

Chapter 3

Process Simulations for Predicting Quality of Composite Wind Turbine Blades

Konstantine A. Fetfatsidis^{*1}, James A. Sherwood²

Department of Mechanical Engineering, University of Massachusetts Lowell
One University Ave, Lowell, MA 01854, USA

^{*1}Konstantine_Fetfatsidis@uml.edu; ²James_Sherwood@uml.edu

I. INTRODUCTION

Wind turbines are often installed in high-altitude and off-shore locations, where wind energy can be converted into electrical power most efficiently. Furthermore, because the power output of a wind turbine is proportional to the area swept by the rotor, there is strong motivation to make the wind turbine blades as long as is physically reasonable from manufacturing, shipping, installation and field-service perspectives. Subsequently, as blade lengths increase, weight, stiffness and strength considerations become more important. The blades must be designed such that they are a good compromise between being aerodynamically efficient and structurally sound.

Continuous-fiber reinforced composite materials are the material of choice to manufacture wind turbine blades. Despite the advantages these materials exhibit over metals, such as high stiffness-to-weight and strength-to-weight ratios and corrosion resistance, blades continue to be overdesigned due to uncertainties in material behaviour and potential defects formed during manufacturing, and thereby the weight and the costs of the blades increase unnecessarily. Prototypes are often built and tested to understand how the materials behave and what effect the defects have on blade reliability and performance. However, this trial-and-error approach is time consuming and expensive. Additionally, the issue of scalability arises when studying the effect of defects in one blade and attempting to predict how the same defect would affect a much larger blade. The cost of blade testing is prohibitive to testing a large number of blades, and therefore, does not provide a sufficient sampling size when quantifying the effect of defects. As wind turbine blades increase in size to capture more wind, there is likewise potentially going to be increases in operating and maintenance costs. A credible design tool capable of simulating the manufacturing process and predicting the structural quality and performance of composite blades would be valuable to evaluate blade designs for weight, performance and cost.

In an effort to keep the cost of wind energy competitive, blade manufacturers often turn to relatively inexpensive fabrication processes such as hand layup and resin transfer moulding. More recently, a vacuum assisted resin transfer moulding process known as the Seemann Composites Resin Infusion Moulding Process (SCRIMP®) is used in which a vacuum compacts several layers of continuous-fiber reinforced composite fabrics and a core material, e.g. balsa, in a mold, and then pulls liquid resin into the dry layup (Fig. 1).

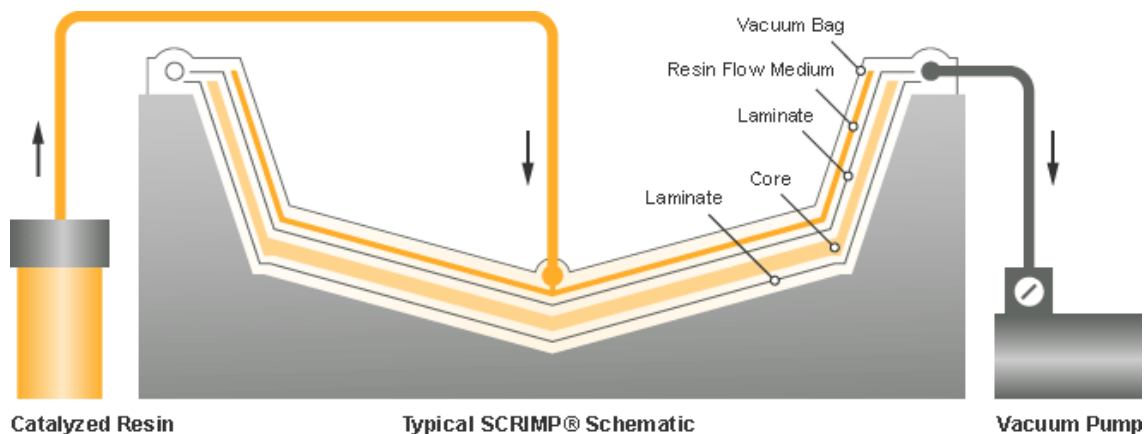


Fig. 1 Typical SCRIMP® Schematic [1]

While several types of continuous fiber reinforcements exist, Non-Crimp Fabrics (NCFs) are particularly attractive due to

the lack of yarn undulations that exist in woven fabrics. The absence of undulations, i.e. crimp, provides better in-plane mechanical properties than the woven fabrics, and the use of through-thickness stitching in NCFs allows for handling stability and delamination toughness [2]. The yarns of NCFs can be aligned in prescribed directions, and the layers held together by a through stitching. Because the stitching is a multi-axial warp knitted stitch, the in-plane shear stiffness in the direction parallel to the stitch can be significantly higher than the stiffness in the direction perpendicular to the stitch [3, 4].

The manufacturing of strength-driven designs with low-cost processes often leads to defects that compromise the overall structural behavior of the blades. These defects are typically in the form of in-plane yarn waviness, and/or out-of-plane waves due to layers of fabric bunching together during the vacuum compaction of the fabric plies. Subsequently, these waves may either fold onto adjacent layers to create wrinkles that can lead to delaminations (Fig. 2a), or the area beneath the waves can be resin rich, creating a weak spot at that location along the blade (Fig. 2b). These defects reduce the fatigue life of the blades and increase costs associated with repairs and replacements. It is estimated that blade failures contribute to 20% of wind turbine downtime [5]. While there are several ongoing efforts dedicated to improving blade reliability, it is believed that improved manufacturing of wind turbine blades offers the best return on investment [6].

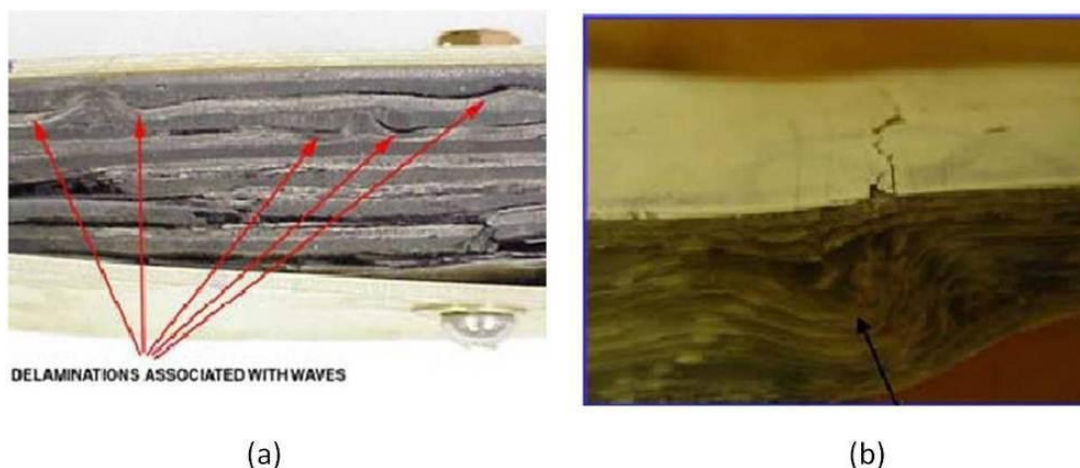


Fig. 2 Typical manufacturing-induced defects in composite wind turbine blades [6]: (a) delaminations, (b) out-of-plane wave defect

High-fidelity forming simulations offer a relatively quick and inexpensive method for studying what manufacturing parameters lead to the formation of defects, and what consequences those defects may have on the blade's structural properties. Many of the currently available design tools that account for fabric deformation use simplified kinematic algorithms to predict how the yarns in a fabric will deform to conform to the blade mold geometry. Areas of high in-plane shear are used to determine where a fabric may buckle out-of-plane. However, these kinematic models do not consider the mechanical behaviour of the fabric, and thus, cannot predict if the fabric may actually buckle out-of-plane or develop in-plane waviness during vacuum compaction, thus changing the yarn orientations. The mechanical behaviour of the fabric includes the in-plane shearing and tensile behaviours, bending stiffness and friction between contacting surfaces. By experimentally characterizing the mechanical behaviour of the fabric and resin materials used in a blade design and incorporating the respective material behaviours in user-supplied material models, a finite element simulation can provide insight into the formability of a given fabric to a given geometry. The simulation is also able to capture fabric stresses, and changes in yarn orientations, including in-plane and out-of-plane yarn waviness, as the fabric layers conform to the shape of the mold during layup (by hand or automated layup) as well as during the vacuum compaction (debulking) stage of the manufacturing process.

