DEVELOPMENT OF AUTOMATED HIGH-FIDELITY FINITE ELEMENT MODELS FOR LARGE WIND TURBINE BLADES

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Abstract

In the final stage of the design of a wind turbine blade, finite element models are used to investigate the stress distribution in the blade under extreme loading conditions. This requires the development of a finite element model, which can either be done manually or in an automated fashion. Often finite element models contain coarse approximations in order to improve the modeling feasibility. Most models are made up from shell elements with top offset and do not contain the adhesive bonds. In this work a program is developed that is capable of generating a complete finite element model of a wind turbine blade. It is capable of representing the blade using shell elements at the outer mold layer (OML), shell elements at the mid surface or solid elements. It can include the adhesive bonds.

1. Introduction

The design of wind turbine blades to date is done using design codes employing simplified models. These are usually based on analytical or beam models. In this case, the whole cross-section is discretized into a single element. These models require very limited computation time, which is a requirement in the initial design phase of the blade, due to the large number of iterations which have to be performed. These models are also required for the aero elastic load calculation, for which codes such as HAWC2, Bladed or FAST and Aerodyn are commonly used.[1-4]. These codes are used to simulate the aero-elastic behavior of the blade under several hundreds of load cases, from which the most critical cases are derived. Such models are however unable to accurately predict the exact stress distribution throughout the blade. For that purpose detailed three dimensional finite element models are used. This is usually only done in a late design stage to assess that the design does not contain unforeseen stress hot spots and to check the buckling resistance of the structure.

A real life blade is typically built from sandwich materials and has a composite layup consisting of a very large number of plies. Consequently, adding all the detail of each ply in the layup to a finite element model one by one manually can be a very lengthy process. In practice, finite element models of wind turbine blades are often built manually or in a (semi)automated way, using software packages that allow users to build models using a graphical user interface (GUI)[5-7]. However, despite partial automation, most models incorporate a number of approximations which simplify the modelling process, at the cost of model fidelity.

In most cases simplifications are made in order to limit the preprocessing and computation time. While this loses correspondence with the actual blade design, including every detail would be highly time consuming and would result in pieces of geometry causing very small or high aspect ratio elements. Thus, some details are left out while others are approximated. Which details are incorporated and which are not is often up to the user, which can potentially lead to inconsistencies. Figure 1 shows a wind turbine blade and its corresponding beam and finite element models.

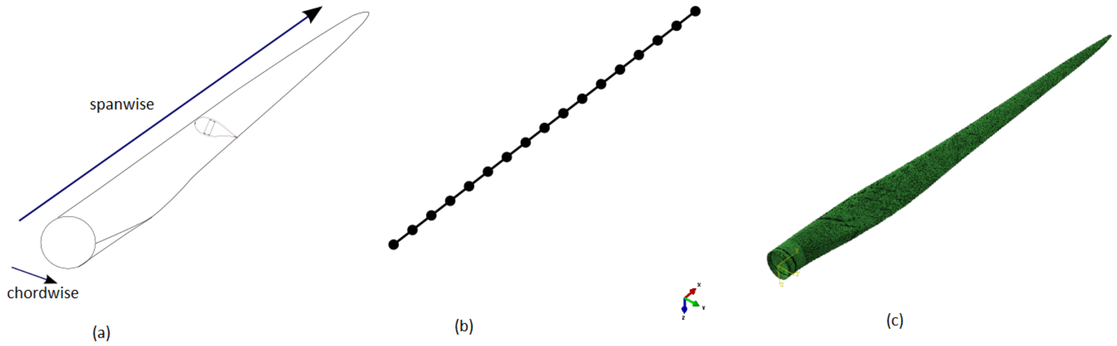

Figure 1: beam model, (a) schematic view of a wind turbine blade, showing spanwise and chordwise directions. (b) Equivalent beam model of a wind turbine blade. (c) 3d finite element model of the wind turbine blade

2. Finite element models of wind turbine blades

2.1. Approximations in wind turbine blade finite element models

Wind turbine blade finite element models can contain approximations occuring in all directions. In the spanwise direction, approximations are made for the exact starting and ending location of the plies. Multiple plies which drop off at spanwise distances close to each other in the actual blade design are merged together, to drop off at the same spanwise position. This makes the preprocessing easier by requiring less spanwise sections or partitions and allows for a less refined mesh. In the actual blade, a transition in layup is made to be very smooth since this ensures a gradual transition in stiffness. This is done to prevent stress concentrations and to avoid delaminations. Figure 2 gives an example of a ply-stack and how it is usually approximated.

