 A typical finite element model.

A small out-of-plane displacement corresponding to the first buckling mode shape (amplitude of 0.5‰ of the panel thickness), was applied as an initial imperfection of the delaminated sub-laminate; see Figure 8 for a scaled illustration of the initial imperfection.

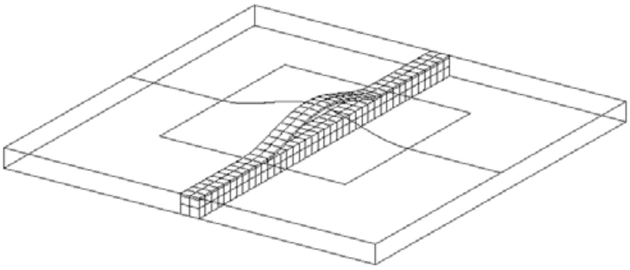


Figure 8 Scaled illustration of initial imperfection and a slice of the respective FE mesh.

The elements were all joined in the interfaces, except for the delaminated area where quadratic contact conditions were applied to prevent penetration. The average numbers of DOFs were approximate 156.000.

Nonlinear geometric analyses were conducted with minimum 100 increments to ensure that a well described and smooth graph could be made for in-plane force vs. out-of-plane displacement. This graph is needed when the buckling load is determined as described in a later section.

2.3.2 Buckling modes for a delaminated panel

A panel with an imbedded delamination subjected to uniaxial compression can buckle in different modes as described earlier.

Combinations of the global and local modes can also appear as so-called combined-modes or sub-modes. The sub-modes are found to appear for special combination of delamination size and through thickness position. In these studies five different mode types have been observed. These modes are illustrated in Figure 9, where the relation between the out-of-plane displacement at the centre of the two delaminated sub-laminates are plotted.

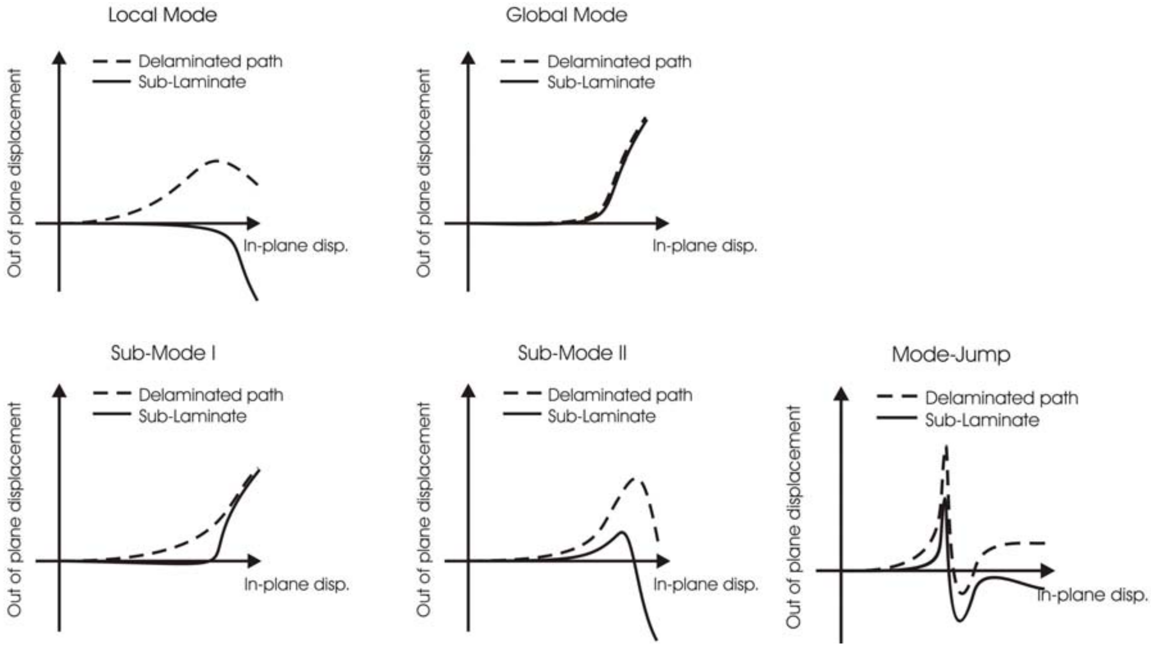
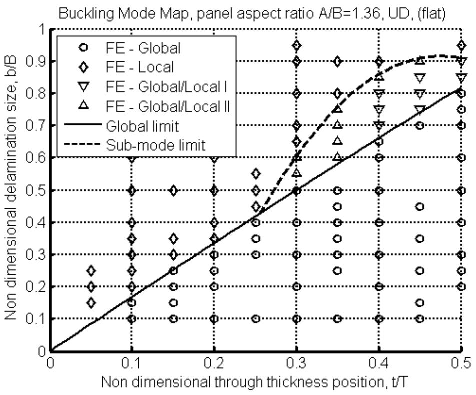


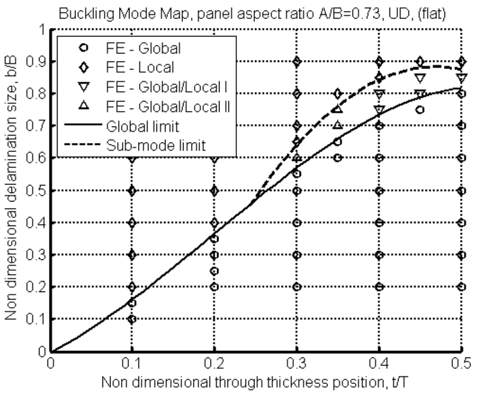
Figure 9 Delamination modes and the respective central out-of-plane displacement for the two delaminated sub-laminates.

