BUCKBLADE
Buckling Load Design Methods for Rotor Blades

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Abstract

In the JOULE-III project *BUCKBLADE* an investigation is performed into the applicability of several buckling load prediction tools and methods to rotor blade design. This investigation concerns the assessment of the relevant aspects for buckling of rotor blades and consequently collect, describe and validate a number of buckling load prediction methods.
The work within the *BUCKBLADE* project started with a survey of the existing buckling load prediction methods with emphasis on layered orthotropic structures. Based on the information from this survey and on analytical models, a set of so-called "Design rules" has been formulated. Together with other buckling load prediction methods these "Design rules" are subjected to a validation.
First validation is carried out for a set of well described more elementary problems for which experimental and theoretical results have been published by others. Next the tools and methods are validated for application to buckling load prediction of rotor blade structures. To this end two rotor blades have been designed and built. On each of these rotor blades two buckling tests have been carried out. Each of these tests was addressed to buckling in another part of the structure.

After analysing and comparing the first test results, parameter studies have been performed to the effects of buckling of rotor blades:
1. Edge constraints;
2. Pre-buckling deformation;
3. Strongest laminate layup;
4. Fibre misalignment;
5. Geometrical imperfections;

The most important conclusions are:
1. For accurate buckling load predictions it is important to have correct values of all orthotropic material properties. This requires tests on batches of material that are made with the same manufacturing process as the rotor blades.
2. All buckling load prediction tools are appropriate for long curved orthotropic panels under compression. The tools that include out-of-plane shear flexibility have shown to be appropriate for buckling load predictions of symmetric sandwiches, which are sandwiches with equal facings.
   The "Design rules" derived in this project allow explicit buckling load predictions that are very accurate for long flat orthotropic sandwich panels under longitudinal compression while they give a reasonable approximation for curved panels and for other load conditions.
3. Calculations in which the longitudinal curvature and the pre-buckling deformation for box-type structures under bending are omitted lead to an overestimation of 25% to 35%.
4. Geometric imperfections of the blade structure leads to a reduction in buckling strength. For an imperfection with the shape of the collapse mode and an amplitude of 1% of the wall thickness the critical load is about 94% to 97% of the critical load of the perfect structure.
   For sandwich panels with thin facings, local imperfections give a strong reduction of the face-wrinkling-buckling load.
   The reduction in buckling strength for curved panels is less severe as for circular cylindrical shells.

PARTNERSHIP

The *BUCKBLADE* project has been co-ordinated by ECN.
Within this project the following participants are involved:

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OBJECTIVES

The design of large wind turbine components addresses to static and fatigue strength of the material and geometric stability of the structure. The *BUCKBLADE* project deals with this last phenomenon, known as "buckling".

The objective of the *BUCKBLADE* project is to improve the reliability of medium to large size wind turbine rotors by exploration of the existing knowledge of buckling and transferring this knowledge to the industry. This is realized by:

- Investigating the state of the art of the buckling load prediction tools and methods;
- Thorough evaluation of these tools and methods for the application to rotor blade design. This evaluation is based on computations and on two tests on representative rotor blade structures;
- Issuing design guidelines and providing computer codes that were subjected to the investigations.

To reduce the complexity of the *BUCKBLADE* project the following aspects are not included:

Instationary effects due to rapidly varying loading.
The rate of load variations of wind turbines is relatively small compared to the process of buckling, although instationary loading is actual for e.g. crash-zones of cars.

Material non-linearities by microscopic fracture or plasticity.
Because large-size weight-efficient rotor blades are usually made of glass- or carbon-fibre composites plasticity is not relevant.

The complex geometrical shape of the part of the blade near the blade root and the hub connection.
In order to compensate for stress concentrations near the blade root and the root-hub connection this part of the blades usually has a relatively large wall thickness for which buckling is not the critical failure mechanism.
If a buckling prediction of this part of the blade is required the most realistic analysis can only be obtained with a non-linear finite element package. Although preparing a model for a non-linear finite element package is time consuming one may use this model also to obtain the stress distribution.

The *BUCKBLADE* project is the first research project that deals with buckling of wind turbine structures. It is addressed in particular to the design environment of rotor blades.