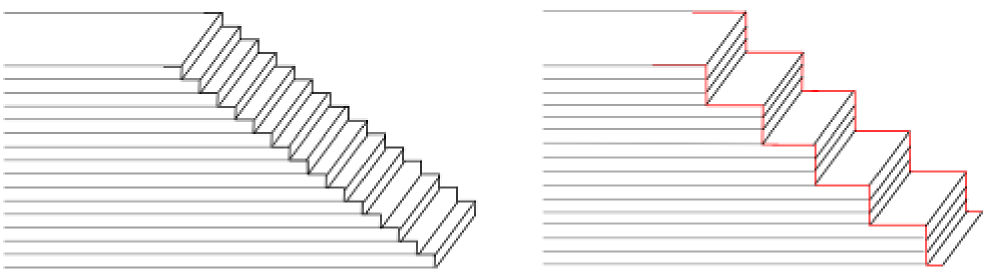

Figure 2: A schematic representation of a transition in laminate thickness. The left picture shows the thickness transition as it occurs in the actual blade, with each of the ply drop-offs spaced. The left picture shows an example of how the same thickness transition is usually modeled, with the ply drops grouped.

Along the circumference of a cross-section, the blade is usually subdivided into a fixed number of panels. The edges of the panels become the edges of multiple plies, which are in the vicinity of this edge. Nevertheless, this is an important approximation since it concentrates ply edges, resulting in more abrupt stiffness transitions. The position and size of multiple plies is approximated, depending on the number and precision of the panels. Another effect of the division of the blade into a series of lengthwise panels is that plies that have edges crossing over the edges of one or multiple panels are not incorporated in the model correctly. Such plies are nevertheless quite common. This is especially true if any additional reinforcements such as girders or externally applied layers (a so called wet-layup, which is applied after joining the different parts) that help join the different blade parts are present. Especially towards the trailing edge, these plies have edges that, in the model would cross-over other ply edges belonging to for example the edge of the core material. Figure 3 shows some reinforcements that are sometimes applied to a blade. It should be mentioned however that when the blade surface is split in panels, the panels are usually chosen so that the structurally most important features are incorporated best.

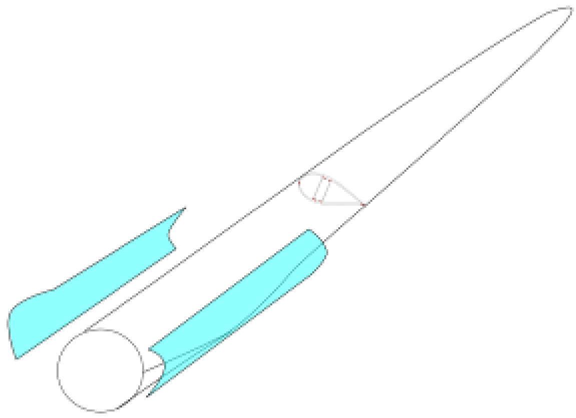

Figure 3: Schematic view of the wet layup that is applied to a blade after the parts have been joined together using adhesive bonds.

2.2. Wind turbine blade finite element modelling approaches

Most finite element models of wind turbine blades use shell elements with top offset. This allows the model to be built in a way that is similar to the way they are actually manufactured, starting from a mold that has the outer aerodynamic shape of the blade, towards the inside. It has been demonstrated however, that shell elements with top offset can give poor results when loaded in torsion [8]. This is mainly true when the elements have a high thickness to curvature ratio, which is the case for the elements in the region near the leading edge. Alternative modeling approaches to circumvent these issues have been suggested and tested.