II. MODELING FABRIC REINFORCEMENTS

A discrete approach utilizing standard beam and shell elements in conjunction with a user-defined material subroutine with a hypoelastic description can be used to model composite fabric blanks. The use of these common element types allows the approach to be extended to popular finite element packages with user material subroutine capabilities such as Abaqus, LS-DYNA and ANSYS, without the need for any special-purpose element types or special software. Such an approach is attractive to industry because the method uses commercially available finite element codes.

This discrete approach captures the deformation and reorientation of the individual yarns and therefore can be referred to as a discrete mesoscopic approach (as opposed to microscopic, i.e. the scale of the individual fibers, which would be too CPU-intensive). In a biaxial NCF model, a unit cell is defined as the distance between adjacent yarns and is represented by the size of a 2-D shell element, as illustrated in Fig. 3 [7]. This shell element defines the fabric shear stiffness. For many fabrics, the in-plane shearing is the main mode of deformation, resulting in a change of the angle between the initially orthogonal yarns. Four 1-D beam elements simulating the yarns of the fabric are merged to the perimeter of the 2-D shell, and these beam elements capture the tensile and bending stiffnesses of the fabric. This discrete unit-cell approach can similarly be extended to a variety of fabric architectures including a balanced plain-weave fabric (Fig. 4a) and a balanced twill-weave fabric (Fig. 4b).

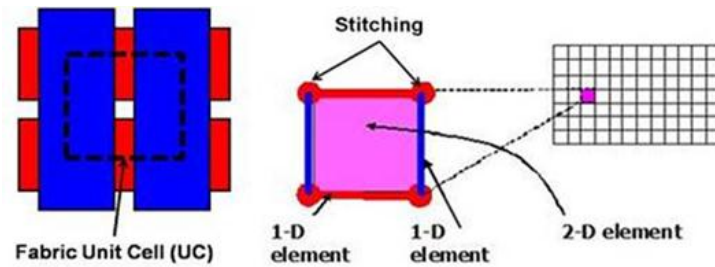


Fig. 3 Principle of the discrete mesoscopic modeling approach using a combination of 1-D and 2-D elements [7]

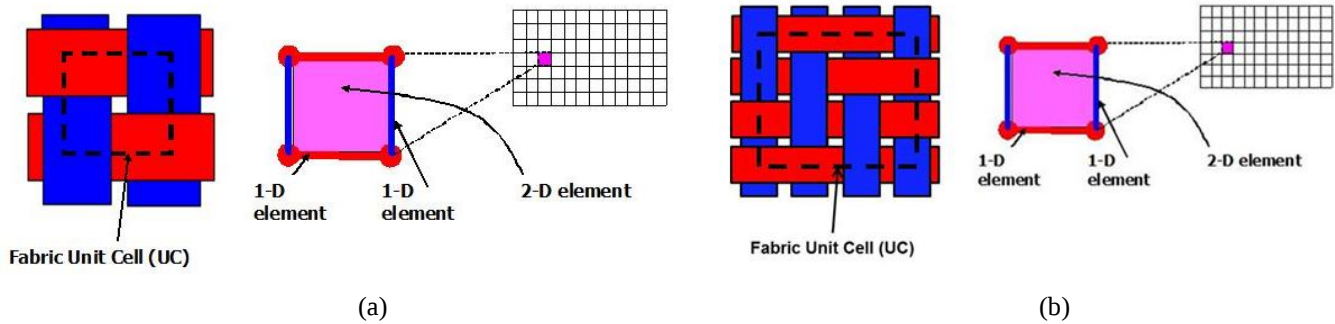


Fig. 4 Principle of the discrete mesoscopic modeling approach for (a) a balanced plain-weave fabric and (b) a balanced twill-weave fabric

In the biaxial NCF unit cell shown in Fig. 3, the effect of the through stitching is captured by the pin-jointed connections at the nodes. However, in other types of NCFs, it may be necessary to incorporate additional 1-D beam or truss elements to explicitly model the stitching (Fig. 5) and to capture the effect(s) that the stitching may have on the fabric behaviour. For example, in a unidirectional or biaxial NCF, out-of-plane deformation is likely due to a combination of in-plane shear, tension, and bending stiffness. However, in many double-bias NCFs, the stitch pattern can cause out-of-plane buckling earlier than it would if the same yarns were simply woven together.

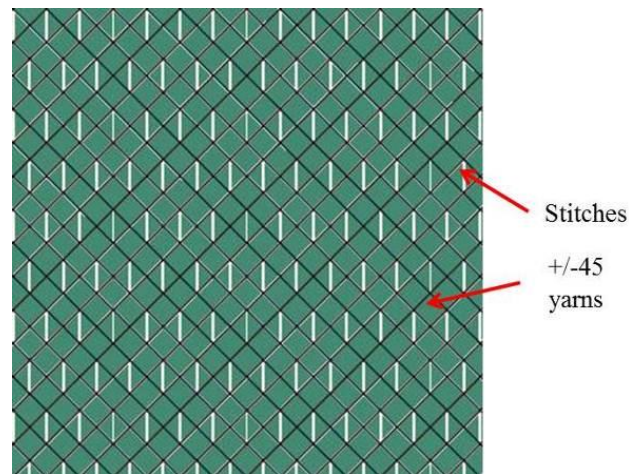


Fig. 5 FE model of a double-bias NCF with cross-stitch pattern

Furthermore, the pin-jointed unit-cell approach fails to capture the slipping of yarns in many NCFs. The so-called NCFs are given their name due to the absence of the crimp that exists in woven fabrics. The lack of crimp improves the drapability over complex curvatures because the yarns are not interlocked and are able to move more freely via sliding to conform to the geometry. However, depending on the geometry, the amount of sliding can negatively impact the design of the part by introducing large voids between yarns and thereby compromising local stiffnesses. Currently, hand layup of the fabric reinforcements in many wind turbine blades is like “patch-work”, where the fabrics are cut and oriented such that the yarns run mostly in their intended directions with little sliding. However, as manufacturers strive to automate the process, yarn sliding could become more of a concern, and it is therefore important to be able to capture this behavior in the model to provide valuable feedback into the design process. The discrete mesoscopic modeling approach could be modified to allow for yarn slipping by placing the yarn crossovers at the centre points of the shells rather than at a node, as demonstrated in Fig. 6. This layout of the unit cells is such that no yarn is “pinned” to any other yarn, thereby allowing sliding of the yarns relative to one another.

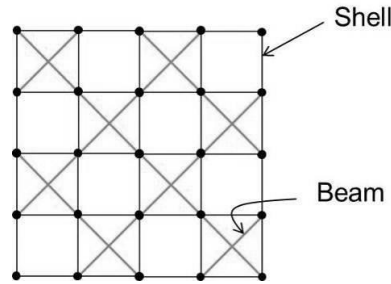


Fig. 6 Discrete model that allows for NCF yarns to slide/separate [8]

Regressions of experimental data are used to conclude empirical models that are then implemented as user-defined material subroutines to capture the mechanical behaviour of the fabric material in the finite element solver [9]. Finite element models of the various tests are completed to validate that the fabric model behaviour can be properly simulated using the finite element method. Additionally, the finite element method allows for contact to be defined between layers of fabric and therefore friction is experimentally measured using a friction-test apparatus [10].