TECHNICAL DESCRIPTION

Investigation of the Existing Knowledge

Publications have been collected by several partners dealing with experimental- and theoretical investigations into buckling of orthotropic shell structures and with design guidelines and graphs.
Investigation of these publications has led to the following results:

Prediction methods Descriptions are obtained of the prediction method of Tennyson and Muggeridge for curved anisotropic panels and of the prediction method of C.W. Bert for curved orthotropic sandwich panels.
In addition several design rules and handbook methods are found which are used to compile the so-called "Design rules";

References on buckling loads Several publications with experimental and theoretical buckling loads for elementary problems (flat or single curved panels) including a complete description of these methods. From these publications a set of reference problems was selected for validation of each of the tools;

Information supporting the final conclusions Some of the conclusions drawn from the *BUCKBLADE* investigation –e.g. on the strongest layup– were also reported in literature.

Information on post buckling analysis Especially for the parameter study into the influence of initial geometrical imperfections much referential knowledge and results were obtained from earlier publications on similar investigations.

The complete investigation has led to more than hundred references of which a list is distributed among the participants.

Validation on the Basis of Elementary Problems

Table 1 gives an overview of the buckling load prediction tools and their specifications that are subjected to the investigation within the *BUCKBLADE* project.
In order to draw meaningful conclusions on the applicability to rotor blade design first the tools were validated on basis of some elementary problems.
To this extent DLR, ECN and SPE selected seven well-described reference problems of which theoretical and experimental results are available. Each of these problems included a specific or additional aspect of complexity in terms of material properties, curvature or sandwich construction. In this way the implementation of each of these aspects could be evaluated.

This validation has been performed by SPE for the *FINSTRIP* code and by ECN for some panel methods and the "Design rules" that were formulated within the project. In addition LASSO has analysed the buckling load of curved anisotropic panel **A5** with the non-linear finite element code LARSTRAN while ECN has analysed the buckling load and the post-buckling path of rectangular orthotropic plate **CB5-1** with the non-linear finite element code MARC. These finite element analyses verified the applicability of these elements for the modelling of orthotropic material properties.

Definition of Buckling Tests

Within the *BUCKBLADE* project three buckling tests were planned on specimen that have been built in the moulds of the DEBRA rotor blades. The goal of these tests was discussed and assessed with all participants.
Based on this goal LM Glasfiber A/S made a pre-design for a number of configurations and performed finite element buckling calculations with ABACUS of which the results were presented to the participants. Based on these pre-designs two configurations were selected for four buckling tests. From the critical location calculated with ABACUS it was concluded that the load could be introduced at 6m from the blade root and that only half of the blade length needed to be built.

Specimen 1

Specimen 1 was used for a validation of the relatively simple buckling mode of the lower and upper contour panel when loaded by flat-wise bending. In between the two webs of the specimen the lower and upper contour panels have a nearly uniform curvature and material distribution. When loaded by flat-wise bending the state of stress in the panels is nearly uniform compression.
The first test was performed on buckling of the lower central panel because this panel has less curvature and thus a lower critical bending moment and therefore the smallest risk of damage. Upper central panel buckling was tested after rotation of the specimen by about 180 deg.

Specimen 2

The tests on the second specimen were addressed to more practical problems of buckling of (1) the leading-edge with a non-uniform curvature and layup and (2) the sandwich tail panel. With one web in the second specimen, the leading-edge and trailing-edge panels had a larger width. Such a specimen has a configuration similar to that for modern rotor blades.

A test on buckling of the shear web was discussed but rejected because the shear web is flat so that buckling can be predicted easily with design rules. In addition web buckling takes place in the blade interior which is not favourable for optical monitoring.

Design and Manufacturing of the Specimen

Based on the pre-design of the specimen by LM Glasfiber, the final layup and the detailed design of the blade root of both specimens was performed by LM Aeroconstruct GmbH. Both specimens were built by LM Aeroconstruct and were not painted to allow visual detection of resin-failure.

Buckling Tests

At DLR the specimen were tested on buckling.
For **specimen 1** the test on lower central panel buckling was performed first and could be repeated with only a very small reduction of the critical load in the successive loadings. After turning the specimen over 180 deg the test on upper central panel buckling was performed. Successive tests under the same conditions showed an increasing reduction in critical load.
The deformed state of specimen 1 is shown in figure 1.

