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Applications of the BEam Cross section Analysis Software (BECAS)

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Summary. A newly developed framework is presented for structural design and analysis of long slender beam-like structures, e.g., wind turbine blades. The framework is based on the BEam Cross section Analysis Software – BECAS – a finite element based cross section analysis tool. BECAS is used for the generation of beam finite element models which correctly account for effects stemming from material anisotropy and inhomogeneity in cross sections of arbitrary geometry. These type of modelling approach allows for an accurate yet computationally inexpensive representation of a general class of three dimensional beam-like structures. Preliminary results are presented where the devised framework is used for stiffness and strength analysis of wind turbine blades, material and structural topology optimization of wind turbine blade cross sections, and evaluation of strain energy release rate in fractured beams. The results show a good agreement with solutions from three-dimensional solid finite element models but require only a fraction of the computation time.

Key words: beam finite elements, wind turbine blades, cross section analysis tools, laminated composite structures

Introduction

The design and certification of wind turbines requires the analysis of a large number of load cases. Each of these load cases corresponds to relatively long time series analysis of the loads and response of the wind turbine. These analyses are typically conducted using specialized wind turbine aero-servo-elastic codes. In here the most important components of the wind turbine are typically modelled using beam finite elements. These type of modelling approach offers a convenient trade off between accuracy and computational efficiency.

The generation of beam finite element matrices entails the determination of the cross section stiffness and mass properties. For isotropic beams with simple geometries (e.g., tower and shaft) the determination of these properties is usually trivial. However, the development of accurate beam models to represent the blades is not so simple. The blades have complex geometries and are made of combinations of different composite materials with different degrees of anisotropy. Simplified approaches have been used in the past to estimate the blade cross section properties. However, these tools do not meet the desired level of accuracy for future blade designs.

The wind turbine blade design and engineering community, in an effort to improve the accuracy of its aeroelastic models, has in recent years looked into new methods for developing high-fidelity beam models to represent the blades. The open source BEam Cross section Analysis Software – BECAS – described here is a result of this effort (see BECAS [1]). BECAS is able to accurately account for effects stemming from material anisotropy and inhomogeneity in cross sections of arbitrary geometry. As a results it is now possible for blade designers to tailor these properties to improve the aeroelastic performance of the blade.

In the next sections, we will describe the basic BECAS workflow and present different application examples which illustrate the potential of such a tool. We conclude with an outlook into future extensions and challenges.

The BECAS workflow

A schematic description of a typical BECAS workflow for structural blade analysis and design is described in Figure 1. BECAS is first used in a pre-processing phase to generate the beam finite elements representing the blade in the aeroelastic analysis code. A series of pre-defined cross sections along the blade are analysed. The analysis is based on a finite element mesh of the cross section. The material properties are defined at each element and may present any level of anisotropy. The resulting beam finite elements are used to represent the blades in the wind turbine assembly inside the aeroelastic analysis tool. Finally, based on the cross section forces and moments resulting from the aeroelastic simulations it is possible to recover the detailed three-dimensional stress components or analyse the strain energy release rate, as will be shown in the next sections.

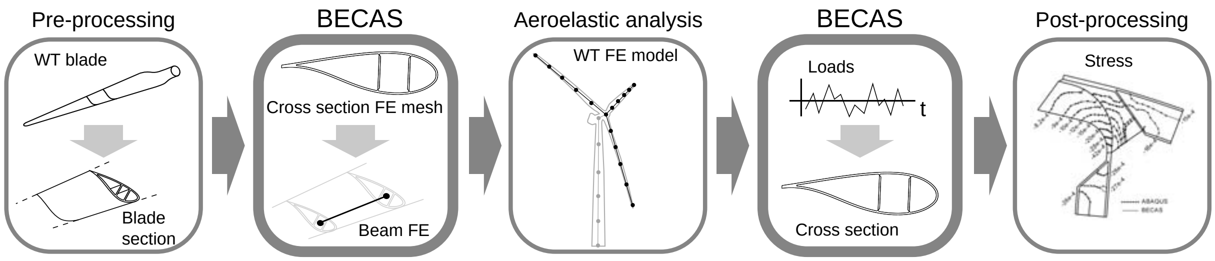


Figure 1. Schematic description of the BECAS workflow for structural analysis and design of wind turbine (WT) blades.