A. Unit-Cell Scaling

The unit cell of each fabric is determined by measuring the number of individual yarns per meter of fabric. These unit-cell measurements assist in concluding the size of the shell elements used in the finite element fabric model. However, relative to the size of a wind turbine blade, if the unit-cell size of the fabric was used, it would lead to a relatively fine mesh of the fabric finite element model and would make the model computationally expensive. Therefore, the unit cell size of each fabric layer can be scaled by some factor in an effort to coarsen the mesh associated with each fabric layer to reduce computation time. It is important to conduct parametric studies to confirm that the credibility of a forming analysis will not be compromised by the “coarse” mesh and thereby reduce the applicability of the model. An example of such a parametric study is illustrated by the forming of a fabric into a hemisphere in Fig. 7. A path is drawn from the center of the hemisphere (apex) to the region of maximum in-plane shear, indicated by the red contours. The shear angles along this path are compared between the measured unit-cell size and the scaled unit-cell size. Fig. 8 shows that if scaled too much, the accuracy of the analysis is compromised.

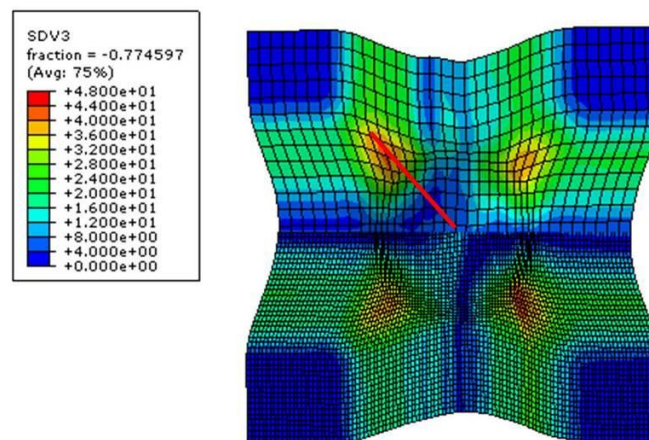


Fig. 7 Forming simulation showing in-plane shear angle contours with the original unit-cell size mesh (bottom) and a scaled (x3) mesh (top)

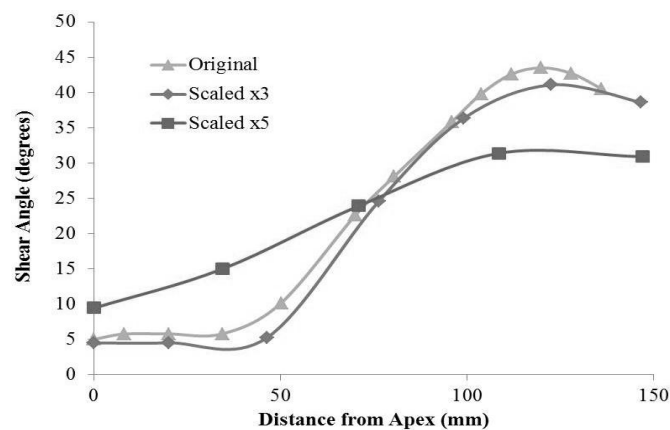


Fig. 8 Comparison of shear angles between refined, coarse (x3), and excessively coarse (x5) meshes in formed hemisphere model

Consider the root section of a 9-meter wind turbine blade. When forming a layer of fabric into this root section, the amount by which the unit-cell is scaled can limit how well the fabric conforms to the mold geometry. Fig. 9a shows the shear angle contours of a layer of biaxial NCF pressed into the root using the fabric's actual unit-cell size. However, this unit-cell size must be scaled to make a simulation of the entire blade model practical, considering the number of layers included in the 9-meter blade. Fig. 9b scales the unit-cell of the same fabric by a factor of 3 and the resulting shear angle contours correlate well to the original unit-cell model. However, if scaled by a factor of 5 (Fig. 9c) the fabric is not able to conform to curvatures in the mold geometry and causes element surfaces to unrealistically penetrate each other during contact, as indicated by the circled area.

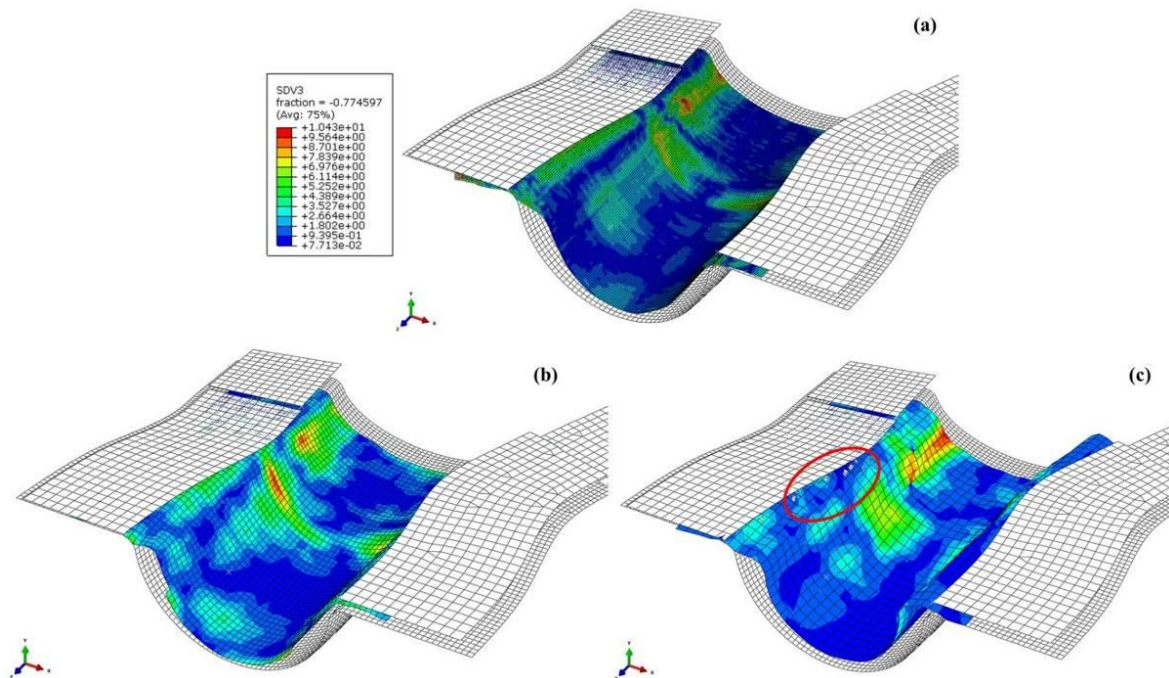


Fig. 9 Forming of a fabric layer in the root section of a 9-meter wind turbine blade using the unit-cell size of a biaxial NCF (a) actual, (b) scaled (x3) and (c) excessively scaled (x5)

B. Simulating the Manufacturing Process

Generally, the manufacture of a composite wind turbine blade consists of hand-laying several layers of fabric and core material into a low-pressure (LP) and high-pressure (HP) mould, followed by a vacuum pressure to first compact (debulk) the layers and then to infuse each mold with resin. The fully cured LP and HP sides are then bonded with a spar to create the full wind turbine blade. In the finite element model for the manufacture of a blade, the hand layup of fabric layers is simulated by using a rigid core (punch) to press the fabric into a fixed, rigid mould (Fig. 10). The punch is allowed to move only in the vertical direction. Additionally, rigid binders which can translate vertically, provide in-plane tension in the fabric to prevent folding and sliding of the fabric layers as they are pressed into the mold by the punch.

