A concept study of a carbon spar cap design for a 80m wind turbine blade

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Abstract. The buckling resistance is a key design driver for large wind turbine blades with a significant influence on the material costs. During the structural design process the choice was made for carbon spar caps and two shear webs, which were set relatively far apart in order to stabilize the panels. This design presented a major challenge for the stability of the spar caps. The topology of these spar caps has been modified with regard to stability, comparing a continuous spar cap with split spar cap concepts and considering both lay-ups with hybrid carbon glass spar caps or sandwich concepts. Within those concepts, parametric studies were conducted varying different geometrical parameters of the spar caps and its layups. In order to determine the buckling resistance of the spar cap, an analytical model considering a 2D cross section discretized blade model was utilized to select the basic concept, after which a 3D numerical finite element model taking the whole blade into account was used to evaluate the chosen design concepts. The stability limit state analysis was conducted according to the certification scheme of GL guideline 2012. The various concepts were evaluated based on the blade's mass, tip deflection and modal properties. The results of this design process of the spar caps and the evaluation of the used analysis tools are presented within the paper.

1. Introduction
This paper describes a concept study of stability-enhanced spar cap topologies and the associated effects on the blade design. The aim of the study was the identification of a preferred topology for further design steps and validation of the used calculation methods. The study was based on a 80m baseline blade model, where unidirectional carbon fibre reinforced plastics (CFRP) as primary structure were placed at the top of the spar cap. CFRPs are commonly used for spar caps of large rotor blades in the multi-mega-watt class [1]. Such blades are thin-walled structures and highly sensitive to buckling due to high and variable loads [2]. Consequently the majority of the blade is designed as sandwich structure to avoid instability. The use of CFRP and the large shear web distance in the baseline blade model led to a distinctively low buckling resistance of the spar caps.

Lund et al. [3] optimized the buckling resistance of a carbon spar cap layup using the Discrete Material Optimization (DMO) method. Layers with varying fiber orientations were added to a CFRP spar cap with constant thickness over the width. Buckney et al. [4] developed a cross section based spar cap optimization method that takes the mass and the bending stiffness as weight function into account. Beyond these investigations Blasques et al. [5] optimized beam cross sections with constraints on the mass properties, the shear centre and the centre of mass.

This formulation was extended to beam eigenfrequency constraints [6].

In contrast to the optimization methods above, this work involves a practical comparison of two specific concepts to increase the buckling resistance of the spar cap section. The application of these concepts on a comprehensive baseline blade model allows an evaluation.

2. Methods

2.1. Design Process

2.1.1. Load cases   For this study three load cases were considered: two major flap-wise extreme load cases that are dimensioning for the buckling resistance of the suction and pressure side spar cap, and the load case, where the tip of the blade was closest to the tower surface (tip-to-tower-clearance).

The flap-wise extreme load cases were a mixed load case of DLC 6.1, DLC 6.2 and DLC 2.3 time series according to IEC 61400 [7]. These loads were extracted from the most conservative load envelope from each cross section.

Furthermore, the tip deflection was evaluated with the tip-to-tower-clearance load case, which was determined from a DLC 2.3 time series.

The loads were linearly interpolated to six load introduction points suitable for the application of shear forces in a 3D finite element model.

2.1.2. Design State   Based on the above mentioned load cases the blade's limit states have already been evaluated according to the GL guideline 2012 [8] and fulfilled the following requirements: the ultimate strength and fatigue limit state, the serviceability limit states (modal properties and tip-to-tower-clearance), and the ultimate stability limit state. The panels and the shear webs were already designed against buckling. However, the spar caps turned out to have severe buckling problems and did not fulfill the GL requirements.

2.1.3. Safety Factors   According to GL, a linear bifurcation analysis (LBA) is mandatory to evaluate the buckling resistance $P_{cr,d}$ in the ultimate stability limit state.

For evaluation of the buckling resistance, the partial safety factor applied on the design load function S is $\gamma_n = 1.0$. This factor takes the consequence of failure for a 'non fail-safe' structural component into account [7]. Moreover the partial safety factor for loads γ_F is applied on the characteristic load L_k (1.1 for DLC 2.3 and 1.35 for DLC 6.1 and DLC 6.2 [7]).

On the resistance side R, the partial material safety factor $\gamma_{M0} = 2.04$ is applied to the moduli. It is the product of $\gamma_{M0} = 1.35$ (general safety factor), $C_{1c} = 1.1$ (scattering of the moduli), $C_{2c} = 1.1$ (temperature effects), and $C_{3c} = 1.25$ (inaccuracy between linear and non-linear analysis).