For **specimen 2** the test on leading edge buckling led to a material failure by compression at 1.1m from the blade root shortly before anticipated buckling at a larger span.
After this failure the state of stress was analysed by ECN and by LASSO for different load directions for sandwich tail panel buckling. Based on these analyses, LM Aeroconstruct repaired the specimen. In addition a load direction (for tail panel buckling) was chosen that gives the lowest stress level in the repaired (damaged-) area. The test on sandwich tail panel buckling led to failure by wrinkling of the outer facing of the sandwich at a load that was twice as high as the theoretical wrinkling load taking into account a reduction factor 0.6 for imperfections.
The wrinkling failure mode of specimen 2 is shown in figure 2.

Analysis of Test Results

Specimen 1

ECN, LASSO and SPE analysed the results of all tests using the "Design rules", panel-based methods, *FINSTRIP* and finite element codes. The first analyses showed that the experimental loads were higher. This discrepancy was the reason for:

- Measuring the geometry of the DEBRA moulds by LM Aeroconstruct;
- Cutting batches of material from the upper and the lower central panel near the critical locations and measuring the mechanical properties of the laminates. These measurements showed a higher fibre-volume fraction and higher stiffnesses in longitudinal and even more in transverse direction than originally specified;
- Taking into account the stiffness of the joints and the thickness of the glue between the shear web and the contour panels in the calculations.

These investigations resulted in two descriptions of specimen 1: "As Designed" and "As Measured", where the "As Measured" description is corrected for the measured contour and material properties. For both descriptions the calculated results were reported. The "As Measured" description shows a better agreement with the experimental results than the "As Designed" description.

Specimen 2

The test on leading edge buckling was performed by loading in a direction which gives a nose-wise lead bending moment and an "up-wind" flap bending moment. The calculated loads for leading edge buckling show a critical area between 1.0m and 1.5m and between 2.5m and 3.0m from the blade root. It can thus be concluded that up to 1.5m from the blade root this specimen should have been built stiff in lead-lag direction.
The deformation pattern for leading-edge buckling calculated with MARC is shown in figure 3.

The test on leading edge buckling led to face wrinkling at 2.3m from the root at a relatively small loading. At this location the mould has a division which left a visible notch in the surface of specimen 2 which could have initiated the failure. The calculations with the finite element packages LARSTRAN and MARC both showed a collapse mode of the tail panel with a smooth growth, initiated by the span-wise variation of the tail geometry. This means that the buckling load is hard to assess and moreover that the pre-buckling state has significant panel bending moments and thus a large compressive stress in one of the facings.

The deformation pattern for sandwich tail-panel buckling calculated with LARSTRAN is shown in figure 4.

Torsional buckling

To find the load direction for tail panel buckling with the smallest failure stress in the damaged area of specimen 2, LASSO performed linear finite element calculations with NASTRAN on torsional buckling. Although for torsional buckling the stress level in the repaired area of specimen 2 appears to be too high, the results of this calculation were used for validation of some of the tools on torsional buckling. The results of this validation showed that the critical torsional moment obtained with the "Design rules" and with *STABLAD* are close to the results with NASTRAN while other methods do not include torsional buckling or give a strong under-prediction.
The torsional buckling mode calculated with NASTRAN is shown in figure 5.

State of Stress in the Web

For specimen 2 (with a single shear web) the state of stress was calculated for the loading during the test on trailing edge buckling. These stresses include:

- shear loading;
- "crushing load" i.e. compressive resultant force between upper and lower contour panels;
- longitudinal load due to restraint of longitudinal Poisson's expansion.

Assuming simply-supported edge constraints of the web the calculated critical load is about four times the experimental load for face wrinkling of the sandwich tail panel, which means that web-buckling is far from critical. The calculations also show that at the critical load for web buckling the transverse compressive ("crushing") load becomes relatively high such that a (prismatic) collapse mode with one (very long) bulge may be the critical failure mode.
On the web of specimen 2 DLR glued a set of strain-gauge rosettes which unfortunately gave a signal too small for a quantitative evaluation.

Parameter Studies

After the first two tests five parameter studies were selected for further investigation. These studies were performed by ECN, LASSO and by SPE and deal with the following aspects.

