# COMPUTIONAL PROGRAMING METHOD FOR ROTOR BLADE BUCKLING STRENGTH DETERMINATION

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**Abstract—** The dimensions of large wind turbines under development still increase, which is partly driven by the offshore-requirements of a ’high energy capture per turbine unit’. The relatively large amount of structural mass, and the dominating weight loads associated with increasing dimensions result in a trend towards material-efficient blade design. The consequence of this trend is that the blade becomes a thin-walled structure that is sensitive to ’buckling’; the geometric instability of the blade cross-section.

For the design of large size rotor blades it becomes necessary to verify the resistance against buckling, also called ’buckling strength’. The verification of the buckling strength can be done with non-linear finite element packages, FEM. These FEM packages however, require a lot of structural detail as input which is not always available. For this reason and also because ’design towards buckling’ requires many (fast) analyses for structural variations, one may use simpler more dedicated tools, in which the blade is represented with sectional models. For each of the sectional models it is assumed that it is part of a long prismatic structure, which is reasonable for the part of the blade outside of the largest chord. In the past ECN has been involved in European and Dutch research projects on the development and verification of buckling-load prediction tools.

A description is given of the so-called ’Design rules’ that require little computational effort. These ’Design rules’ are addressed to buckling of curved composite panels (such as in a rotor blade structure) and can therefore be applied in the pre-design stage of rotor blades and of other slender composite structures.

Various codes are used as buckling tools for improved conditions and implemented in the rotor-blade design. The improvements are mainly addressed to the modelling of buckling of sandwich layup, and the inclusion of shear loading such that the buckling of shear webs it predicted more realistic. The final aim of these developments is to bring simple and fast buckling load prediction tools in the design process. This must allow optimisation of the number of shear webs, and the location of each shear web. These tools also help the designer to find the layer-stacking sequence with the strongest buckling strength, and the (minimum) required stiffness and thickness of the core of sandwich panels.

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## I. INTRODUCTION

### *1.1 General description of buckling*

Because historically the phenomena of ’buckling’ was not a serious problem for wind turbines, a short description is given first. The most well-known example of ’buckling’ is that of a slender column loaded by axial compression (Euler beam) for which an ’educative’ analytical solution is pos-sible. In aerospace engineering buckling is also ob-served and investigated for flat plates loaded under compression and/or shear loading. For such plates relatively simple engineering rules can also be de-rived analytically, even if they are of layered fibre material. In general ’buckling’ is the phenomenaof (rapid) deformation of structures under loading. During this deformation, the elastic strain energy in the structural elements (bars, flat or curved plates) is transferred to local bending energy of the structure.

From this definition it becomes clear that buckling is not likely to occur under tension because the tensile stresses are not released with local bending of the structural elements. It also follows that buckling only occurs if the elastic strain energy of the loaded structure exceeds the ’local’ deformation energy of the collapsed structure. This description in terms of deformation energy in the structure is also the basis on which several buckling load solution methods are derived.The general bukling procedure and other analysis methods along with types of acting loads are shown here.