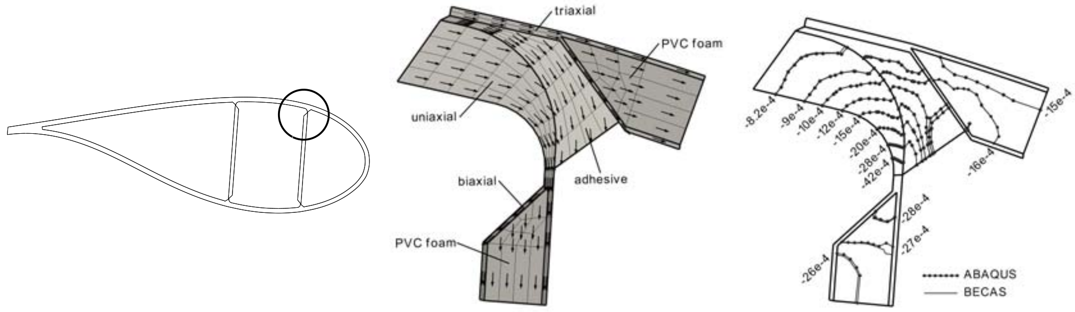
The framework described previously was recently employed in the stiffness and strength design of the DTU 10 MW Reference Wind Turbine (DTU10MW-RWT) (Bak et al. [2]). The geometry and material distribution were automatically generated based on a shell finite element model of the blade. The resulting cross section stiffness and mass properties were employed in the generation of the beam finite element representing the blades in the wind turbine aeroelastic analysis tool HAWC2 (Larsen and Hansen [3]). The strength of the laminates in the blade were analysed based on the resulting aeroelastic loads. The procedure was repeated until the final structural configuration of the blade was obtained.

Applications

The following sections give a brief account of the main developments within the BECAS framework. These are mostly preliminary results intended to illustrate the potential of such a tool.

Stiffness and strength analysis

The first step in the development consisted of the validation of the cross section stiffness and mass properties. Results show that the deformation and eigenfrequencies given by beam finite element models generated using BECAS match closely the results from detailed shell finite element models. Moreover, the three-dimensional stress components on a detailed wind turbine cross section have been analysed. The results from Figure 2 show that the three-dimensional stress components estimated by BECAS match well with that obtained from three-dimensional finite element models.

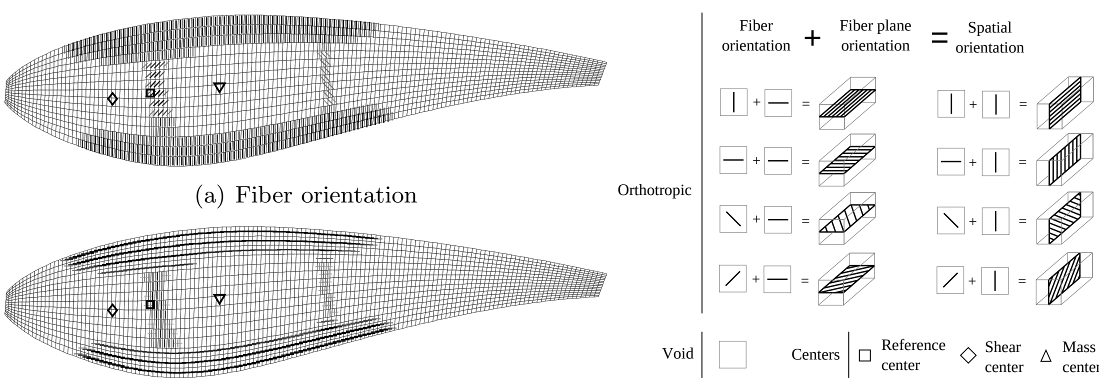


(a) (b) (c)

Figure 2. Analysis of strength in a wind turbine cross section using BECAS. (a) Wind turbine cross section and region of detail. (b) Finite element mesh, and material distribution and orientation at detail. (c) Element strains ϵ_{12} in material coordinate system as obtained by BECAS and a three-dimensional solid finite element model in ABAQUS.