The design evaluation is then expressed as:

$$\gamma_n S_d \left(\gamma_F F_k \right) \leq R_d \left(P_{cr,d} \left(\frac{\text{Moduli}}{\gamma_{M0} \ C_{1c} \ C_{2c} \ C_{3c}} \right) \right) \tag{1}$$

The safety reserve factor is defined as ratio between design resistance R_d and design load S_d:

$$\underline{S}afety \ \underline{R}eserve \ \underline{F}actor \ (SRF) = \frac{R_d}{S_d} \tag{2}$$

2.2. Analysis Tools

To evaluate the buckling resistance of the blade concepts, three tools were used: (i) the panel based buckling tool (PBB) implemented in the FOCUS6 (version 6.2.7071.776) wind turbine design software developed by Energy research Centre Netherlands (ECN) and Knowledge Centre

(a)   (b)   (c)
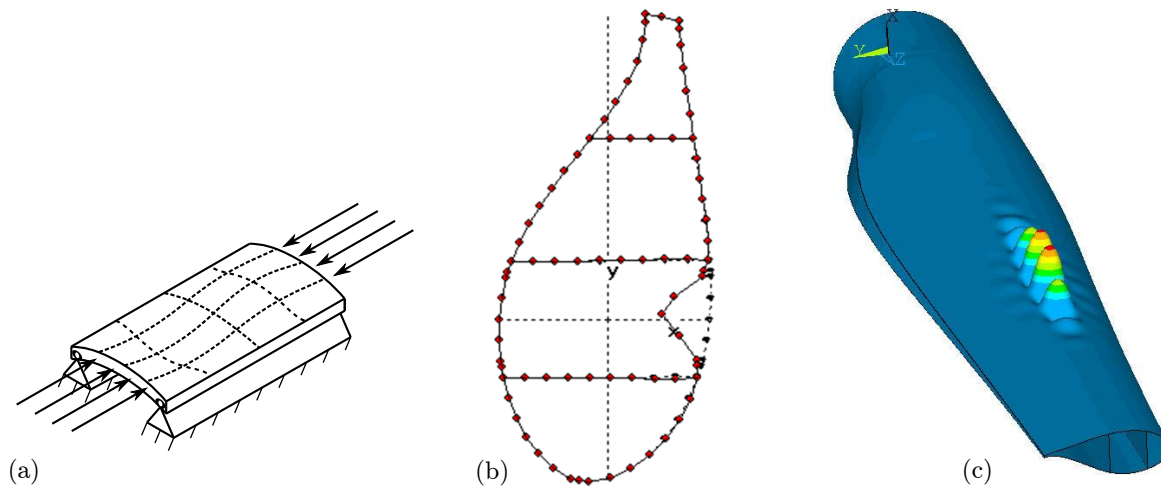
Figure 1. Models of the analysis tools used in this study, (a) simply supported plate model as used in PBB, (b) finite strip model of a cross-section (FINSTRIP), and (c) finite element model

Wind turbine Materials and Constructions (WMC) [9, 10], (ii) the prismatic cross section based finite strip tool FINSTRIP distributed by WMC [11], and (iii) a 3D finite element shell analysis, where the model was generated by FOCUS6 and analyzed with ANSYS (version 14.5.7).

PBB is a relatively fast tool to determine the buckling resistance of each panel over the blade length. Whereas FINSTRIP requires a little more computational cost. FEA requires the most computational effort.

An additional transverse loading due to the geometrically nonlinear Brazier effect [12, 13] is not taken into account by all three analysis tools.

2.2.1. Panel Based Buckling The modeling in PBB is represented by an infinity long, and simply supported panel as shown in Fig. 1a. The edges of the panel are defined by two arbitrary lines on the blade surface. A third line is defined in the centre of the panel at which PBB determines the material topology for the panel. Thus, a panel can merely consist of a single orthotropic layup configuration that can be symmetric or antisymmetric. All three lines define the panel surface as spline in circumferential direction. Further, the curvature due to the deflection of the blade is taken into account. Axial and shear loading on the panel are determined from the cross-sectional load distribution over the blade span. The solution of the eigenvalue problem is found analytically.

