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Structural optimisation of composite wind turbine blade structures with variations of internal geometry configuration

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ABSTRACT

Structural optimisation techniques are frequently used as part of the design process for composite wind turbine blades. Most commonly this is achieved by modifying material placement within a standard structural design; less attention has been paid to the possibility of varying internal geometry to create novel structural configurations. In this work, a series of wind turbine blade designs with differing structural configurations have been created and compared to investigate the effect of allowing various aspects of the internal structural geometry to be varied. The geometry of the structural spar is thoroughly investigated by modifying the width of the spar caps, and the number and location of shear webs including the spanwise starting and ending locations. The location and extent of a trailing edge reinforcement are also considered, along with the material thickness distribution of the spar and trailing edge reinforcement. A series of five parametric 2D finite element models with geometry and materials placement variables were created and incorporated into a genetic optimisation algorithm. This method allows the optimisation process sufficient freedom to generate designs without being constrained by preconceived ideas of how the internal geometry should be configured. The optimum designs had mass reduced relative to the baseline by 3.5–7.4%. Structural analysis of the optimum designs revealed that the active constraint varied greatly between the different designs, and it is therefore recommended that a wider range of loading cases and constraints needs to be accounted for in optimisations that allow the structural geometry to vary compared to those that use a standard geometry.

1. Introduction

Modern wind turbine blades are large structures, with complex geometry and varying composite materials configurations including sandwich constructions. These factors complicate the design and analysis process as the number of design variables is large. In addition, wind turbine blades are subjected to a large number of aerodynamic loading cases and design constraints, which further increases the challenge. Most modern wind turbine blades have an internal structural configuration of the type shown in Fig. 1. The main structural function is performed by an internal spar: spar caps at the location of maximum thickness resist flapwise bending and one (Fig. 1a) or two (Fig. 1b) shear webs resist torsional loads. A small number of studies have considered structural configurations that vary from the standard design, for example Berggreen et al. [1] investigated the effect of adding a lightweight core layer to the spar caps. The result was improved buckling capacity at the expense of increased global deflection. Tarfaoui et al. [2] considered five different spar configurations with varying shear web placement for a 48 m blade for a 5 MW turbine, but did not investigate the structural implications of the different configurations, other than modal analysis. Other researchers used optimisation processes to develop novel structural configurations.

Structural optimisation is a technique frequently used in the design of composite wind turbine blades. Finite element models are commonly used for design verification, and may be easily modified to include parameters for various material layer thicknesses and fibre angles which can then be used as variables in the optimisation algorithm. In this manner, a feasible and manufacturable optimised design is fairly straightforward to obtain. There are a large number of examples of this type of optimisation in the literature, e.g. Grujicic et al. [3]. Less commonly, structural optimisation has been used to create novel structural configurations by modifying the geometry of the blade structure. Pirrera et al. [4] used 2D cross sectional analysis to determine the optimal location of the corners and layup of the walls of a spar. Each cross section was optimised separately. The optimised spar geometry had slanted shear webs, oriented in the direction of the applied load,

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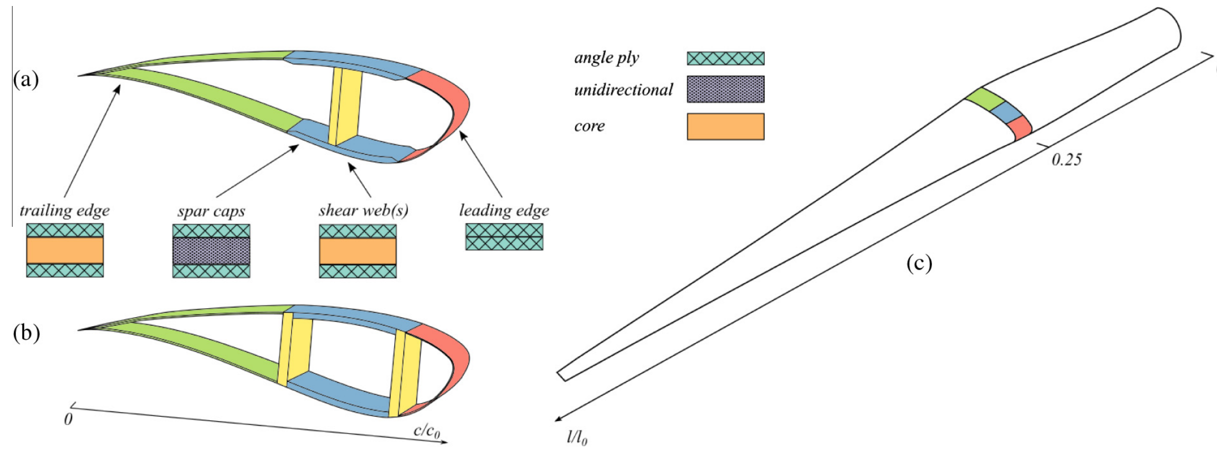