2.3.3 Buckling mode maps

The buckling mode maps illustrate the panel's response to uniaxial compression. These are made in a similar manner as was done by Short *et al*. (2001). The maps can be divided into the following 3 areas:

- Local buckling; seen for large delaminations close to the surface
- Global buckling; seen for small and deep delaminations
- Sub-mode; seen for large and deep delaminations





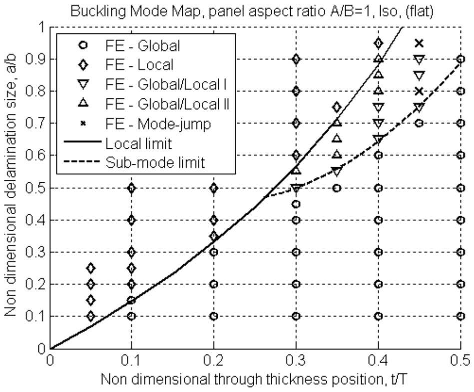


Figure 10 Buckling maps for an isotropic material and for a unidirectional fibres composite laminate with two different aspect ratios.

2.3.4 Estimating the buckling load

Buckling loads of delaminated panels can be divided into two types of buckling loads, a buckling load for the most thin sub-laminate *(P_{DB})* and a global buckling load of the remaining most thick sub-laminate (P_{GB}). In these studies is it mainly the buckling load of the remaining most thick sub-laminate (P_{GB}) which is studied.

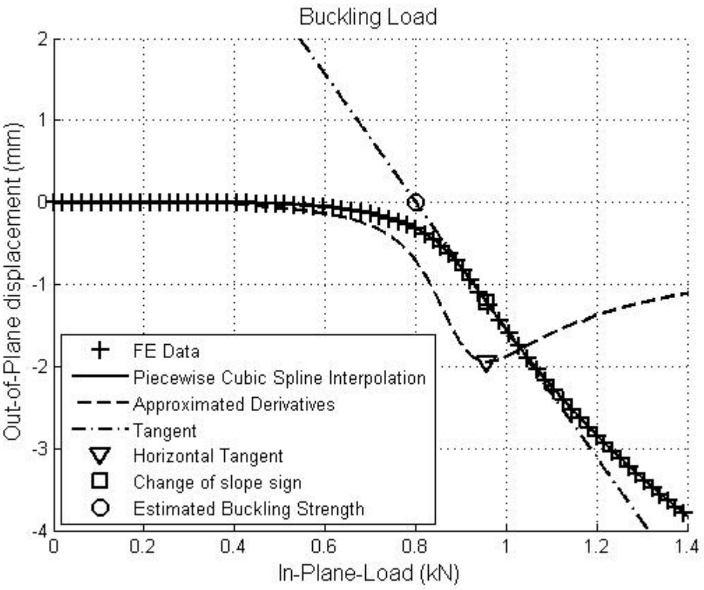


Figure 11 Buckling load based on central out-of-plane displacement as a function of the in-plane load.

The buckling load is normally given by the bifurcation point, but with the introduction of delaminations, a traditional bifurcation point can generally not be expected. However, a nonlinear relation between the applied load and the out-of-plane displacement is observed. In order to ensure consistency for all delamination sizes and through thickness positions, the buckling load is defined as the intersection between the x-axis and the tangent to the curve where the sign of slope changes for an in-plane force vs. out-of-plane displacement graph, illustrated in Figure 11.

2.3.5 Compressive strength

Based on the nonlinear numerical study done for the development of the buckling mode maps, it is also possible to estimate the compressive strength for the panels based on the method to determine the buckling load described above.

Figure 12 shows the normalised compressive strength for the panels as a function of the delamination size and through thickness position. The normalised compression strength of a perfect panel is unity.