2.2.2. FINSTRIP Within this tool the entire cross section of a rotor blade is modeled. Its structure is prismatically dicretized by finite strips in circumferential direction. Materials are modeled symmetrical having either isotropic or orthotropic properties. Axial, flap- and edge-wise loading are applied to the blade axis of the cross section (shown as coordinate system origin in Figure 1b). From that loading, axial strains for each finite strip are determined. The solution of the eigenvalue problem is found numerically.

2.2.3. Linear Finite Element Analysis The 3D model for the finite element analysis consisted of approximately 70,000 ANSYS 8-node elements (SHELL281 in ANSYS element library [14]). The load was applied via shear forces at six positions along span axis using linear interpolation

elements elements (RBE3 in ANSYS element library [14]). The solution of the eigenvalue problem was then found numerically using Block Lanczos solver.

2.3. Topology Concepts

Due to the previously described lack of stability in the spar cap region in the baseline model, the following design concepts are based on a topology modification in the area bordered by the shear webs (see Figure 2c).

The concept development requires a predefined geometry and topology of the blade: Besides the outer blade geometry derived by airfoil shapes, relative thickness, twist angle and chord length, the shear web positions were defined. The shear web distance decreased in direction to the tip and was set as a constraint parameter for this study.

Furthermore we defined the materials used in the spar cap region: Uni-directional CFRP served as primary structure, balsa wood as core material and multi-directional glas-fiber reinforced plastics (GFRP) as cover laminate.

Balsa wood instead of foam was chosen as core material because of its structural properties that are beneficial to resist the high stress level that these blade regions are encountered. The upper bound for the core thickness was set to 45mm, derived from balsa wood pre-products available on the market. Referring to the preliminary results determined by Lund et. al. [3], GFRP with a $\pm 45°$-fiber orientation was selected as sandwich skin material on the in- and outside of the panel.

The split spar cap (SSC) design is presented in Figure 2a: The primary structure is split into two separate sections supported by the webs in order to keep them compact. These spar caps are kept at constant width over the blade span. The section in between the spar caps is filled with a sandwich panel.
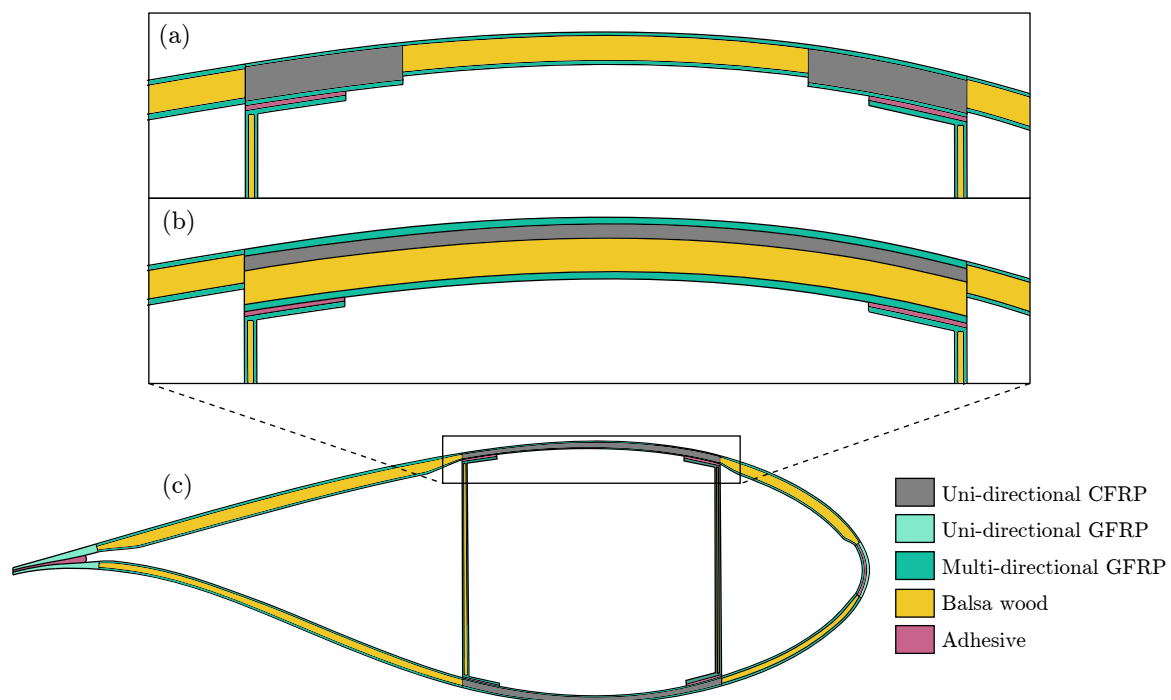
Figure 2. Topologies of (a) split spar cap (SSC) concept, (b) continuous spar cap (CSC) concept, and (c) baseline.