One approach would be to position the nodes so that no shell offset has to be used. Yet, due to ply drop-offs, the thickness at every location is the sum of the thicknesses of a discrete number of plies. This means that an actual mid surface is discontinuous. While it is possible to connect the discontinuous mid-surfaces using tie constraints, it has been demonstrated that this leads to an increased stiffness in spanwise direction [9]. However thickness transitions within the laminate are usually very smooth. This makes a continuous mid-surface model a relatively good approximation.

Some researchers have tried to resolve the issues with shell elements with material offsets by using solid models [10-12]. These models are computationally much more expensive and are more difficult to obtain. Yet, besides having correct torsional behaviour these solid models also have the advantage that the inside surface is physically present. This allows adhesive bonds to be modelled much more accurately, since they can be attached directly to the inner surface and their properties and dimensions can correspond to what is physically present in the blade. Figure 4 shows schematic cross-sections of finite element models using shell elements with top offset, solid elements and shell elements on a continuous mid-surface.

Another solution that has been used is that in the regions that have a strong curvature, the thickness of the shell is reduced to a safe level and the stiffness is scaled proportionally [13].

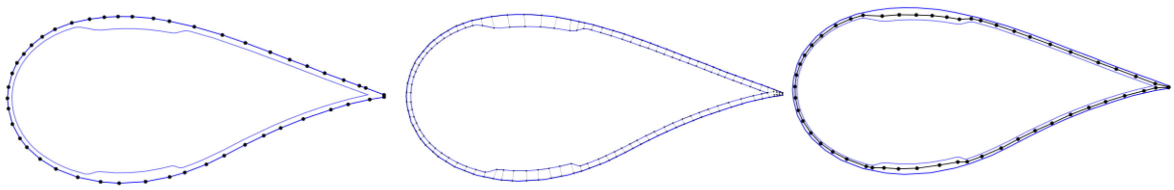

Figure 4: Schematic overview of cross-sections as they result from different modelling techniques: shell elements on the outer mould layer (OML) with offset; Continuum elements; shell elements on a continuous mid-surface.

2.3. Adhesive bonds in wind turbine blades

Most wind turbine blade manufacturers produce blades in multiple parts, which are infused, cured separately and then adhesively bonded together. At the leading edge, a joggle lap joint is typically used. At the trailing edge and between the pressure and suction side shells and the flanges of the shear webs a single lap joint is used. The bonds are made of an adhesive which has a stiffness that is significantly lower than that of the laminate. Figure 5 shows a typical cross-section of a modern wind turbine blade with the typical adhesive bonds. Usually these bonds are not included in the finite element models and only the mass they bring is accounted for. Mostly, the elements of the shear webs are directly attached to the nodes of the pressure and suction side shells and the two aerodynamic shells are connected at the leading edge by sharing nodes or by a tie constraint. This is because the inclusion of the adhesive bonds in the model is difficult. Since most finite element models have the elements positioned on the outer mold layer (OML), the inside surface of the blade is virtual and not physically present in the model. While it can be visualized by rendering the shell thickness, it cannot be used to attach the elements of the adhesive onto. This problem is sometimes circumvented by increasing the thickness of the adhesive so that the nodes fit onto the outer mold surface and by scaling the density and stiffness inversely proportionally and proportionally respectively [9].

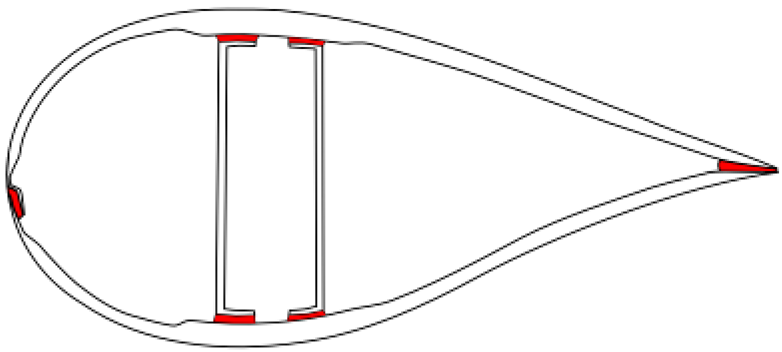

Figure 5: Typical cross-section of a wind turbine blade. The blade is comprised of multiple parts, the pressure and suction side shells and one or more shear webs. The different parts are held together by adhesive bonds at the leading edge, trailing edge and between the flanges of the shear webs and the pressure and suction side shells.