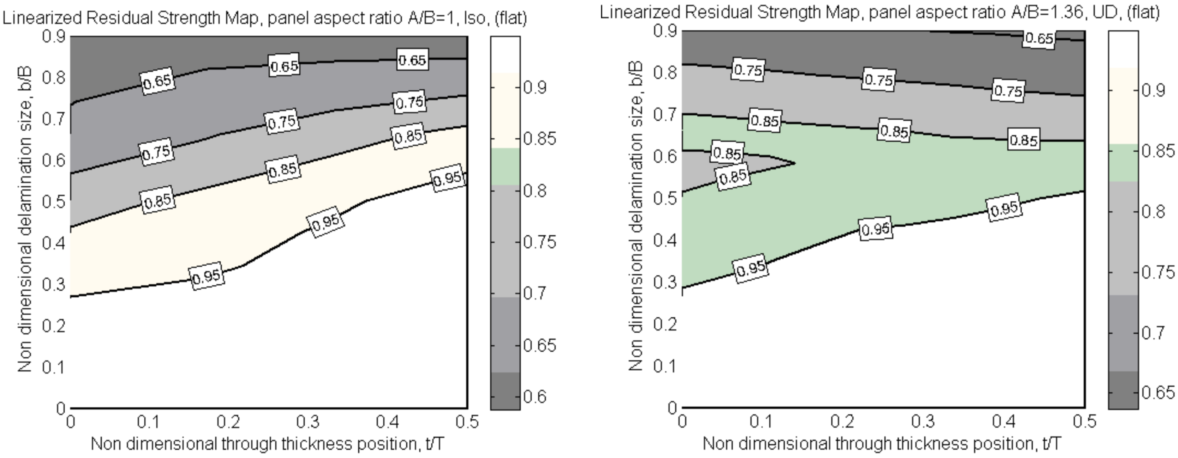


Figure 12 Reduced compressive strength maps for simply supported panels with imbedded delaminations. (a) isotropic material (b) UD composite laminate.

2.4 Conclusions

In this work buckling maps are made for both an isotropic material and a unidirectional composite laminate. The buckling maps show the border between local and global buckling modes. Other combined-modes or sub-modes are also found numerically for large and deep delaminations. Good comparison between numerical predictions and panel tests are generally found.

From the experiments it is found that large and deep delaminations caused local buckling and instant failure. Smaller delaminations closer to the surface are in some cases found to develop stable growth of the delaminated zone. Not enough experiments have been made to draw solid conclusions. Instead, more experiments are planned in Phase 4.

This work is a step towards a design criterion for how large and deep delaminations can be accepted without increasing the risk of blade collapse.

3 Materials joints and material transitions

3.1 Purpose and approach

The overall idea (see Figure 13) is (i) to characterise the fracture properties of bimaterial interfaces by fracture mechanics testing, (ii) to use the measured fracture parameters for the prediction of the load-level that causes delamination cracking in medium-size specimens, and (iii) validate the predictions by experimental testing of medium-size specimens.

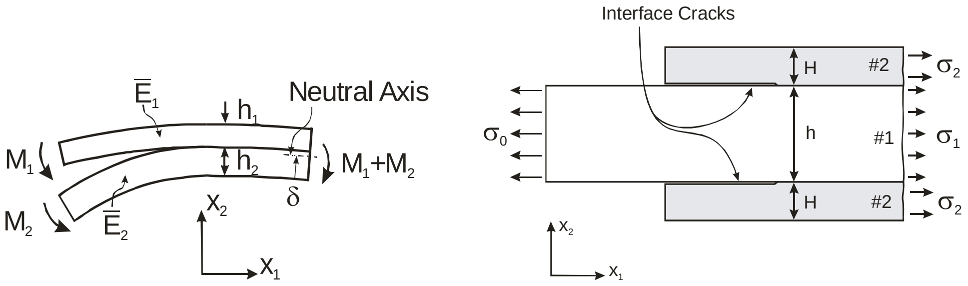


Figure 13 Outline of the approach: The fracture mechanics properties of the material interface are characterised by the use of a double cantilever beam specimen loaded with uneven bending moments (DCB-UBM) (left): and used for the prediction of the stress level that causes delamination crack growth in medium size specimens (right).

In comparison with cracking of specimens made of a single material, the problem of cracking of bimaterial specimens is more complicated: The analysis must account for that the two different materials that have different elastic properties and the presence of the residual stresses building up due to uneven curing and shrinkage of the two materials involved. In this study, two types of bimaterial specimens (material systems) were investigated:

- Material System 1: Carbon fibre / glass fibre bimaterial system
- Material System 2: Two different types of glass fibre composites.

3.2 Analysis of residual stresses

The residual stress is expressed in terms of the so-called misfit stress, σ^T, which corresponds to the residual stress in one of the materials, when a thin layer is bonded to a thick layer of the other material (Evans and Hutchinson, 1995). The misfit stress, σ^T, was determined from curvature measurements of asymmetric bilayer specimens, following an approach described by Evans and Hutchinson (1995). Apart from the misfit stress, the curvature of a bilayer depends on the layer thickness ratio, η, and Σ the stiffness ratio, defined as

$$\eta = \frac{h_1}{h_2} \qquad \Sigma = \frac{E_1}{E_2} \tag{4}$$

where h_i is the thickness of layer number i and E_i is the Young's modulus of material number i, see Figure 13.

It is of interest to design the bilayer specimens so that the curvature is maximised, such that the misfit stress can be determined with the greatest accuracy. The "optimal" layer thickness ratio, η_{opt}, was determined as (Wahlgren, 2009)

$$\eta_{opt} = \left(\frac{1}{\Sigma}+\sqrt{\frac{1}{\Sigma^2}-\frac{1}{\Sigma^3}}\right)^{\frac{1}{3}} + \frac{1}{\Sigma}\left(\frac{1}{\Sigma}+\sqrt{\frac{1}{\Sigma^2}-\frac{1}{\Sigma^3}}\right)^{-\frac{1}{3}} . \qquad (5)$$

With Σ and σ^T fixed, η_{opt} is the layer thickness ratio that maximizes the curvature. A plot of this universal relationship is shown in Figure 14. In practise, Figure 14 can be used as follows. Knowing the Young's moduli of the two materials, Σ is calculated from (4) and η_{opt} is read-off from the figure.