Table 1. Concept evaluation in terms of global blade properties.

	Mass [t]	1st flap-wise [Hz]	1st edge-wise [Hz]	Tip deflection [m]
Reference	30.70	0.67	1.01	11.4
Split spar cap (200mm width)	31.34	0.65	1.03	11.5
Split spar cap (300mm width)	31.60	0.65	1.00	11.4
Continuous spar cap	33.03	0.66	0.97	11.2

The continuous spar cap (CSC) design is presented in Figure 2b: The primary structure is kept close to the outer surface to utilize the structurally most effective area of the cross section [2]. Buckling prevention is reached by adding a continuous wood core and GFRP cover laminates.

3. Results

3.1. Concept Evaluation

The results of the spar cap design concept evaluation are listed in Table 1. To reach the required buckling resistance over the full blade span, both concepts were applied on the baseline blade model (compare Figure 3). The concepts' quantitative buckling resistance was determined using FEA.

A further design objective was a constant tip deflection. Basis for evaluation were the comprehensive blade properties such as mass and eigenfrequency.

To analyse the effect of the spar cap width, we set this parameter to 200 and 300mm. A design including split spar caps of constant width was not feasible along the entire blade span because both spar caps would collide (see Figure 3a). For the 300mm spar cap design this position was at 76% blade length and for the 200mm variant at 88% blade length. From this position the continuous design was applied up to the blade tip.

The application of the continuous design entailed specific features induced by the defined thickness limitation of the wood core. Thus up to eight layers of biaxal GFRP were added as cover laminate to reach the required buckling resistance.

The design modifications caused a weight increase compared to the baseline: The SSC (200mm width) has a relatively low increase of 640kg mass, whereas the CSC has an increase of 2,335kg.
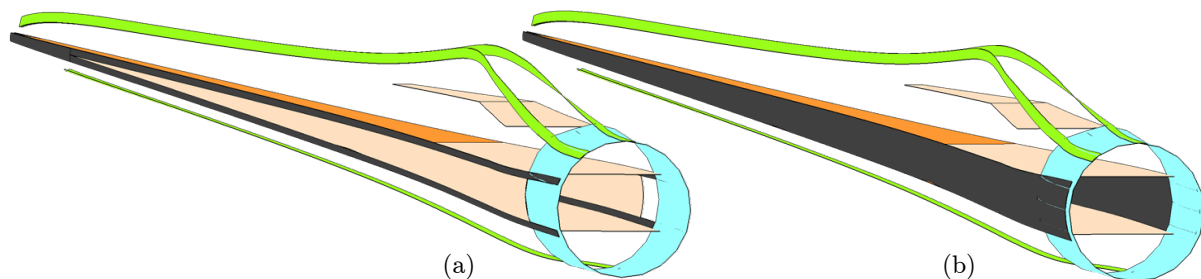
Figure 3. Blade topologies of (a) split spar cap (SSC) concept and (b) continuous spar cap (CSC) concept.

Further SSC has the highest edge-wise eigenfrequencies in contrast to the CSC, which has a noticeable reduction of both eigenfrequencies.

3.2. Analysis Tool Evaluation
Within this study three analysis tools were used to evaluate the buckling resistance of the spar cap concepts.

The evaluation is exemplary shown in Table 2 for the baseline blade (Figure 2c). The most critical section and radius for the two flap-wise ultimate load cases were used as benchmark. The PBB tool is very close to the LBA based on FEA, whereas FINSTRIP's reserve factors are far too optimistic.

The usability of the PBB tool within the design process of the split spar cap concept was limited, because PBB's panels can merely consist of a single layup (see Section 2.2.1). To deal with this issue we defined two panels both consisting of the layup between the two carbon reinforcements (see Figure 2a): (i) a first panel having its edges at the outer borders of the two carbon reinforcements (intersection between the shear webs and the shell) and (ii) a second panel having its edges at the inner border of the two carbon reinforcements. With this strategy the panel based buckling tool showed a qualitative tendency but it was not able to obtain results close to FEA.