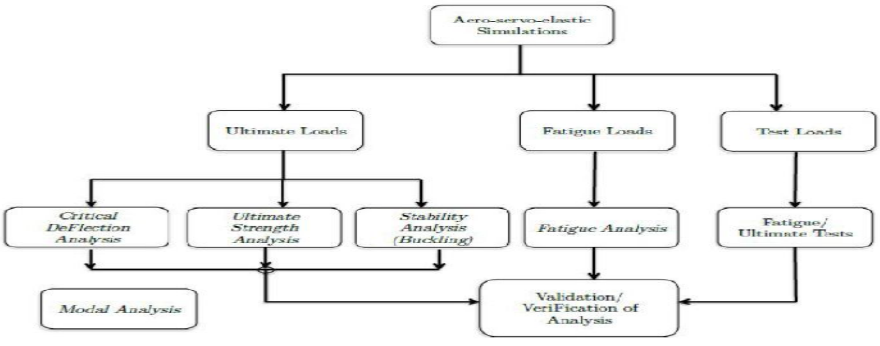

**Fig1: Various analysis methods for blade testing**

### *1.2 Buckling of rotor blades*

The dimensions of large wind turbines under development still increase, which is partly driven by the offshore-requirements for a high energy capture per turbine unit. The relatively large amount of structural mass, and the dominating weight loads associated with increasing dimensions result in a trend towards material-efficient blade design. This material efficiency is realised by a large cross-sectional area of the blade root, more layers with UD fibres (sometimes carbon), and a larger fibre-fraction due to vacuum production techniques. The consequence of this trend is that blades become thin-walled structures that are sensitive to 'buckling'; the geometric instability of the blade cross-section. Structural modifications to avoid buckling are the use of sandwich material, and/or more shear webs. These modifications lead to an increased complexity of the manufacturing process and of the buckling strength predictions. The phenomena of buckling has been studied for decades in aerospace engineering, although this was addressed for a large extent to isotropic (e.g. aluminium) materials. The buckling of wind turbine rotor blades is characterised by a strongly varying load direction (sectional bending moments) and by the strong variation/difference in material layup within a cross section.

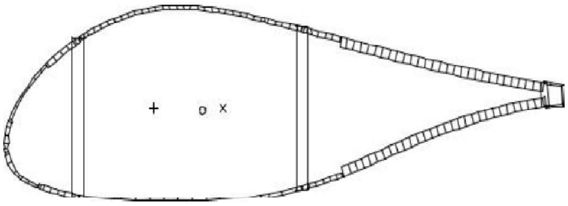

**Fig 2. Blade aerofoil with web sections**

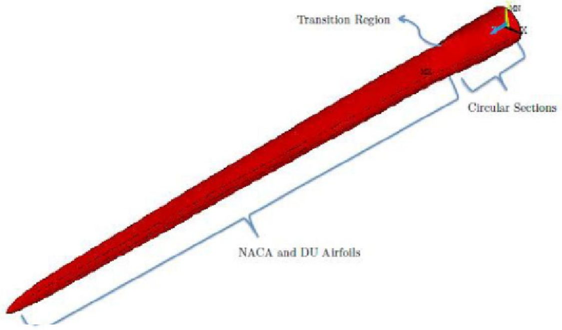

**Fig3. FEA model of blade**

## II. INVESTIGATIONS ON BUCKLING OF ROTOR BLADES

Several buckling load analysis tools and methods have been investigated. These tools range from the elementary rules for flat plates that can be found in literature (e.g. Roark & Young [5], Plantema [4]) up to non-linear finite element packages (Larstran and MARC). A substantial part of the work within the project BUCKBLADE was addressed to programs for the buckling of rotor blades, among which were CROSTAB [2, 3] and FINSTRIP [6]. Although the modelling and the solution strategy of these programs is completely different, they both describe buckling of rotor blades on basis of sectional properties, as if each section is part of a long prismatic thin-walled beam. The availability of two different tools allows for each blade verification by comparison of their results. Within the BUCKBLADE project two blade specimen were designed, built, and tested on buckling. Comparisons of test results with the predictions learned that for thin-walled orthotropic panels buckling can be predicted reasonably well. The buckling-strength predictions of sandwich panels within a blade appears to be too optimistic due to local imperfections of the sandwich facings and secondary bending stresses within a blade loaded by bending.The cross section details in FEA is shown below.

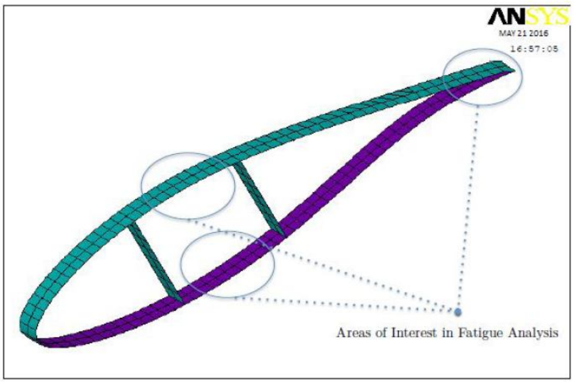

**Fig 4. Cross sectional view of blades model in ANSYS**

## III. BUCKLING OF ROTOR BLADES

The panels within the structure of large rotor blades have a curved geometry in chordwise direction. The 'buckling' of a curved panel involves not only bending deformation of the shell wall, but also some transverse and shear strain. For this reason the buckling strength of curved panels is larger than for flat panels with the same width and material layup. The increased buckling strength of curved panels have the implication that this strength is sensitive to deviations of this curvature, which usually leads to a reduction in strength. These curvature deviations can be from the longitudinal curvature from a bending moment, and from geometric imperfections.