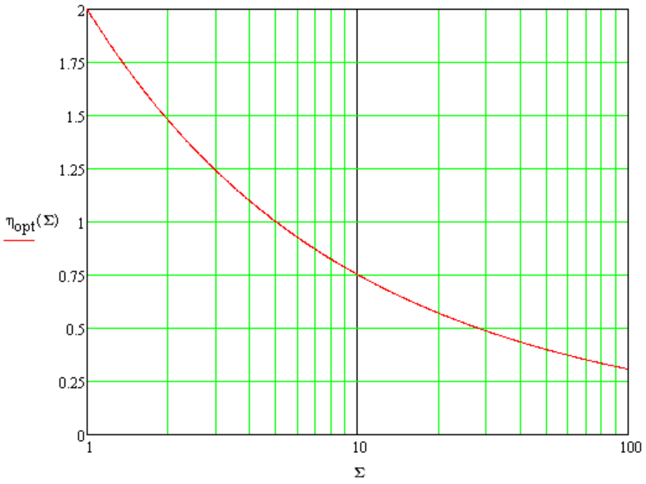


Figure 14 The thickness ratio that give the maximum curvature for a fixed misfit stress, η_{opt}*, is shown as a function of the elastic stiffness ratio,* Σ *(from Wahlgren, 2009).*

The misfit stress was determined for Material System 1 bilayer specimens. The manufacturing processes for these specimens were set up in the laboratory and they may not be completely representative for wind turbine blades. The layer thicknesses and curvatures of 8 specimens were measured and the misfit stress was calculated to be 80 MPa. The standard deviation of the measurements was only 5%, showing that the method gives results with high reproducibility.

3.3 Fracture mechanical characterisation

The resistance to crack growth along the interface between two materials was characterised by fracture mechanics testing using the DCB-UBM (double cantilever beam specimen loaded with uneven bending moments) (Sørensen *et al.*, 2006) developed in an earlier projects (Phase 1 and Phase 2). This test configuration allows a large variation in the ratio between the shear and normal stresses field at the crack tip by controlling the relative magnitude and rotation direction of the two moments, M_1 and M_2, that are applied to the cracked beams, see Figure 13. The fracture properties can be described in terms of the J integral and the mode mixity.

In general, it was found that the fracture resistance of the interface was not constant. The fracture resistance increased from an initiation value with increasing crack extension. Eventually, a steady-state fracture resistance value was attained. The rising fracture resistance is a well known phenomenon that can be attributed to fibre bridging (Sørensen and Jacobsen, 2009). The two most important fracture parameters are thus the value of J at the initiation of cracking and the steady-state value of J. Figure 14 shows the fracture resistance (at the onset of crack and the steady-state / maximum fracture resistance) of the interfaces of Material Systems 1 and 2 as a function of the mode mixity, ψ. Note that the data have been normalised with the maximum values. It is seen from the Figure that the fracture initiation values of J is relative constant for $0 < \psi < 50$ degrees; for $\psi > 50$ degrees, the fracture parameters increases relatively rapidly with increasing ψ.

In the calculation of the data in Figure 14, no account was made for the residual stresses. However, during cracking, the presence of residual stresses affects both the energy release rate and mode mixity; residual stresses give an additional energy release rate and a shift in the mode mixity angle. For this material system, accounting for the residual stress led to a critical energy release rate that is only 5-20 % higher than if the residual stresses are neglected. Accounting for residual stress leads to a mode mixity that is about 5 degrees higher (Wahlgreen, 2009). Thus, the effects of residual stresses are relative small and it is concluded that for this material system it is not of great importance to account for the residual stresses.

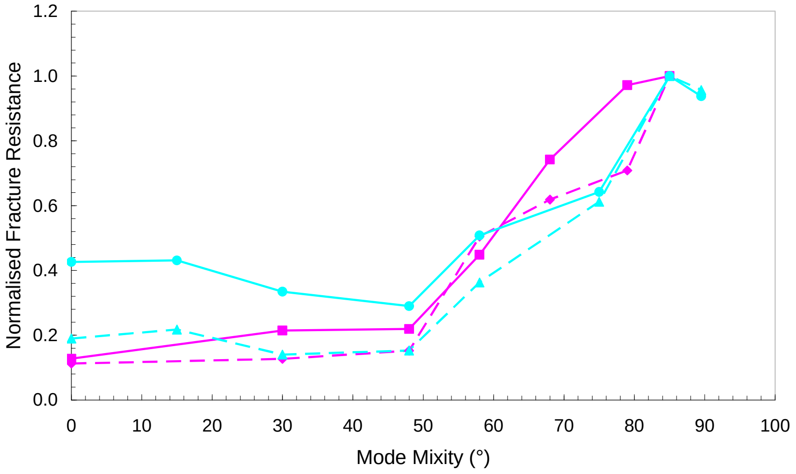


Figure 14 Normalised value of the J integral at initiation of cracking (dashed lines) and steady-state or maximum value (solid) are shown as a function of the mode mixity (colours: Pink: Material System 1 (carbon fibre / glass fibre); Cyan: Material System 2 (glass fibre / glass fibre)).