Multi-material topology optimization

An optimal design framework was developed by Blasques and Stolpe [4] combining BECAS and multi-material topology optimization techniques. The optimal design problem concerns the distribution of a limited amount of different materials within a design domain represented by the cross section finite element mesh. A change in the material distribution in the cross



(a) Fiber orientation

(b) Fiber plane orientation

(c) Legend

Figure 3. Optimal material distribution and laminate properties for the load carrying structure of a wing profile cross section subject to 15 static load cases of aerodynamic nature. Solution to the minimum compliance problem with a weight constraint. It is assumed that the outer aerodynamic shell is non-structural and exists around the perimeter of the cross section shape outside the design domain. (a) Fiber orientation. (b) Fiber plane orientation. (c) List of 9 candidate materials (laminated composite material in 8 different directions and void) and legend to figures (a-b) for interpretation of the three-dimensional orientation of the fibers.

section results in a consequent change of its stiffness and mass properties and in turn, of the structural response of the beam. The approach was applied, among other, to the optimization of the material properties and structural topology of an idealized wind turbine blade. The resulting topology presented in Figure 3 agrees well with results reported in the literature using computationally significantly more expensive three-dimensional solid finite element models.

Evaluation of strain energy release rate

The most recent work has focused on the analysis of strain energy release rate (SERR) in fractured beams. The Virtual Crack Closure Technique (Krueger [5]) has been implemented in BECAS. The validation work includes the analysis of SERR for cracks along the beam length in mono- and bi-material interfaces. The resulting SERR values show a good agreement when compared with three-dimensional solid finite element models (cf. Figure 4).

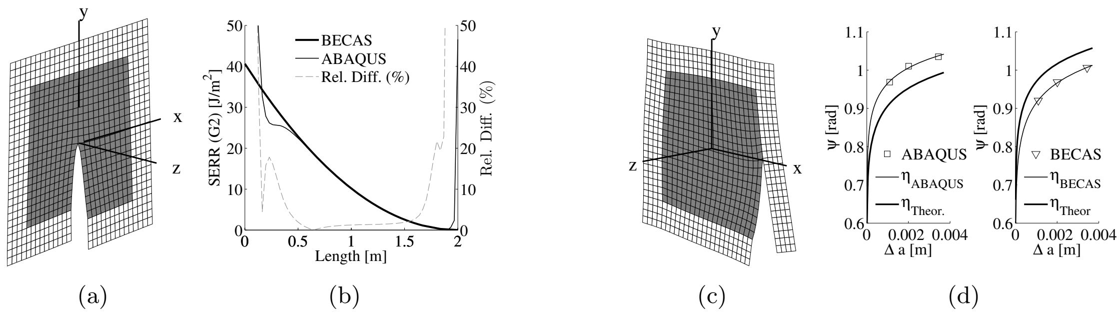


Figure 4. Selected results comparing the VCCT results from BECAS and three-dimensional finite element models in ABAQUS for cantilever beams subjected to tip loads. The origo of the length coordinate is at the clamped end of the beam. Strain energy release rates G1, G2, and G3 are associated with mode 1, 2 and 3 crack opening, respectively. (a-b) Bi-material cross section with crack in the center subjected to transverse force in the x direction. (a) Cross section warping deformation and finite element mesh. (b) Variation of the strain energy release rate GII along the beam length. (c-d) Bi-material cross section with crack at the material interface subjected to tension force in z direction. (c) Cross section warping deformation and finite element mesh. (d) Dundurs parameters as estimated based on measurements for different mesh sizes using BECAS (right) and a solid finite element model in ABAQUS (left).

Current developments and future challenges

Ongoing developments concern mostly the extension of the previously presented results. The strength analysis module is being further extended to address material based fatigue damage estimations and reliability analysis. The main challenge in this module is the incorporation of effects stemming from geometrical non-linearities, e.g., panel buckling for thin-walled cross sections. The topology optimization framework is currently being extended to include aeroelastic stability constraints. The aim in this case is to fully exploit the fact that the analysis of the global response of the beam is relatively inexpensive to consider novel computationally intensive and complex multi-physics constraints. Finally, the aim with the fracture analysis module is to perform multi-scale modelling using loads stemming from aeroelastic analysis simulations to study the development of debond and delamination damage.

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