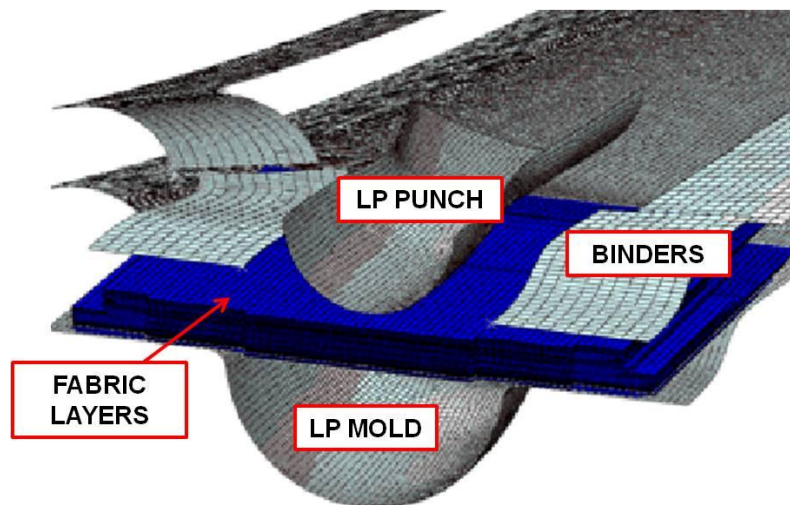


Fig. 10 Punch pressing fabric layers into the LP mould (binders are used to provide in-plane tension in the fabric)

Typically, an explicit formulation (Abaqus/Explicit) is used to perform this type of forming simulation due to its computing time efficiency, its relatively robust contact algorithms and its option to account for the mechanical behavior of the fabrics via user-defined material models. To save computation time, layers are pressed into each mould in groups. After initially being pressed into the mold using the rigid punch, additional pressures are subsequently applied to press the layers tightly into each mold. After all of the layers of fabric have been pressed into the molds, the compaction of the fabric layers is simulated by applying a pressure equivalent to atmospheric pressure directly onto the surface of the top layers. It is believed that during this stage in the manufacturing process, fabric layers may bunch together to form out-of-plane wave defects that eventually compromise the performance and reliability of wind turbine blades [11]. Because the formation of wave defects most likely occurs during the hand layup and vacuum compaction stages of the manufacturing process, the resin infusion process is not simulated. Instead, it is assumed that once the layers of fabric have deformed, the resin is evenly distributed across each mold with a fiber volume fraction of 55%, which is typical for the blades manufactured using the SCRIMP® process [11]. After the LP and HP molds are individually modeled, they are bonded together with tie constraints, resulting in the full blade model.

III. EXPERIMENTAL CHARACTERIZATION TECHNIQUES

When required to deform over double-curvature geometry, the yarns of a non-crimp fabric may be pulled in a certain direction to conform to the features of the geometry. However, the absence of yarn undulations such as those in woven fabrics allows for very little stretching of the fibres at the mesoscopic scale during deformation. Thus, the in-plane shearing of the fabric yarns becomes the principal mode of deformation. This in-plane shearing results in a change of the angle between the initially-orthogonal yarns of a biaxial non-crimp fabric. In addition, the fabric bending stiffness and the friction between fabric layers can result in unwanted in-plane and out-of-plane waviness and/or folds in the fabric. To capture these modes of deformation using the beam and shell elements in the fabric model, the mechanical behaviour of the fabric must be characterized.

C. Shear-Frame Testing

The standard test for measuring the shear behaviour of fabrics is the shear-frame test [12], also known as the trellis-frame test, or the picture frame test, as shown in Fig. 11. In this test, a fabric specimen is clamped with the yarns typically directed perpendicular and parallel to the four clamping bars. Shear deformation is developed by fixing one corner and applying a tensile load on the opposing corner. The shear-frame test assumes that the shear angle is uniform over the entire sample and equal to the frame angle. These two assumptions have been verified for woven fabrics via Digital Image Correlation (DIC) [13, 14]. The deformation of the fabric in the shear-frame test is shown in Fig. 12.

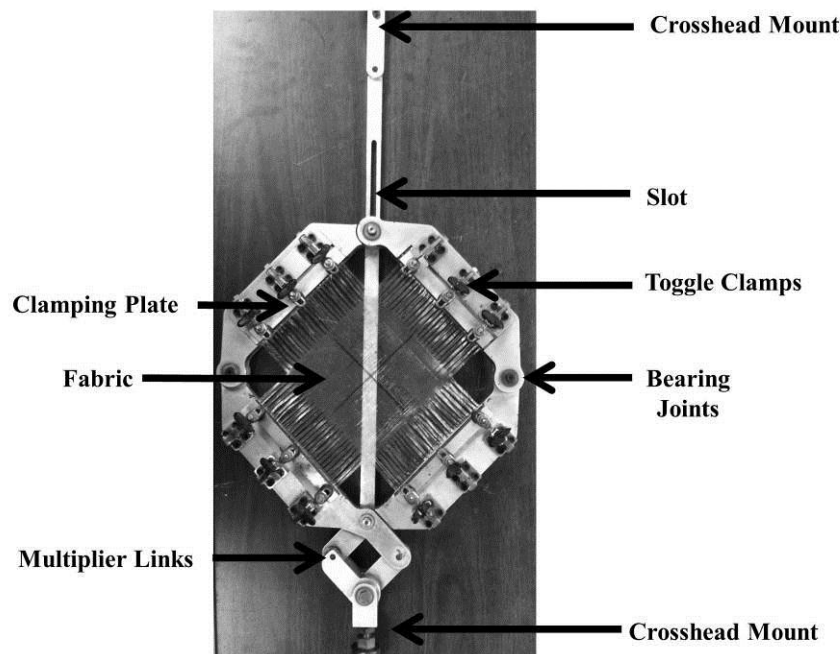


Fig. 11 Shear-frame test

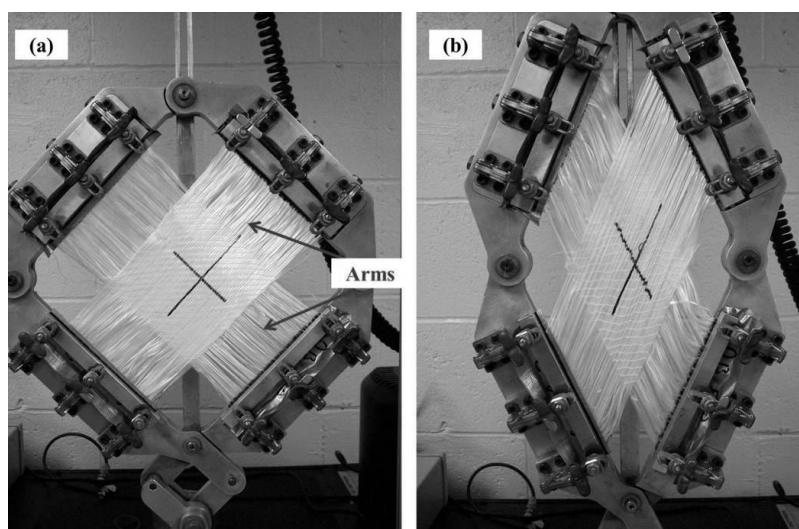


Fig. 12 Deformation of shear-frame test (a) before deformation and (b) after deformation

The cross yarns are removed in the arms of each sample to minimize edge effects and allow the yarns to rotate freely relative to each other. Consider a unidirectional NCF shown in Fig. 13. This fabric is mounted in the shear frame in only one direction, because there are no perpendicular yarns. Without the presence of “arms” in the sample, an out-of-plane wave pattern is observed across the width of the test sample and extending along its whole length when pulled in the frame (Fig. 13a). The out-of-plane deformations are caused by the clamped fabric edges, which do not allow individual fibers to slide relative to each other. The stitching between the yarns can be partially cut to create 50-mm arms at each end of the sample (Fig. 13b). The addition of arms allows for in-plane sliding of the yarns in the middle of the sample, as shown in Fig. 13c, and significantly reduces out-of-plane deformation [15].