3.4 Testing of medium size specimen

For each of the two materials systems, medium size specimens having 3 different layer thickness ratios were manufactured. Six specimens were made for each layer thickness. During manufacturing, a slip foil was inserted between the layers at one of the ends to act as a crack starter (Figure 15). The specimens were tested in uniaxial tension at a universal testing machine. Two LVDTs (linear variable displacements transducers) were mounted at the pre-crack, parallel to the crack to record the relative displacement between the two layers. In order to ease visual observation of delamination cracks, the side of the specimen was painted white using correction ink and markers were made along the interface. In order to avoid cracking from both ends, the end without slip foil was clamped by the use of a vice.

Data for the applied load and the displacement recorded by the LVDTs were collected with a PC during each test. Images of the specimen, including data for the elapsed time and the applied load level were recorded with a few seconds interval. The crack length was later determined as a function of time and load from the images.

With increasing load, delamination cracks formed from the slip foils. With increasing load, the crack propagated along the material interface. Figure 15 shows a photograph taken during a test. Two delamination cracks have propagated along the interfaces; the crack tips are marked with arrows in the Figure.

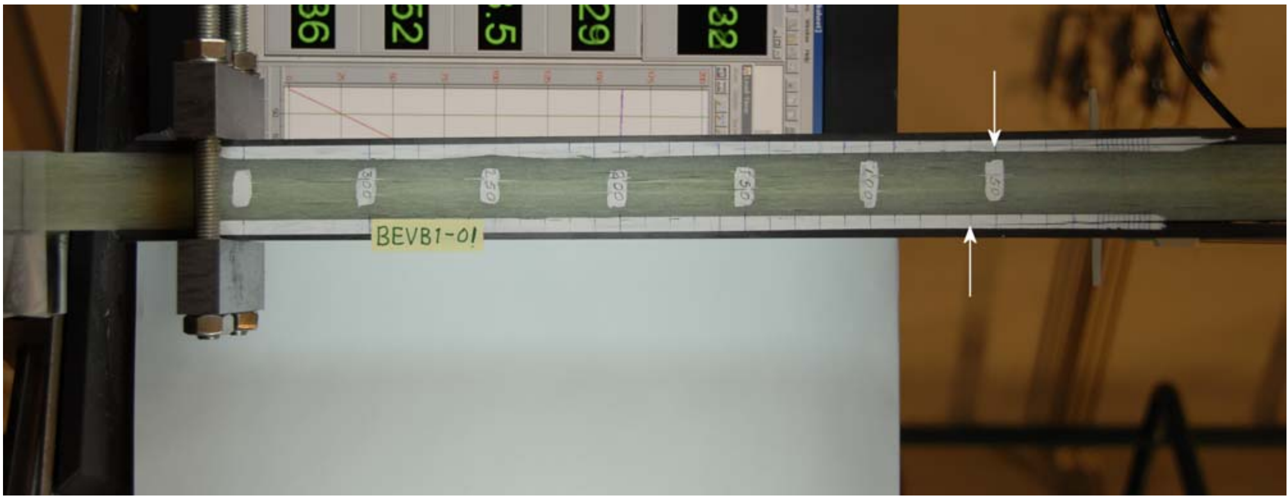


Figure 15 Photograph of a medium scale specimen during testing; the medium size specimen is mounted in a materials testing machine and subjected to uniaxial tension at the ends. The end shown to the left is clamped (to prevent cracking from this end) by the use of a vice. The area of anticipated crack is painted white. Cracking has occurred along the interfaces between the carbon fibre and glass fibre (right hand side of image; direction of crack growth: right to left). The positions of the crack tips are shown by arrows.

3.5 Comparison of predictions and measurements

An analytical model was developed for the prediction of the applied stress, σ_0 , at which delamination cracking occurs in the medium size specimens. In the following, the residual stresses are neglected, since their effect was rather small as shown in the previous section. Then, the model predicts the delamination stress as

$$\frac{\sigma_0}{E_1} = \sqrt{\frac{2(2+\Sigma\eta)J}{E_1 h}}\,, \tag{6}$$

where E_1 is the Young's modulus of materials number 1 (the middle layer, as indicated in Figure 13), h is the thickness of the middle layer,

$$\eta = \frac{h}{H}\,, \tag{7}$$

H is the thickness of each of the surface layers, and *J* is the J integral value corresponding to crack initiation or steady-state growth.

No solution is available in the literature for the calculation of mode mixity for this specimen geometry; an approximate value is: $\psi \approx 52°$ (Bao *et al.*, 1992).