Edge constraints The influence of edge constraints and of the stiffness of the edge joints on the buckling load is investigated by ECN with correction rules (derived from panel-based solutions) and by SPE with *FINSTRIP* .
With panel-based methods for simply-supported edges a correction for the stiffness of the edge constraints gives an over-estimation of the critical load.
Using the solution method for clamped panels however, it is shown that a correction on the transverse bending stiffness for the additional stiffness of the joints in the structure gives an increase in the critical load which is of the same amount as derived with *FINSTRIP* . The experimental loads are below the loads in this investigation because the longitudinal curvature, the pre-buckling deformation and the geometric imperfections are not included.

Pre-buckling deformation The influence of including the pre-buckling deformation in the buckling load analyses is investigated by LASSO with the linear finite element package NASTRAN and with the non-linear finite element package LARSTRAN. ECN performed investigations on panel-basis in which the elastic longitudinal curvature is included and in which the out-of-plane pre-buckling deformation of the panels is described with either a correction on the transverse curvature or with a modal description of the deformed state. Both these models for the out-of-plane pre-buckling deformation give about the same reduction in the critical load. Also including the geometric longitudinal curvature of the panels in a rotor blade leads to a total reduction of the calculated load by 20% to 30%. The difference between the predictions with LARSTRAN (non-linear) and with NASTRAN (linear) is of the same order.

Search for the strongest layup (by ECN) Considering the fact that the amount of fibres of a rotor blade is dictated by strength and fatigue requirements an investigation is performed in which the buckling loads of all stacking sequences are analysed sorted. Most panel-based prediction methods show that the layup as used in the specimen is (nearly) the strongest. The difference between the strongest and the weakest layup is also of the same order which shows that these methods are suitable for selecting the strongest layup.

An exception however is the tool for clamped panels which shows an opposite trend in the strength of the upper central panel for the different layups.

Fibre misalignment With three different tools the influence of misalignment of the UD fibres has been studied by ECN for both the upper and the lower panel of specimen 1. Although the results of one method differ somewhat from the results of the other methods, all results show that at misalignment angles of up to 10 deg there is no serious reduction in buckling strength.

For strong anisotropic laminates –e.g. when using "elastic tailoring"– the fibre-misalignment does have a serious effect, in which case one may perform an analysis with *STABLAD* or with the method of Tennyson.

Influence of geometric imperfections For circular cylindrical shells it is well known that due to geometrical imperfections the buckling load of the real structure may be as small as 15% to 50% of the predicted load for the perfect geometry. For the long double-curved orthotropic panels in a rotor blade structure ECN derived a method to calculate the post-buckling path. The method for imperfect panels considers longitudinal curvature and also takes the pre-buckling deformation into account. The influence of an elastic core (as for sandwich panels) is not modelled. This method has been implemented in a prediction program that searches for the collapse mode with the smallest "imperfect load". The "imperfect load" is the load maximum of the post-buckling path. The imperfections are described as a prismatic $(cos - 1)$ correction on the panel curvature and a periodic function with the shape of the collapse mode.

This method is used for all the validations with an imperfection that has the shape of the collapse mode and an amplitude of 1% of the wall thickness.

The results show that this imperfection may give a buckling load that is 94% to 97% of the bifurcation load of the perfect geometry.

RESULTS AND CONCLUSIONS

Results

The results of the *BUCKBLADE* project are compiled below with the name of the responsible contractor between brackets.

- A compiled list with more than 130 publications on buckling (DLR, ECN, LASSO, SPE)
- A set of seven well-described reference problems that can be used for validation of buckling load prediction methods (DLR, ECN, LASSO, SPE).
- The buckling tests have learned that a continuous increase in applied loading does not lead to a sudden failure by structural instability (DLR).
- From tests on specimen 1 it is observed that the critical buckling load can be determined by strain-gauge signals, even if the strain gauges are not mounted on a bulge. The reason for a variation in strain-gauge reading is that in the environment of a bulge the entire state of stress varies discontinuous during buckling (DLR).
- Validated "Design rules" for buckling load prediction of long single-curved orthotropic (sandwich-) panels under various loading conditions (ECN).
- Descriptions of all buckling load prediction tools and methods that are involved in the *BUCKBLADE* investigation. The descriptions of the panel-based methods are given in such detail that these methods can be reproduced. An overview of the specifications of the different prediction tools is given in table 1 (All participants).
- Knowledge on the sensitivity of the buckling load for the pre-buckling deformation, stiffness of panel-joints, different layups, fibre-misalignment and for geometric imperfections (All participants).