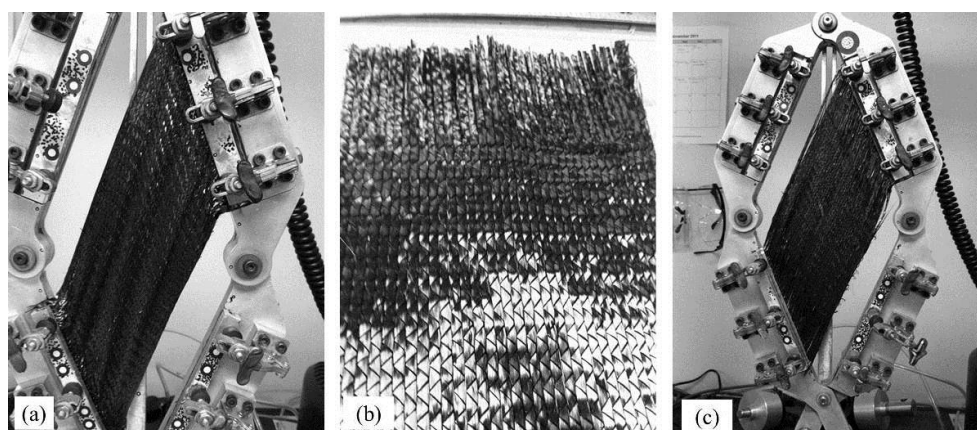


Fig. 13 Unidirectional NCF loaded in the shear frame (a) without arms. The absence of arms causes out-of-plane deformation due to edge effects, which necessitates the (b) addition of arms in the sample. The arms (c) significantly reduce the out-of-plane deformation

Woven fabric samples are typically loaded and unloaded several times in the shear frame before measuring the shear stiffness. The intent of this mechanical conditioning is to reduce the effect of undesired tension in the yarns that could arise from a misalignment of the yarns [12, 16]. The mechanical conditioning also allows for increased repeatability from sample to sample even though in reality, a fabric will be taken off of a roll and laid into a mold without any mechanical conditioning. Typically for a given sample, the measured loads during the first shear-frame test run will be higher than those of the subsequent runs, in which the load curves appear to be very similar. Non-crimp fabrics, however, are more sensitive to mechanical conditioning because of the through-thickness stitching which can tear after repeated loading and unloading of the same sample. This stitching plays a very important role in the shear stiffness and in the wrinkling characteristics of a NCF and cannot be neglected. Therefore, NCFs should not mechanically condition, and the first load-displacement curve should be taken as the representative shear deformation curve.

The measured load is converted to a force that is normalized by the length of the frame. This normalization accounts for various shear-frame sizes that may be used. The normalized force can then be divided by the thickness of the fabric sample to obtain the shear stress. Similarly, the shear angle can be determined by knowing the length of the frame, length of the fabric sample, and the measured displacement data. This angle can then be converted to a logarithmic shear strain, which is consistent with the shear strain definition used by the finite element code. After testing a minimum of three samples, the average shear stress and logarithmic strain are calculated and plotted with error bars of one standard deviation.

A typical load-shear angle curve from a biaxial NCF is shown in Fig. 14. The yarns are initially orthogonal to one another. Upon initiation of intra-ply shear deformation, the yarns begin to rotate and possibly to slip relative to one another. The shear stiffness steadily increases as the yarns continue to rotate and compress against each other, thus increasing the friction between adjacent yarns. As the yarns continue to rotate, an angle referred to as the locking angle is reached where the yarns are no longer able to compact easily and the shear stiffness increases rapidly. In addition to a significant increase in stiffness, deformation beyond the locking angle can also cause the fabric to buckle out-of-plane, as the deformation mode becomes a combination of shear, yarn compaction and tension. The locking angle is determined from the intersection of two lines tangent to the load-shear angle curve.

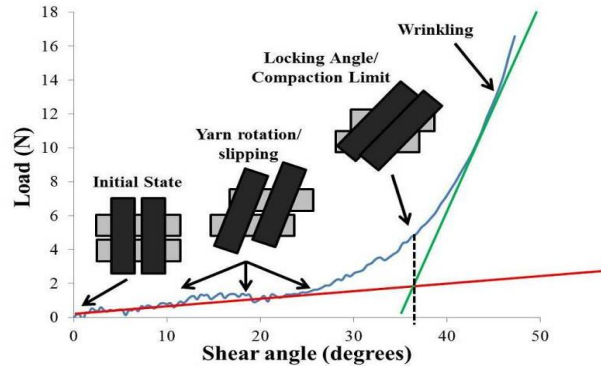


Fig. 14 Load-shear angle curve with schematics of shear behaviour for a biaxial NCF

After all of the stress-logarithmic strain plots have been generated, polynomial fits are made to these curves. These functions are implemented into the finite element code via its user-defined material subroutine, which for Abaqus/Explicit is VUMAT, to capture the shear behaviour of each fabric. Abaqus/Explicit uses rate-independent constitutive equations, also called hypoelastic laws, to model large deformation and strains. Stresses are updated using the following equations:

$$\sigma_{ij}^{t+1} = \sigma_{ij}^t + \Delta\sigma_{ij}^{t+1} \quad (1)$$

$$\Delta\sigma_{ij}^{t+1} = C_{ijkl} \Delta\epsilon_{kl}^{t+\frac{1}{2}} \quad (2)$$

where $\Delta\sigma_{ij}^{t+1}$ is the stress increment at time step $t+1$, C_{ijkl} is the constitutive matrix and $\Delta\epsilon_{kl}^{t+\frac{1}{2}}$ is the midpoint strain increment obtained from the integration of the strain rate tensor. The custom constitutive models obtained through regressions of experimental data and implemented into the VUMAT subroutine are linked with the overall solver to update the stress (Eq. 2). The strain increment, $\Delta\epsilon_{kl}^{t+\frac{1}{2}}$, is given by the solver to VUMAT that subsequently returns the corresponding stress increment to the solver. The stress update is made in the local reference frame for the element, i.e. a co-rotational frame that rotates with the element. The summation of the strain increments gives a logarithmic (or true) strain in the principal-stretch directions. Details associated with the constitutive equations as they pertain to the 1-D and 2-D elements of the current unit-cell model are provided in [9].

A finite element model of the fabric shear-frame test, including the “arms” of the specimens, is generated to ensure that the 2-D shell elements are accurately capturing the shear stiffness of each fabric (Fig. 15a). The arms are modeled using 1-D beam elements, and the frame is modeled using four aluminum trusses. The constants that define the tangent shear modulus are obtained by deriving the polynomial fits of the experimental stress-logarithmic strain curves and are defined in the Abaqus input file material card. The model correlates with the assumption of pure shear in the fabric sample (Fig. 15b).

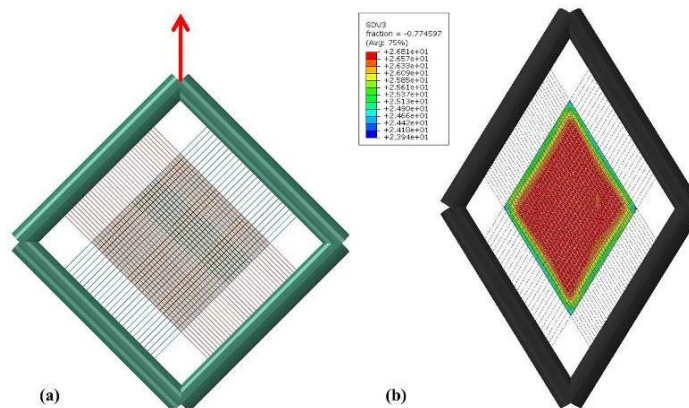


Fig. 15 Finite element model of (a) the shear-frame test and (b) the resulting uniform shear angle contours

D. Tensile Testing

As fabric is pressed into a mould, certain yarns may exhibit high tensile stresses as they bridge undulated regions of the geometry, i.e. peaks and valleys. These high tensile stresses can ultimately cause the yarns to break, leading to a poor-quality part. High stresses can be used to indicate local areas where fiber breakage could be a problem. Furthermore, failure criteria could be implemented into the beam elements of the fabric model to cause them to visually break. Therefore, to characterize the tensile mechanical behaviour of the yarns, uniaxial tensile tests are performed on individual yarns extracted from each fabric. To prevent slipping at the pneumatic grips (Fig. 16a), tabs are created by consolidating small pieces of Twintex® commingled glass/polypropylene woven-fabric (Fig. 16b).