3. Proposed method for generating finite element models of wind turbine blades

A program has been developed that generates the complete blade finite element model starting from a description of the blade. For the geometry, normalised airfoil data files are used. Given the specific details of each station on the blades planform, such as values of the chord, twist, twist centre, offsets and rotations to the x,y and z-axis, the geometry of the blade is determined by lofting the profiles. This is achieved using b-spline interpolation.

Given the blade's layup and the requested spanwise mesh size, the lofted shape is intersected at a range of spanwise locations, resulting in a large number of spanwise cross-sections. On each of these cross-sections key locations are determined. These will form the edges of the plies in the specified layup. They can be specified based on any reference such as a plane, line, point or any specific location on the airfoil such as the leading or trailing edge. Each reference can be given an offset of a specific arc length on the airfoil shape. This is necessary to include the precise width of some of the plies since some, such as the girders, are usually made from rolls of material having a fixed width. Figure 6 demonstrates this using an example.

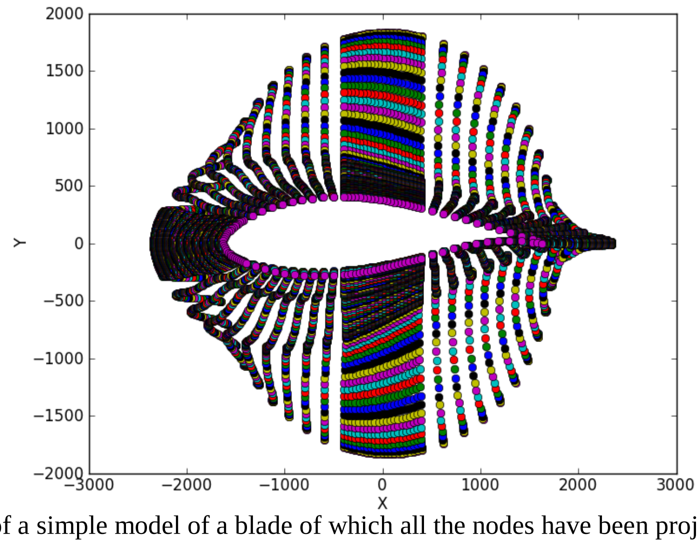

Figure 6: An example of a simple model of a blade of which all the nodes have been projected to the XY-plane. The main girder on the suction side has edges determined by the intersection with two YZ-planes at a fixed distance apart, while the edges of the main girder on the pressure side are determined by a fixed arc length along the circumference from the intersection of an YZ-plane. As a consequence, the main girder on the pressure side seems wider if the profile it is applied to is less curved.

Once the geometry and key locations are determined, some necessary corrections are applied in order to improve the mesh. Essentially, key locations are merged at the sections where ply edges cross-over each other and where they are closer to one another than a user specified proximity. This allows ply edges to cross-over smoothly and prevents very sharp or high aspect ratio elements from being formed. Figures 7 and 8 show key locations on finite element shell models and how they can cross-over or how they are merged. At the same time this proximity tolerance can be used to coarsen the model in a consistent manner.