### *3.1 Influence of longitudinal curvature*

The dominant loading of a rotor blade is the bending moment. Large bending moments give a longitudinal curvature of the blade that is concave on the side loaded by compression. The combination of this concave longitudinal curvature with the convex airfoil curvature (negative Gaussian curvature) is weaker than a shell with a curvature that is either concave or convex in all directions.

Within the BUCKBLADE project investigations were carried out into the difference in predicted buckling strength if this longitudinal curvature is included or not. Because this longitudinal curva-ture is already present before buckling occurs it is also called ’pre-buckling deformation’. This pre-buckling deformation can be included or suppressed in the analysis with CROSTAB. For the blades investigated within the BUCKBLADE project the influence of this pre-buckling deformation was in-vestigated with CROSTAB and with a linear and a nonlinear Finite Element package. With both CROSTAB and the Finite-Element packages the influence of the prebuckling deformation gave a reduction in the order of 20% to 30%.

### *3.2 Sensitivity for geometric imperfections*

In aerospace engineering it was already concluded that for relatively thin-walled cylindrical shells (e.g. in launch rockets) the buckling strength under compression can be reduced to 15% to 50% of the the-oretical value. It was found that this reduction is mainly caused by the initial imperfections in the shell geometry. With a dedicated version of the ECN tool CROSTAB the sensitivity for geometric imperfections can be investigated. For rotor blade structures, the ’free width’ of the panels is some-what smaller while the relative panel thickness is larger so that the strength reduction due to geomet-rical imperfections is in the order of 75% to 90%.

## IV. ENGINEERING RULES TO PREDICT BUCKLING

From the design graphs and -rules found in litera-ture a set of so-called Design rules was composed within the project while seeking a relatively simple parametric form. The basis of these Design rules are the so-called load-interaction formulas in terms of the relative compressive load levels: foraxial **c**ompression, **b**ending and **s**hear

## V. OPTIMISATION OF LAYUP

Within the project some parameter studies were performed. One of these studies dealt with variation of the stacking sequence within a laminate that gives the largest buckling strength, which was studied for a flat panel, and for panels with 2 different curvatures. The stackings consist of a given set of layers where the outer layer was prescribed. For all these panels the "strongest stack-ing" has a theoretical strength that is 19% to 28% higher than the weakest layup which appears to be independent from the thickness.Variation of buckling strength with stacking order.It was concluded that strong laminates are obtained if the "minority-layers" are located away from the neutral plane. For strong curved panels it was shown (also reported by Hutchinson and Frauenthal for cylinders) that laminates with the UD layers on the outer (convex-) side have the highest buckling load.

## VI. RESULTS FROM FORMER INVESTIGATIONS

The investigations within the former projects have resulted in:

**Design rules** A set of engineering rules for thebuckling-strength prediction of flat/curved or-thotropic panels.

**Cross-sectional tools** The programs CROSTABand FINSTRIP for the buckling-strength pre-diction of complete blade cross-sections.

**Buckling options in FOCUS** The rotor-blade de-sign package FOCUS has a module for buckling-analysis while input files for CROSTAB and FINSTRIP can be generated.

**Knowledge on layup** Because the tool CROSTABworks relatively fast and because its mate-rial description has a lot of detail, parameter studies can be (and have been) performed to find the layer-stacking sequence that has that largest buckling strength. This together with similar studies within aerospace engineering on stiffened shells gave insight into characteristics of ’strong layups’.

Already early in current project, it was noticed that accurate material properties are essen-tial for realistic buckling load predictions, which fits to the expectations.

It was finally concluded that rotor blades are not very sensitive to geometric imperfections, except for the relatively thin facings of sandwich panels. If these facings are relatively thin compared to the sandwich core, they may fail in a local deformation pattern such as ’face wrinkling’.

## VII. OBJECTIVES FOR FUTURE INVESTIGATIONS

Future investigations are addressed to reduction of the uncertainty for buckling-strength prediction of sandwich material layup with inclusion of shear stresses due to sec-tional shear loading;

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