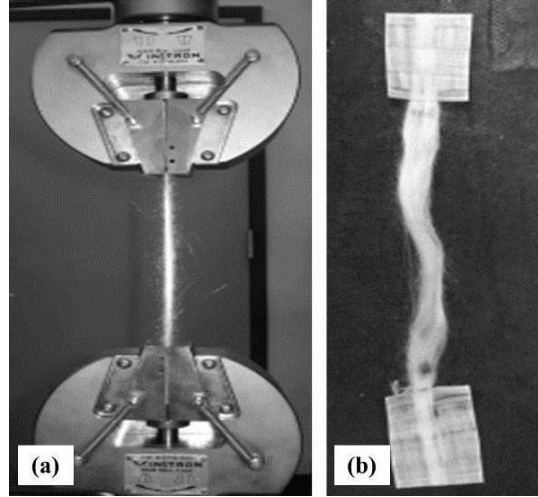


Fig. 16 Tensile test setup with (a) pneumatic grips and (b) Twintex® tabs to prevent yarn slippage

The tensile tests quantify the fracture load (Fig. 17a) and modulus of the yarn. The modulus of each yarn is obtained from the slope of the associated stress/true-strain curve (Fig. 17b), where the stress is determined by dividing the measured load by the effective cross section of the yarn, A_{eff} . This effective cross section of the yarn is determined based on the linear density of the yarn ρ_{linear} and the fiber material density ρ_{mat} :

$$A_{eff} = \frac{\rho_{linear}}{\rho_{mat}} \quad (3)$$

The true strain is used to again be consistent with the finite element code:

$$\varepsilon = \ln\left(1 + \frac{l}{l_0}\right) \quad (4)$$

where l is the measured length of the sample and l_0 is the initial length.

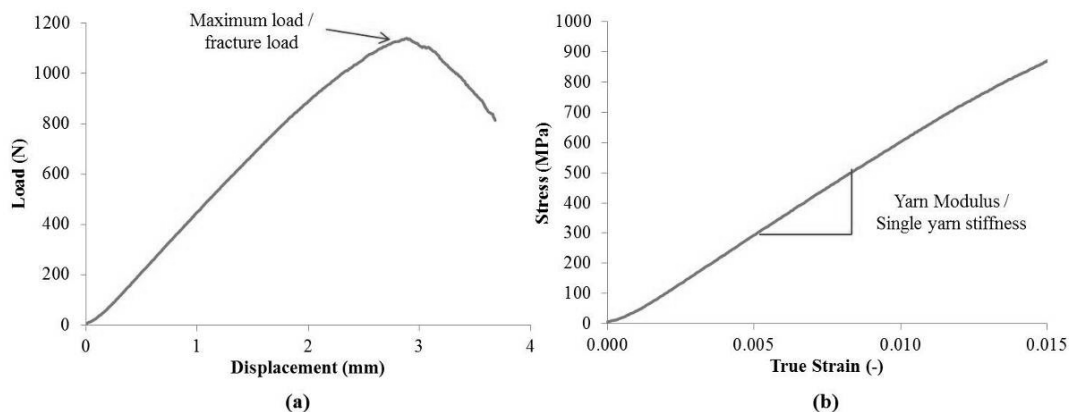


Fig. 17 Yarn tensile testing resulting in (a) a typical load-displacement curve and (b) the determination of the fabric tensile behaviour from the yarn modulus for a typical yarn

Abaqus/Explicit applies Eq. (2) to the definition of the 1-D beam element material behaviour, where C_{ijkl} is the tangent tensile modulus, or yarn modulus. A single yarn is modeled using a set of beam elements and pulled uniaxially. The slope of the stress-true strain curve is determined from the model and is compared to the yarn modulus obtained experimentally to ensure that the tensile stiffness is being accurately captured in the finite element fabric model.

E. Bending Stiffness Test

To use the finite element method for predicting the formation of in-plane and/or out-of-plane waviness during the manufacture of composite wind turbine blades, the overall mechanical behaviour of the composite fabric reinforcements must be thoroughly defined. The in-plane shearing behaviour is often used as an indicator via the “locking angle” as to when wrinkles may develop in the form of in-plane and/or out-of-plane waves. As yarns rotate relative to one another, they eventually reach a point where they can no longer rotate in-plane and must buckle out-of-plane. However, it has been shown that simply relating wrinkling to the shear angle is not sufficient. The formation of wrinkles and/or waves depends on the combination of in-plane shear, tension and bending behaviours of the fabric [17]. Thus, it is important to characterize the bending stiffness of the fabrics.

When characterizing the dry fabric bending stiffness, a cantilever “beam” method is often used [18], where the fabric is allowed to bend due to its own weight (Fig. 18). However, depending on the length of the sample, the effective direction of the distributed load on the sample changes due to the large deformations, and thus, a single value for the fabric bending stiffness cannot be concluded for all lengths despite efforts to compensate for the effect of gravity. An alternative method for characterizing the bending stiffness is to align the length of the beam with gravity and thereby reduce the nonlinear loading effects [19]. Fabric samples are clamped at one end and hung vertically. A horizontal load is applied to displace the tip of the fabric a known amount. This load is applied by attaching masses to a string tied to the tip of the fabric sample (see Fig. 18).

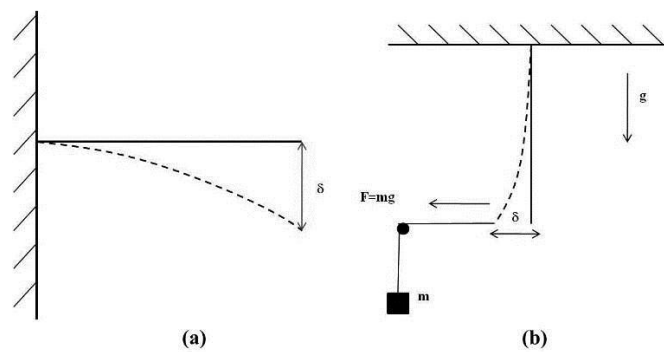


Fig. 18 Schematic of (a) cantilever experimental setup and (b) hanging-fabric bending stiffness setup

With the effective fabric length positioned in the clamp, various tip displacements are applied using an appropriate load, and a digital image of the fabric is captured. Individual data points are generated along the fabric length (Fig. 19a) and plotted (Fig. 19b).