Figure 16 shows the predicted delamination stress as a function of the thickness ratio, η for the medium size specimens made of Material System 1. The predictions are made using the measured fracture resistance from the DCB-UBM tests (interpolated to ψ = 52°) corresponding to initiation and steady-state cracking. It is seen in Figure 16 that the model predicts that the delamination stress increases with increasing η, corresponding to a decreasing *H*.

The experimental values for the stress at initiation of crack growth are superimposed in Figure 16 (circles are the average value of 5-6 specimens; error bars indicate the standard deviation). The experimental values are generally higher than the predictions. This suggests that the value of the fracture resistance of the experiments is higher than the ones used in the predictions. This would be the case if the mode mixity was higher than the 52° used in the predictions. This will be studied in "Phase 4", where the medium size specimens are analysed by finite element simulation.

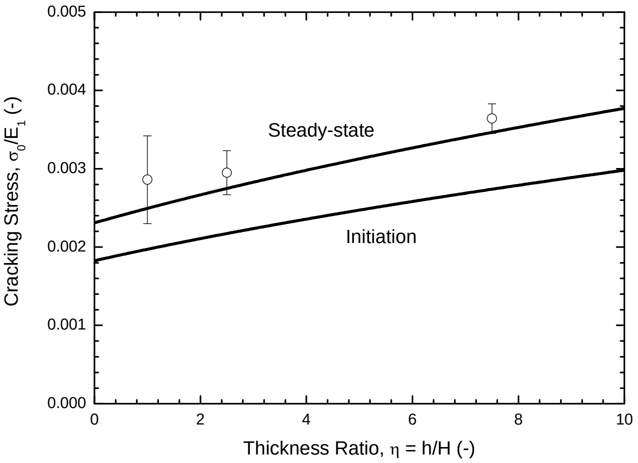


Figure 16 Comparison between predicted and measured stress values at the initiation of crack growth in the medium size specimens for Materials System 1 (the carbon fibre /glass fibre system): The applied stress at initiation of crack growth is shown as a function of the thickness ratio. Predictions are shown as curves and measurements are shown as points. The symbol indicates the average of 5-6 specimens; error bars indicate the standard deviation.

4 Implementation of cohesive laws in FEM program

A general mixed mode constitutive model for cohesive 2D and 3D elements has been established based on a multi-scale cohesive zone model that takes into account large scale fibre bridging (Hansen and Lund, 2008; Hansen and Lund, 2009). The model is capable of modelling crack initiation and propagation on 2D and 3D structural problems by use of the Finite Element (FE) method. Model parameters are determined from DCB experiments based on measured fracture resistance curves under mixed mode loading conditions. A damage mechanics formulation of the constitutive model has been implemented in a stand-alone Matlab program that generates a material data set that can be used together with the commercial FE software named Abaqus. This program has been given to LM Glasfiber and they have rewritten it into a Fortran program. Furthermore, the multi-scale cohesive zone model has been implemented in the in-house FE program at ME-AAU named MUST. Hence, it is possible to run the same type of problems on both Abaqus and MUST which has been used to verify the implementation of cohesive elements in MUST (Overgaard and Lund, 2009).

The multi-scale cohesive zone model has been used to simulate crack growth on DCB test specimens in order to validate the model (Hansen *et al.*, 2009a). Furthermore, it has been used to predict crack initiation and growth of a 2m long adhesively bonded beam specimen made of glass fibre laminate under mixed mode loading conditions (Hansen *et al.*, 2007; Hansen and Lund, 2009; Sørensen *et al*., 2009). Numerical results are in fine agreement with experimental measurements. Hence, it has been possible to predict the strength and damage tolerance of a large scale composite structure based on material measurements obtained using DCB specimens that are 10 times smaller. In continuation of this work, 3D structural problems are now being analyzed with respect to prediction of crack growth in composite laminated plates under compressive loading (Hansen *et al.*, 2009c). The numerical results obtained so far show that the numerical model is capable of modelling the structural behaviour observed from similar experimental tests conducted by K. Branner and co-workers. However, the problem is very sensitive to boundary conditions at the edges of the plate and on-going work is focused on achieving better correlation between the experimental setup and the FE model. Based on the multiscale cohesive zone model and the FE models of the compressive panels, it is now possible to numerically investigate the effect of fibre bridging on crack growth in shell-like composite structures. Furthermore, the Hierarchical FEM approach has been utilized to generate the FE models of the compressive panels more effectively.

5 Hierarchical FEM

5.1 Implementation

A hierarchical finite element method has been developed to adaptively refine solid shell models such that local effects can be studied on composite structures. The method has been implemented on the in-house FE program MUST and it works with 3D solid shell finite elements. A robust stabilized solid shell finite element formulation based on single layer shell theory has been implemented in MUST (Johansen & Lund, 2009, Johansen *et al.*, 2009). The formulation has been verified on various benchmark examples with respect to analysis and sensitivity analysis on linear and non-linear problems. Hence, the solid shell element implementation in MUST can be used for both structural analysis (Overgaard *et al*., 2009a; Overgaard and Lund, 2009; Overgaard *et al*., 2009b; Hansen and Lund, 2009) and optimization on geometrically linear and non-linear problems (Johansen & Lund, 2009, Johansen *et al.*, 2009).