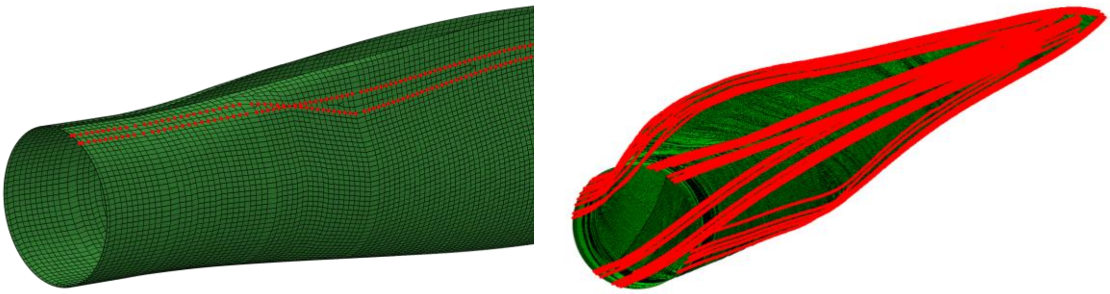

Figure 7: left: An example of a coarse demonstration mesh showing two ply edges (red) crossing over each other. Right: A demonstration model with all the ply edges coloured red.

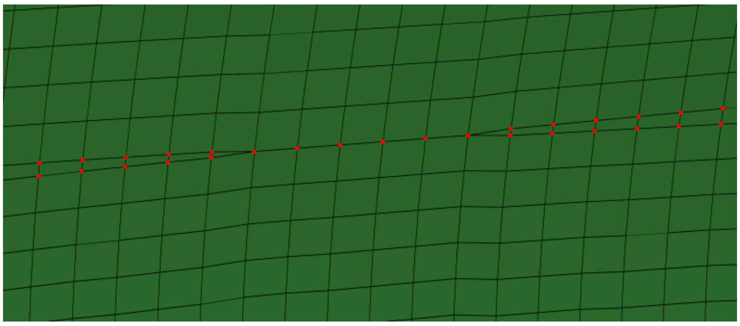

Figure 8: An example of the proximity tolerance merging key locations together, avoiding high aspect ratio or very sharp elements.

When this is completed, the interpolating nodes on the OML are formed and a mesh can be generated. The mesh size can vary along the length of the blade and can be different for the spanwise and chordwise direction. In case a model with shell elements on the mid-surface is requested, the nodes are offset from the OML towards the inside onto the mid-thickness surface. Similarly, a continuum model is formed by extruding the mesh on the OML towards the inside and towards the outside if necessary.

Element sets are formed for each ply and node sets for each key location. After that everything is written to an input file which can be imported in Abaqus/CAE where the element sets are used to apply the layup in an automated fashion. Figure 9 shows an example of such an element set that is used to assign a ply in the composite layup. When a continuum model is generated, there is the option of having layers of mesh that are chamfered. These can be used to model the core material. Chamfers can be used both in the chordwise and in the spanwise direction making it possible to include the gradual thickness transitions throughout the blade.

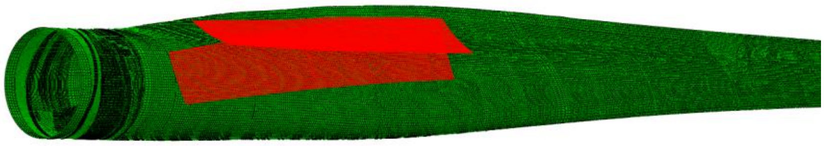

Figure 9: An example of an element set that is used for the layup application. Elements belonging to the set are indicated in red.

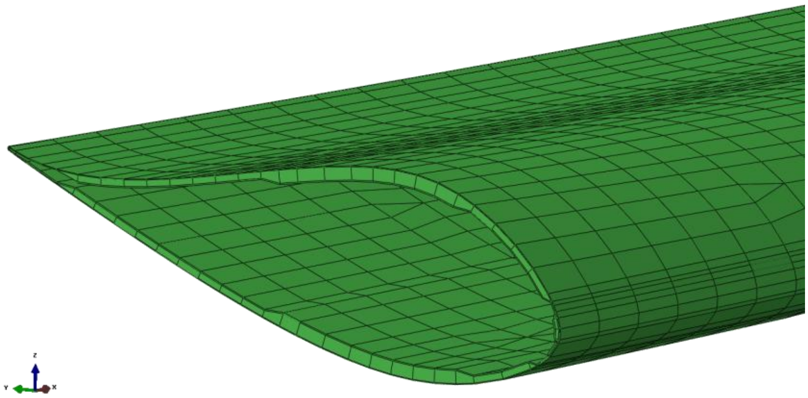

Figure 10: A typical cross-section of a model obtained with the program

The adhesive bonds can be included in the continuum models. In that case, an inside surface is physically present. The bonds are modeled using solid elements that have been assigned a continuum cohesive section, which allows the modeling of adhesive with just one element through thickness.