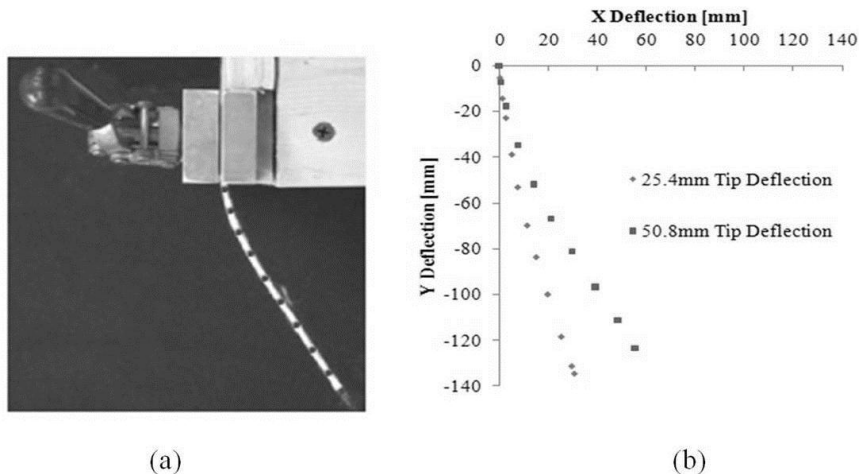


Fig. 19 Postprocessing of experimental data including (a) generation of x and y data points and (b) plotting of data points

Finite element models similar to the experimental fabric samples are used to calibrate the fabric bending stiffness. The bending stiffness is defined per yarn and is therefore assigned to each of the 1-D beam elements in the fabric. Equivalent tip displacements are prescribed in the models, and a range of bending-stiffness values are used to replicate the experimental profile shape of the sample. While several values of bending stiffness may lead to a similar profile shape, the force required to displace the tip a known amount is compared to the experimental force to ensure that the correct bending stiffness is being used in the model. Note that for the effective bending stiffness as used here the unit for moment, M , is N-mm and for curvature, κ , is mm^{-1} . Thus, the bending stiffness M/κ defined in the finite element model is given as N-mm^2 . As a means of verifying that the bending stiffness is valid, the bending stiffness is applied to models with different tip displacements and different fabric sample lengths (Fig. 20).

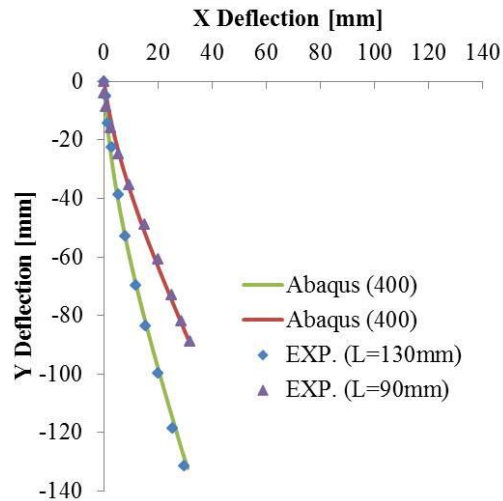


Fig. 20 Comparison of experimental data to FE model of a biaxial NCF for varying tip displacements and fabric lengths

As mentioned previously, the formation of wrinkles and/or waves depends on the combination of in-plane shear, tension and bending behaviours of the fabric. It is certainly possible to predict defects based on the in-plane shear and tension behaviours alone. However, the bending stiffness is needed to describe the wrinkle/wave shape. For example, compressing a fabric sample model from two sides will yield a different number of out-of-plane waves with different amplitudes depending on the magnitude of the bending stiffness. A much stiffer fabric will result in fewer waves with greater amplitude (Fig. 21a) than a fabric with a low bending stiffness (Fig. 21b).



Fig. 21 FE model of a fabric sample compressed from each side with (a) high bending stiffness and (b) low bending stiffness

In the unit-cell discrete modeling approach, the 1-D beam elements carry the bending stiffness of the fabric yarns. The bending stiffness is assigned to the beam elements' section properties. Without explicitly defining the bending stiffness as part of the beam section properties, finite element codes will by default consider the product of the elastic modulus, E , and the area moment of inertia, I , of the elements to define the bending stiffness. This default definition is typically much higher than the measured bending stiffness.

F. Friction Testing

As layers of fabric are laid into the LP and HP moulds of a wind turbine blade, on top of other layers of fabric and the core material, their ability to deform and develop in-plane and out-of-plane waviness depends highly on the friction between adjacent surfaces. Often, a tackifying spray is used to increase the friction between layers of fabric during hand layup. Therefore, it is important to capture the effect of this increased friction in the simulation of the manufacturing process.

Friction between contacting surfaces can be measured using an apparatus similar to that developed in [10]. This apparatus consists of a fabric holder that is sandwiched between two platens. The bottom platen is fixed while the top platen provides a normal force, N , onto the fabric clamped inside the holder. The holder then pulls the clamped fabric from between the two platens and the tensile force, T , is measured. The effective coefficient of friction, μ_{eff} , can be obtained by:

$$\mu_{eff} = \frac{T}{2N} \quad (5)$$

where the normal force N is multiplied by a factor of two to account for the two contacting surfaces. When plotting the effective coefficient of friction versus the pull-out distance (as shown in Fig. 22), a sharp peak is initially observed, representing the static coefficient of friction or the frictional force needed to be overcome to initiate motion. This peak then decays exponentially to a somewhat steady-state value of the friction coefficient referred to as the dynamic coefficient of friction. The value of the normal force is chosen such that the pressure on the fabric sample in the holder is equivalent to the atmospheric pressure applied by the vacuum during the compaction stage of the manufacturing process.

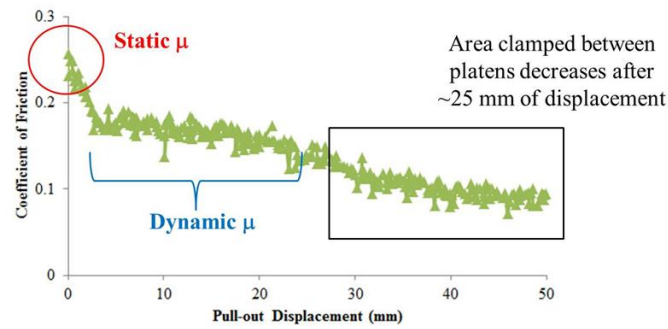


Fig. 22 Typical friction-test curve for determining the static and dynamic coefficient of friction

While the pressure from the vacuum will be constant during the manufacturing process, the interlaminar slip velocity can vary as a function of position and the degree of forming. To explore whether or not the dry Coulomb friction varies with velocity, the fabric samples can be pulled at different rates. Fig. 23 shows the resulting static and dynamic coefficients of friction between two dry fabrics at two pull-out velocities (i.e., 2 mm/s and 25 mm/s). The error bars denote one standard deviation. In this particular case, the friction was shown not to be rate dependent.

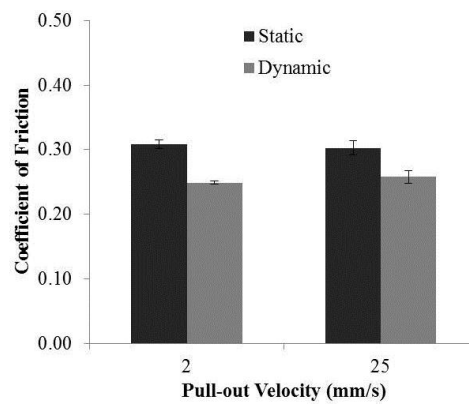


Fig. 23 Coulomb friction between carbon unidirectional and glass biaxial NCF as a function of pull-out velocity

Exponential decay model:

The static coefficient of friction defines the force necessary to initiate slipping between contacting surfaces. Once motion is initiated, the coefficient of friction generally drops to a lower value known as the dynamic coefficient of friction. Most commercially available finite element codes have a built-in static-dynamic exponential decay function (Eq. 6) that can be used to define this transition from the static to the dynamic coefficient friction,

$$\mu_{eff} = \mu_d + (\mu_s - \mu_d) e^{-\beta \dot{\gamma}} \quad (6)$$

where μ_s is the static friction coefficient, μ_d is the dynamic friction coefficient, β is the decay constant and $\dot{\gamma}$ is the slip rate. The decay constant defines the transition rate from zero velocity to final velocity (static to dynamic friction coefficient), as shown in Fig. 24. This relationship can thus be used in forming simulations to define the frictional behaviour between the various contacting fabric layers.