The starting point of the hierarchical FEM is a 3D solid shell model of the global structure, e.g. a wind turbine blade. A linear or non-linear structural analysis is then performed such that stresses and strains can be evaluated. A number of failure criteria related to intra- and interlaminar failure have been implemented in MUST (Johansen &

Lund, 2009; Hansen *et al.*, 2009c). Based on the evaluation of failure criteria, local load critical regions are identified. Based on user input, the load critical regions on the global model are refined by one or more solid shell elements through-the-thickness. On boundaries between refined and non-refined regions, compatibility of displacements is enforced by use of the Lagrange Multipliers method. This formulation works on both geometrically linear and non-linear problems (Johansen & Lund, 2009, Johansen *et al.*, 2009).

In order to model delamination of laminates and debonding of structural components, cohesive elements are automatically embedded between solid shell element layers (Hansen and Lund, 2009b; Hansen *et al.*, 2009c; Overgaard and Lund, 2009). This implementation makes it possible to effectively generate models of large layered composite structures in which imperfections due to debonded regions are present.

5.2 Evaluation of blade collapse

Evaluation of a wind turbine collapse has been the main focus of the Ph.D. thesis by Overgaard (2008). Wind turbine blades are manufactured from layered composite material systems ranging from prepreg technology to resin transfer moulding, which is often combined with after and/or co-cured structural elements. Different materials and manufacturing philosophies are widely used whereas the structural and geometric design of wind turbine blades are often very similar. The ultimate strength of all types of wind turbine blades is governed by instability phenomena caused by interacting material and geometric nonlinearities.

The structural behaviour of a wind turbine blade has been predicted based on a nonlinear fracture mechanical formulation in a geometrically nonlinear framework, i.e. interdisciplinary analysis of instabilities in the form of progressive delamination growth and buckling induced by geometric and material nonlinearities. This work has been focused on the assessment of a full-scale flap-wise static test to collapse of a generic wind turbine blade performed in phase two of the project. Finite element predictions have been done in relation to an equivalent single-layer theory formulation with the use of linear elastic shells, as well as solid shells formulation for elastic and nonlinear fracture mechanical modelling in a geometrically nonlinear framework. Finite element results and test results of the blade during loading and after collapse have been studied based on various numerical approaches. Based on a phenomenological approach, these analyses have provided an overview of the sequence of events causing the progressive collapse on the generic wind turbine blade. Based on a top-down approach to structural instability phenomena in wind turbine blades, it has been possible to identify the physics determining the ultimate strength of a generic wind turbine blade. The top-down investigation has shown that the major energy up-taking failure mechanism is delamination at well-defined lamina regions in the laminate lay-up. It has been shown that the proposed methods can predict the structural behaviour of a large three-dimensional generic wind turbine blade based on nonlinear fracture mechanics in a geometrically nonlinear framework. A framework for the damage and failure analysis including numerical preprocessing, solution and post-processing of large three-dimensional laminated composite structures with geometric and material nonlinearities under mixed-mode loading has been established. Interactions between both material and geometric induced instability phenomena occur in the generic blade, which causes a progressive chain of events resulting in a catastrophic structural collapse. The numerical methods are further demonstrated in case studies of the generic laminated composite wind turbine blade.

6 Discussion and summary

6.1 Major results of the Phase 3 project

The major results concerning compressive strength of composite panels are:

- The establishment of buckling maps that show the border between local and global buckling modes. A good agreement was obtained for the numerical predictions and the observed behaviour of the panel tests are generally found.

- From the experiments it is found that large and deep delaminations caused local buckling and instant failure.

The major findings concerning materials joints between dissimilar materials are:

- an equation was derived for the selection of the optimal layer thickness ratio of bimaterial specimens, so that the curvature of bi material specimens can be maximised and the misfit stress can be determined with the greatest accuracy

- fracture mechanics characterisation of bimaterial interfaces (by DCB-UBM) bimaterial specimens was successfully achieved. Both the J value at the initiation of cracking and the J value during steady-state cracking were found to be almost constant for mode mixities in the range of 0° to 50° and increased with higher values of the mode mixity angle reaching a value about three times higher.

- symmetric bimaterial medium size specimens were manufactured and tested in uniaxial tension. The propagation of cracks along the material interface (mixed mode interface cracking) was monitored, included the applied stress at which interface cracking initiated.

- an analytical model was developed for the prediction of the stress level for the initiation of interface cracking in the bimaterial medium size specimens subjected to uniaxial tension. The predicted stress level, based on fracture data from the DCB-UBM tests at an assumed mode mixity of 52°, was compared with the stress values found experimentally. The stress level found experimentally was found to be higher than the predicted.

The major results concerning cohesive laws are:

- the automatic creation of cohesive elements between solid shelle element layers for the modelling of delamination of laminates and debonding of structural components. This implementation makes it possible to effectively generate models of large layered composite structures in which imperfections due to debonded regions are present.

The major result concerning hierarchical modelling is:

- A framework for the damage and failure analysis including numerical preprocessing, solution and post-processing of large three-dimensional laminated composite structures with geometric and material nonlinearities under mixed-mode loading has been established.