While a simulation using a model of a complete blade made of continuum elements is computationally expensive, the program can also be used for the generation of detailed continuum sub-models. In a sub-modeling approach, the solution of a global model (the whole blade) is used to extract the boundary conditions for a sub-model (a portion of the blade). This would make it possible to obtain detailed results in specific critical regions of the blade while keeping computational times acceptable.

4. Conclusion

Finite element models of wind turbine blades often include rather coarse approximations. Since most models use shell elements with top offset, the inside surface is not physically present. Therefore the shear webs are often attached to the outside surface and the adhesive bonds are not represented in a way that corresponds to reality. The only option to completely avoid these issues and to represent everything in a way that corresponds to reality is the use of a detailed continuum model. A program has been developed that allows the generation of shell models with and without offset as well as continuum models, which can incorporate the adhesive bonds. The generated models can be used as global models or as sub-models to obtain detailed results at critical areas.

References

[1] Larsen, T.J. and A.M. Hansen, *How 2 HAWC2, the user's manual*. 2007, Risø National Laboratory Technical University of Denmark Roskilde.

[2] DNV_GL. *Bladed*. [cited 2014; Available from: http://www.gl-garradhassan.com/en/software/GHBladed.php.

[3] Jonkman, J.M. and M.L.B. Jr., *FAST User's Guide*. 2005, National Renewable Energy Laboratory: Golden.

[4] Laino, D.J. and A.C. Hansen, *USER'S GUIDE to the Wind Turbine Aerodynamics Computer Software AeroDyn* 2002, National Renewable Energy Laboratory: Salt Lake City.

[5] Bonnet, P.A. and G. Dutton, *Parametric Modelling Of Large Wind Turbine Blades*, in *2007 Abaqus UK Regional User Meeting*. 2007. p. 211 - 225.

[6] Berg, J.C. and B.R. Resor, *Numerical Manufacturing And Design Tool (NuMAD v2.0) for Wind Turbine Blades: User's Guide*. 2012, Sandia National Laboratories.

[7] *FOCUS6 - The Integrated Wind Turbine Design Suite*, K.C. WMC, Editor. 2012.

[8] Laird, D.L. and F.C. Montoya, *Finite Element Modeling of Wind Turbine Blades*, in *43rd AIAA Aerospace Sciences Meeting and Exhibit*. 2005, American Institute of Aeronautics and Astronautics: Reno, Nevada.

[9] Branner, K. *Torsional performance of wind turbine blades - Part 2: Numerical validation*. in *16th International Conference on Composite Materials*. 2007. Kyoto, Japan: Japan Society for Composite Materials.

[10] Bottasso, C.L., et al., *Structural Optimization of Wind Turbine Rotor Blades by Multi-Level Sectional/Multibody/3DFEM Analysis*. 2012, Dipartimento di Ingegneria Aerospaziale: Milano, Italy.

[11] Fedorov, V.A., et al., *Investigation of Structural Behavior due to Bend-Twist Couplings in Wind Turbine Blades*, in *NAFEMS NORDIC Seminar: „Simulating Composite Materials and Structures "*. 2010: Esbjerg, Denmark.

[12] Ashwill, T., *Sweep-Twist Adaptive Rotor Blade: Final Project Report*. 2010, Sandia National Laboratories: Albuquerque.

[13] Griffith, D.T. and T.D. Ashwill, *The Sandia 100-meter All-glass Baseline Wind Turbine Blade: SNL100-00*. 2011, Sandia National Laboratories.