Recommendations for Buckling Load Predictions

Sectional analysis

Evaluation of the buckling strength of a rotor blade on basis of cross-sectional analysis –as if each section is part of a prismatic structure– gives a **conservative prediction** for the most critical cross section.

Geometric twist

Comparison of the critical loads calculated with *STABLAD* for a prismatic structure does **not** show a serious reduction in buckling strength due to twist. It has not been investigated to what extent this conclusion holds in combination with shear loading e.g. from an edge-wise force.

Material properties

Modelling of full **orthotropic** material properties is a prerequisite. For unsymmetric orthotropic laminates (with non-zero B-matrix) the use of the "reduced stiffness matrix" $\tilde{D} = D - B\,A^{-1}\,B$ gives a convenient approximation.
The influence of **anisotropy** due to fibre-misalignment is not harmful for misalignment angles up to 10 deg. Stronger anisotropy e.g. due to "elastic tailoring" can be evaluated with the tool *STABLAD* or with the method of Tennyson.
Not modelling the **out-of-plane shear** flexibility leads to an over-estimation. For sandwich panels the out-of-plane shear flexibility should be taken into account. For sandwich panels with a very flexible core, not all prediction methods give accurate (face wrinkling) loads.

Longitudinal curvature

The geometry of rotor blades is nearly prismatic. When loaded by a bending moment the rotor blade panels also have a serious longitudinal curvature with opposite signs. This gives a smaller buckling load compared to single-curved panels and can therefore not be neglected.

Pre-buckling deformation

It is shown that modelling of the pre-buckling deformation is relevant. Describing this deformation in terms of elastic longitudinal curvature and a correction on the transverse curvature reduces the calculated buckling load by 20% to 30% (for the specimens investigated) and is closer to the experimental buckling load.

Combined loading on contour panels

Since rotor blades are usually closed structures the torsional stiffness is high and the shear loading will not be dominant. The combination of edge- and flat-wise bending moments gives a panel loading that varies (mainly linearly) over the panel width. This load variation can be analysed with load-interaction rules, using the IMperfect-Panel-ANALysis, *FINSTRIP* or a finite element package.

Combined loading on the shear web

Buckling of the shear web deals with a combination of shear loading, in-plane bending and transverse compression from crushing. Because shear webs are usually flat handbook methods may be applied.

Structural Aspects of Rotor Blades

Stiffness of the joints

For the specimen that is built and tested within the *BUCKBLADE* project the joints between the shear web and the outer contour cover 30% of the panel surface. Even for predictions with clamped edge constraints the joint stiffness gives a 9% to 25% increase in calculated buckling load. Omission of the joint-stiffness is thus conservative.

Fibre-resin fraction

Tests on coupons of the first test specimen showed a higher fibre-resin fraction while the transverse stiffness appeared to be larger compared to the design specifications assumed. Calculations with the measured material properties showed a better agreement with the experimental buckling loads for which reason it is recommended to perform coupon tests on batches of material that are made with the same manufacturing process as the actual product.

Geometric imperfections

For cylindrical shells the reduction in buckling load due to geometrical imperfections is strong. Due to the supports along the longitudinal edges of long panels (which is the case for rotor blades) the influence of geometric imperfections is not as severe as for cylindrical shells.

For panels with a weak curvature the post buckling path has a positive slope which means that the strength of these panels is insensitive to imperfections.

For the test specimen a geometric imperfection of 1% of the wall thickness reduces the critical loads by 3% to 6%. With a geometric imperfection of 10% the critical loads are reduced by 10% to 25%.

Local material imperfections

For sandwich panels local material imperfections in the facing have shown to lead to a considerable reduction in buckling strength. Due to a local imperfection in the material and facing geometry the experimental "face wrinkling load" was even smaller than half the theoretical value which already included a safety factor of 0.6 for imperfections.