A number of scientific publications have emerged from the project. A list of 13 journal papers and 45 papers or presentations are listed in Section 7.

6.2 Comments regarding industry collaboration

In this project, like the Phase 1 and Phase 2, the researches from the industry partners (LM Glasfiber A/S and Vestas Wind Systems A/S) have participated in the project by manufacturing various types of test specimens, by participating in project meeting, exchanging ideas and providing knowledge to the project through interaction with the research groups at the universities.

6.3 Further implementation in industry

The knowledge created in the research project has carried the industry forward by providing new tools. As a result of the research conducted in the project, the industry has begun adopted the fracture mechanics approach in the research and development.

However, the damage tolerant approach must be integrated not only in the design, but also manufacturing, quality control, maintenance and repair. Inspection and identification of defects and damage is a cornerstone when considering defects and damages on a more rational basis.

For wind turbine blade design and manufacture, standardisation is required for terms, damage progression models, procedures for analysis of damages. Such procedures should involve certification bodies (e.g. DNV and GL). Furthermore, for maintenance and long term reliability, in-service repair inspection and maintenance manuals, training courses and certification of inspection personnel are required. Such procedures are already established in the aeronautic industry.

6.4 Future research goals

The research conducted in this Part 3 project points to further research ideas to exploited in future research projects. Some goals are direct continuation of Phase 3:

- Modelling interfacial cracking in the bimaterial medium size tensile specimens tested in Phase 3, using cohesive zone modelling - this will be conducted in Phase 4
- modelling of buckling of curved panels
- development of more robust methods for modelling of cracking of large structures

Within the area of damage and crack evolution, other, longer terms topics need more research. Examples are

- fatigue crack growth (e.g. delamination and cracking of adhesive joints under cyclic loading) - this will be initiated in Phase 4
- how well-defined damage and cracks initiate from processing flaws

7 Publications from current project

7.1 Publications in international scientific journals

Berggreen, C., Branner, K., Jensen, J. F. & Schultz, J. P.. 2007, "Application and analysis of sandwich elements in the primary structure of large wind turbine blades", *Journal of Sandwich Structures and Materials*, Vol. 9, pp. 525-552.

Hansen, A. L. and Lund, E., 2009, "A mixed mode cohesive law for modeling interfacial fracture and fiber bridging". Submitted, 27 pages.

Hansen, A. L., Sørensen, B. F., and Lund, E., 2009, "Simulation of crack growth and r-curve behavior using cohesive zone modeling". Manuscript in progress, 16 pages.

Johansen, L. and Lund, E., 2008, "Optimization of laminated composite structures using delamination criteria and hierarchical models". *Structural and Multidisciplinary Optimization*. Vol. 38, pp. 357-75, doi: 10.1007/s00158-008-0280-1.

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Overgaard. L.C.T., Lund, E., and Camanho, P.P., 2009b: "A methodology for the structural analysis of composite wind turbine blades under geometric and material induced instabilities". Submitted to *Computers & Structures*.

Overgaard. L.C.T., Lund, E., and Thomsen, O.T., 2009a, "Structural collapse of a wind turbine blade. Part A: Static test and equivalent single layered models". Submitted to *Composites Part A.*

Sørensen, B. F., and Jacobsen, T. K., 2009, "Delamination of fibre composites: determination of mixed mode cohesive laws", *Composite Science and Technology*, Vol. 69, pp. 445-56.

Sørensen, B. F., Goutianos, S., and Jacobsen, T. K., 2009, "Strength scaling of adhesive joints in polymer-matrix composites", *International Journal of Solids and Structures*, Vol. 46, pp. 741-61.

Toftegaard, H. L., Sørensen B. F., and Goutianos, S., 2009 "Delamination of medium size specimens: experiments and modelling", manuscript in progress.

7.2 Proceedings papers, books and reports

Berggreen, C., Tsouvalis, N., Hayman, B. & Branner, K., "Buckling strength of thick composite panels in wind turbine blades – part I: Effect of geometrical imperfections", 4th International Conference on Composites Testing and Model Identification, 20-22 October 2008, Dayton, Ohio, USA.

Branner, K., 2006a, “Modelling failure in cross-section of wind turbine blade”, 2nd NAFEMS Nordic Seminar, 31 May - 1 June 2006, Copenhagen/Roskilde, Denmark.

Branner, K., 2006b, “Static testing of cross-section of wind turbine blade”, 3rd International Conference on Composites Testing and Model Identification, 10-12 April 2006, Universidade do Porto, Portugal.

Branner, K., 2007, "Resultater fra forsøg med trykstyrke i tykke kompositpaneler med fokus på delaminering", Presented at Dansk Forskningskonsortium for Vindenergi's Vinddag 2007, Risø DTU, Roskilde, Denmark, 27. november 2007.

Branner, K., Berring, P. & Berggreen, C., 2008, "Buckling strength of thick composite panels in wind turbine blades – part II: Effect of delamination", 4th International Conference on Composites Testing and Model Identification, 20-22 October 2008, Dayton, Ohio, USA.

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