Fig. 1. Blade design: a – single shear web; b – double shear webs; c – external geometry.

and the spar was located closer to the trailing edge than in the standard design. Bottasso et al. [5] included a range of geometric variables such as chord and twist distribution along with material thickness variables in a combined aerodynamic and structural optimisation, which was performed in two stages. In the first "coarse" stage, a beam model was used with a large range of loading conditions and global design constraints. A shell model was used in the second "fine" stage to verify several local design constraints.

The selection of an appropriate optimisation algorithm is challenging for composite structural design problems that contain a large number of variables as well as a large and potentially complex design space. Most of the published literature used either a genetic algorithm (e.g. [4]) or a gradient-based algorithm (e.g. [5]) to drive the optimisation process. Genetic algorithms are able to find the global optimum within a complex design space, but are limited in the number of variables that can be used within reasonable limits on resource requirements and duration. Gradient-based algorithms on the other hand may use a larger number of variables but require computationally expensive numerical differentiations and therefore tend to be restricted to a smaller design space, and risk converging to a local optimum rather than the global.

Another approach to structural optimisation is topology optimisation, which is used to determine where material should be located within a structure in order to best resist the applied loads. For a 3D model, topology optimisation begins with the entire volume meshed, and then a prescribed proportion is removed in such a way as to minimise the objective function. Wind turbine blades are in some ways well suited to topology optimisation as the asymmetrical structure and complex loading makes it difficult to intuitively arrive at optimal layouts. However, topology optimisation does not readily account for realistic composite materials properties. The resulting structures are not manufacturable designs, and topology optimisations are therefore typically followed by interpretation by the designer and sizing optimisation to ensure that the full range of design constraints is met.

Joncas et al. [6] performed topology optimisation on a thermoplastic wind turbine blade segment, which produced a structure with wider spar caps further towards the leading edge than in the standard design, and the addition of a trailing edge reinforcement. This work was extended by Forcier and Joncas [7], who performed a topology optimisation of a longer, thermoplastic wind turbine blade section. Their results indicated the presence of rib-like features, and the subsequent sizing optimisation considered the number of shear webs and the addition of ribs. Buckney et al. [8,9] used topology optimisation on a 45 m blade structure. The resulting structure had trailing edge reinforcement at the root and middle sections and offset spar caps. The subsequent sizing optimisation was performed on a critical blade section, and assumed a structure with a trailing edge reinforcement in addition to the typical layout of two shear webs.

The presence and configuration of shear webs or ribs was an interesting aspect of the wind turbine blade topology optimisations cited above. In no cases did the shear webs clearly resemble those of a standard wind turbine blade structure, which have single or double continuous shear webs. In [6,7], the structure contained "rib-like" features, likely necessitated by the lower material stiffness used in that case. Single and non-continuous shear webs were present at various locations along the span, and in some locations there were no shear webs connecting the spar caps. The sizing optimisation in [7] investigated the presence of ribs and the possibility of a single or double shear web configuration although the location of the webs was not varied. The topology optimisation results in [8] also had unclear shear web configurations, mostly showing no connection between the spar caps at all, with sparsely-spaced "shear posts" in places, and material connecting the spar caps to the trailing edge reinforcement in others. However, in the sizing optimisation, a typical double shear web construction was assumed, so the design implications of the topology optimisation results were not fully investigated. The structural efficiency of two 2D blade sections was investigated further in [9], using a novel shape factor method. It was found that the presence of trailing edge reinforcement increased stiffness in the edgewise direction due to increased edgewise second moment of area as well as a larger product second moment of area relative to a conventional blade structure. The chordwise location of the shear webs was varied in [4], but the spanwise extent was not varied in any of the studies referenced here, or in any other published wind turbine blade design study, as far as the authors are aware. A trailing edge reinforcement in some form was present in all of the topology optimisations [6–8]. This was not included in the sizing optimisation in [7], but it was included in [8] and also in [5], although the location and extent was not considered in either.

This review of the existing literature indicates that the geometry of the wind turbine blade internal structural configuration has not yet been thoroughly investigated, and warrants further attention. Specifically, none of the design processes in the literature allowed sufficient freedom in the optimisation problem formulations to establish whether the short or absent shear web designs that were present in the topological optimisation results are beneficial in a realistic structural model. Likewise, the spanwise location of trailing edge reinforcement has not investigated in detail.