Prediction Methods

Although time consuming and comprehensive, a non-linear **finite element package** still gives the most reliable prediction of the critical load of the complete structure/rotor blade. A model with a mesh that has 9 elements over the dimension of one half-wave allows an accurate solution of the critical load both for finite element packages and *FINSTRIP* .

Because of the smaller amount of input compared to finite element packages the program **FINSTRIP** is a practical tool for buckling load predictions of complete cross sections of (quasi-) prismatic structures. When using *FINSTRIP* one must be aware of the fact that the longitudinal geometric curvature and the pre-buckling deformation are not included.

The complexity of the problem of buckling of rotor blades has resulted in a large set of **panel-based tools** each having its specific features, see table 1.
All tools are capable of modelling orthotropic material properties and transverse curvature. With some tools sandwich panels can be also modelled.
The use of panel-based methods

- requires little input;
- allows fast analyses for variations in e.g. layup;
- is detailed on some aspects depending on which method is used, see table 1;
- gives a conservative prediction for the critical load of perfect panels,
  if the longitudinal curvature and pre-buckling deformation is modelled
  (except for the "Clamped panel" solution).

For application of methods that describe a panel with a uniform transverse curvature, the curvature of a circular arc through the panel edges and the middle of the panel shows to be convenient for realistic buckling load predictions.

The **Design rules** that are formulated allow buckling load predictions that:
\+ are nearly exact for long flat orthotropic sandwich panels;
\+ give a close approximation for long curved orthotropic sandwich panels
which is at least conservative if the sandwich core is not very weak;
\- do not include the longitudinal curvature, nor the pre-buckling deformation.
For buckling load predictions including these aspects the panel-based program *STABLAD* can be applied.

EXPLOITATION PLANS

Knowledge

All knowledge resulting from the project is available for use by European rotor blade designers. All information resulting from the *BUCKBLADE* project is compiled in four final reports, two of which are issued by ECN, one by DLR and one by LASSO.

The knowledge suitable for application includes:

- A list of more than 130 references of earlier investigations on buckling;
- A set of "Design rules" for application to long single-curved orthotropic panels, compiled from several publications;
- Design recommendations including estimated reduction factors for the influence of pre-buckling deformation, fibre-misalignment and geometrical imperfections.

Prediction Tools

At ECN several buckling load prediction tools are developed. In order not to leave the designer with the choice between all these tools, the most functional tools were distributed within the consortium. This development includes version control such that design calculations can be reproduced after several years.

The tools that are put under version control are:

STABLAD This tool existed already at the beginning of the *BUCKBLADE* project. It is selected for general application because it deals with anisotropic material properties, shear loading and geometric twist of layered panels of which one layer may have out-of-plane shear flexibility. From the validation within the *BUCKBLADE* project the program proves to function correctly. The pre-buckling deformation can be included.

IMperfect Panel ANALysis Contrary to the previous tool this model does not describe out-of-plane shear flexibility which is necessary to analyse sandwich panels. Also asymmetric aspects such as shear loading, geometric twist and anisotropic material properties are not described. The reason for selecting this tool is that panels with a geometric imperfection similar to the shape of the collapse mode can be analysed for which the load-maximum of the equilibrium path is calculated. Since this deformation pattern is described with some functions (multi-mode description) it gives a realistic description of the collapse mode for panels with a non-uniform loading and curvature in transverse direction of the panel.

CLAMPED A spin-off of the tool IMPANAL is an approximate solution for panels with clamped edges. This tool gives an upper bound and can thus only be used to evaluate solutions from other methods or for dimensioning of a test set-up.

The tools are available on diskette for application on a DOS operating system and for application under Windows-95/-NT.