For the continuous spar cap concept PBB's results were qualitatively in good accordance with FEA. This was especially the case for the mid blade region between 15 and 60m blade length where panel based buckling analysis revealed a safety factor of $SRF_{\mathrm{PBB}} = 1.12$. PBB's SRF is too optimistic quantitatively compared with FEA's $SRF_{\mathrm{FEA}} = 1.01$.

For the baseline blade FINSTRIP revealed the correct buckling modes. However, for the two developed concepts FINSTRIP did not reveal the buckling modes as FEA.

Table 2. Buckling analysis tool comparison.

	Safety reserve factor SRF	
Critical section	Pressure side	Suction side
Critical radius [m]	23.6	17.4
Panel based buckling (PBB)	0.19	0.31
FINSTRIP	1.63	2.42
FEA (Linear bifurcation analysis)	0.22	0.31

4. Discussion and Conclusions
The main objective of this study was to evaluate the spar cap design concepts to give recommendations for further design steps. The concept that involved split spar caps (SSC) with a width of 200mm led to the most favorable results. In comparison with the other concepts, this variant revealed the lowest blade mass and increased the edge-wise stiffness. A higher edgewise stiffness allows subsequent material saving on load carrying structures in the trailing and leading edge. Consequently a SSC design was identified as best topology concept to increase the buckling resistance of the spar caps.

A further goal was to analyze the applicability of the calculation methods. The panel based buckling method (PBB) turned out to be feasible for continuous panel designs, whereas PBB is restricted for discontinuous panel configurations as the SSC design. With PBB, panel-wise

analyses over the full blade span could be conducted efficiently compared to FINSTRIP and FEA.

The FINSTRIP tool was applicable for validation of cross-sectional mode shapes when the spar cap laminate was relatively thin and not designed as either continuous sandwich (CSC) or partly sandwich and thick laminate (SSC). This discrepancy might be caused by restrictions of the sandwich element [11] used in FINSTRIP when: (i) the sandwich consisted of relatively thick cover laminates, i.e. sandwich-thickness to core-thickness ratios of $c/h > 1.25$ [15], (ii) the sandwich layup's unsymmetry is disregarded [10], or (iii) the sandwich core from balsa wood had an in-plane stiffness in the order of the cover laminate stiffness such that the core contributes to the bending stiffness [10]. For these layup configurations FINSTRIP is evidentially not qualified as also concluded in [15].

FINSTRIP's deviation of the calculated eigenvalues (Table 2) from the linear finite element analysis (FEA) is far too high for a qualitative evaluation.

The results of this study can be seen as basis for further investigations considering the spar cap width as design parameter. Optimizing this parameter in terms of blade weight is required. In this paper we evaluated the possible design modifications only partially. With the assumptions of fixed shear web distance and the reduction of the modified cross section area, several alternative concepts for buckling avoidance were not considered.

Acknowledgments

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Corrigendum: A concept study of a carbon spar cap design for a 80m wind turbine blade

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Due to a software bug in FOCUS6 (version 6.2.7071.776) the content of the following sections should be replaced.
Table 2 should be replaced by:

Table 2. Buckling analysis tool comparison.

	Safety reserve factor SRF	
Critical section	Suction side	Pressure side
Critical radius [m]	23.6	17.4
Panel based buckling (PBB)	0.19	0.31
FINSTRIP	0.21	0.32
FEA (Linear bifurcation analysis)	0.22	0.31

Paragraph 2 in *3.2. Analysis Tool Evaluation* should be replaced by:
The evaluation is exemplary shown in Table 2 for the baseline blade (Figure 2c). The most critical section and radius for the two flap-wise ultimate load cases were used as benchmark. The PBB tool and FINSTRIP are close to the LBA based on FEA.

Paragraph 5 in *3.2. Analysis Tool Evaluation* should be replaced by:
For the baseline blade and the two developed concepts FINSTRIP revealed the correct buckling eigenvalues and modes. However, for the two developed concepts FINSTRIP revealed too optimistic buckling eigenvalues compared to FEA ($SRF_{\text{FEA}} \approx 1.00$), i.e. for CSC $SRF_{\text{FINSTRIP}} = 1.71$ and for SSC $SRF_{\text{FINSTRIP}} = 1.15$.

Paragraph 4 in **4. Discussion and Conclusions** should be replaced by:
FINSTRIP's calculated eigenvalues (Table 2) are close to the linear finite element analysis (FEA) and panel based buckling (PBB) when the laminate was relatively thin but respectively far too high to moderately too high for the spar cap layup of the continuous sandwich (CSC) and partly sandwich and thick laminate (SSC).