Table 1 *Overview of aspects for the prediction tools*

Method	"Design rules"	Clamped-panel solution	Tennyson	Bert	IMperfect-Panel ANALysis	*STABLAD*	Novozhilov's	*FINSTRIP*
Material properties								
Asymmetric orthotropic		●	●		●	●	●	
Including $\tilde{D}_{16}$, $\tilde{D}_{26}$						●	A	
Incl. A_{16}, A_{26}, B_{16}, B_{26}			●			●	A	
Out-of-plane shear								
Symmetric sandwich	●			●		●	●	●
Similar facing material	●			●		●	●	
Asymmetric sandwich							●	
Loading								
Axial- and transverse-	●	●	+	+	●	●	●	
In-plane bending	E	C	+C	+C	M	C	C	●
Non-uniform axial load	C	M			M	C	C	●
Shear loading	E					A	?	
Geometry								
Transverse curvature	V.d.Neut	●	●	●	●	●	●●	●
Non-uniform trans. curv.		M	L	L	M ?	L	L	●
Transv. & longit. curv.		●	+	+	●	●	●	
idem including twist						A		
Edge constraints								
Clamped edges	E	M						●
Full cross sect. integrity								●
Pre-buckling solution								
Longitudinal curvature		●	+	+	●	●	●	
Out-of-plane equilibr.		M	C	C	M	C	C	

Legend:
- ● the modelling is analytically correct;
- ●● the strain displacement relations of Novozhilov are used which give accurate failure modes for complete cylinders;
- \+ is added to the description in this report;
- ? is present but works bad;
- A is modelled Approximately;
- C is included in terms of a Correction rule;
- E described with an Empirical fit;
- L using the Local curvature, averaged over each of the half-waves;
- M approximation with a Modal description.

With finite element programs such as LARSTRAN and MARC all aspects listed in this table can be modelled.

Figure 1 *Deformation of specimen 1 for central panel buckling.*

Figure 2 *Deformation of specimen 2 for sandwich tail panel buckling.*

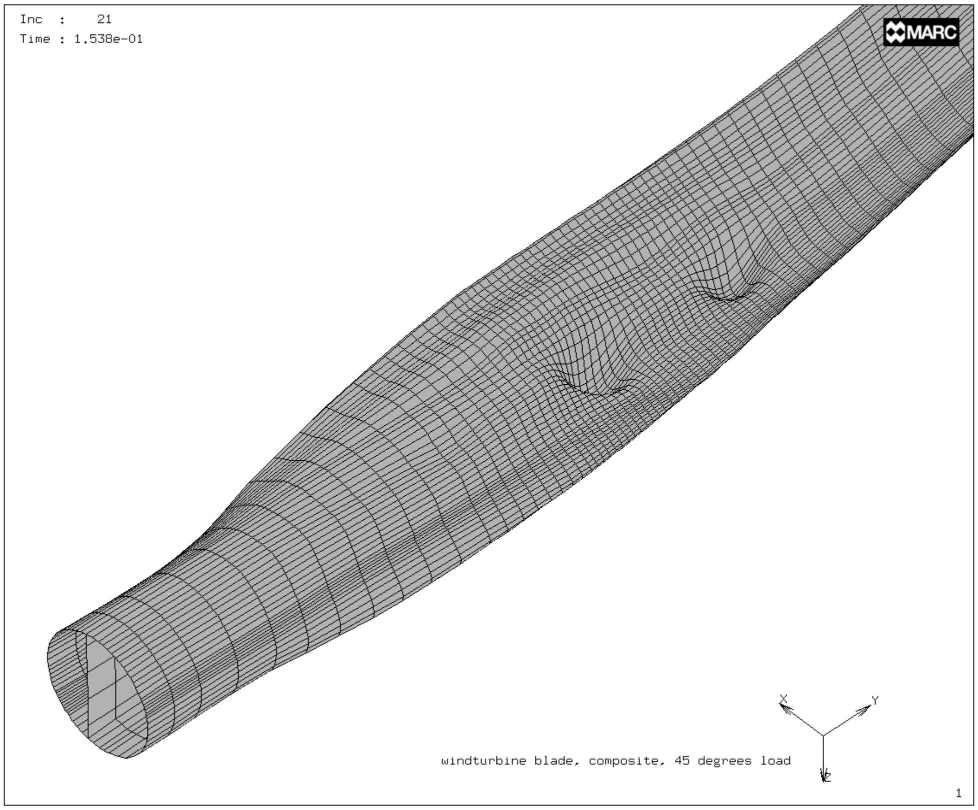

Figure 3 *Deformation for leading edge buckling calculated with MARC.*

Figure 4 *Deformation for sandwich panel buckling calculated with LARSTRAN.*

Figure 5 *Collapse mode for torsional buckling calculated with NASTRAN.*