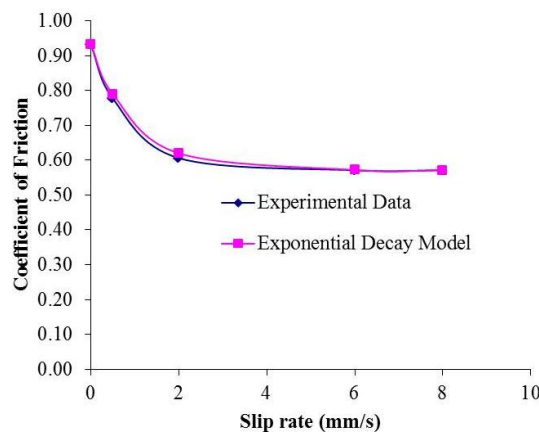


Fig. 24 Determination of the decay constant for static-dynamic exponential decay model

IV. PROCESS SIMULATION RESULTS

With the mechanical behaviour of the NCF reinforcements defined, forming simulations are conducted to explore the deformation of the fabrics, specifically the reorientation of the fabric yarns, and the fabric stresses during the hand layup stage of the manufacturing process. These simulations serve as a design tool to determine the number of layers and fabric orientations for drapability as well as for structural stiffness. While the fabric layers of most blades are currently placed by hand, the hand layup process can be loosely simulated by using a rigid mould paired with a matched core. These rigid tools are generated by dividing a solid CAD model of the blade into two parts to represent the LP and HP moulds (Fig. 25).

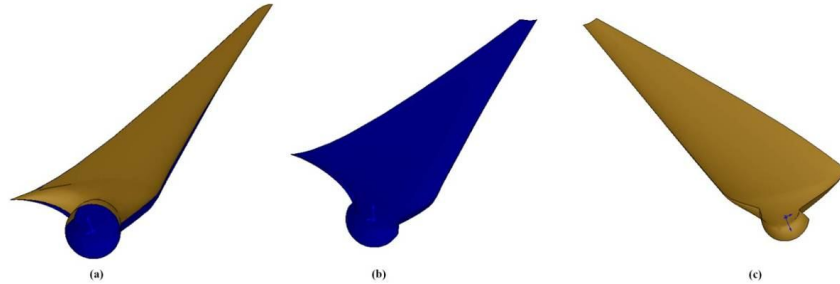


Fig. 25 CAD model of (a) 9-meter blade split into (b) LP mould and (c) HP mould

The rigid mould geometries are scaled down based on the radius of the root sections to create cores that could accommodate the thickness of the layers that would be pressed into each mould (Fig. 26). The moulds and cores are meshed with enough resolution of rigid shell elements to maintain smooth curvatures. Fig. 27 shows that without sufficient resolution, the mold surfaces would be jagged and the fabric layers would subsequently conform to those jagged surfaces.

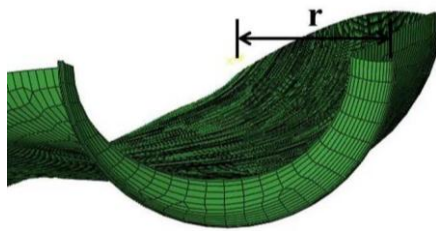


Fig. 26 Scaling of rigid cores for forming simulations

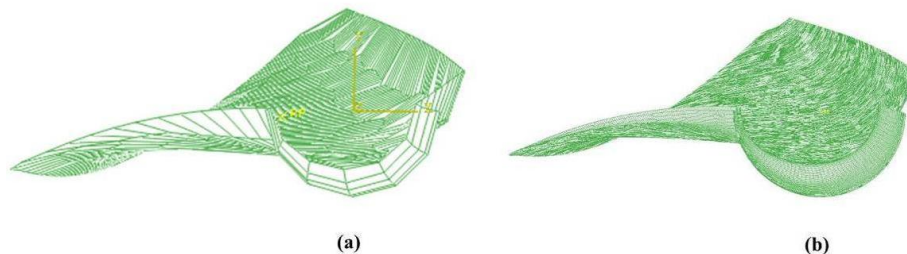


Fig. 27 Blade tooling meshed using rigid shell elements with (a) insufficient resolution and (b) sufficient resolution

To provide a smooth surface finish, a gelcoat typically covers the entire inner mould surfaces. This gelcoat is then covered by a mat of random chopped fibers, followed by a few additional NCFs. The deformation of these initial fabric layers is insignificant and defects are not likely to form in these layers [11]. However, the thickness of these layers is considered in the finite element model by using the built-in Composite Ply feature in Abaqus. The ply-stack plot shown in Fig. 28 shows the thickness and the fiber orientations of each of the first four layers.

With the thickness of the first few layers accounted for, the placing of the root layers is simulated next. During the manufacturing process, fabric layers are laid into a mould individually by hand. However, to simulate the placing of layers individually, the core would need to be changed each time to account for the changing thickness due to additional plies. Therefore, to save time, all of the fabrics are pressed into the root section of each mould simultaneously, and the core is scaled accordingly to account for the thickness of all of the root layers. To prevent folding and sliding of the fabric layers as they are pressed into the mould, flanges are added to the molds with matching rigid binders to provide in-plane tension in the fabric layers. This in-plane tension is analogous to the hand stretching of the fabric layers as they are manually positioned in the mold during the layup process. Because of ply drops in the root section, the effective overall thickness tapers down as viewed from the base of the blade looking to the tip, and thus the binders are segmented (Fig. 29b) to maintain binder contact along the tapered plane, as shown in Fig. 29a. Otherwise, a continuous binder would provide in-plane tension in the thickest section but would not induce such tension in areas where the thickness had decreased.

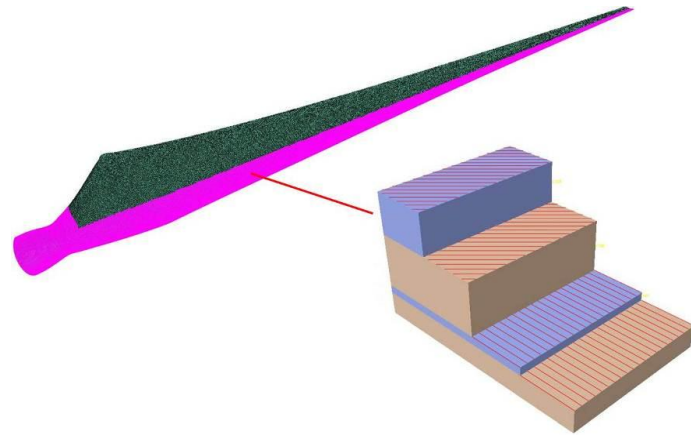


Fig. 28 Ply-stack plot of first four layers laid over the initial gelcoat

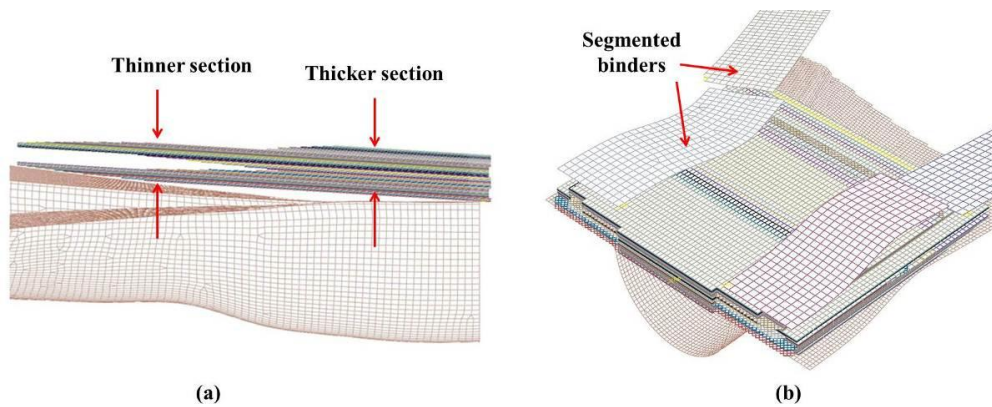


Fig. 29 Forming simulation with (a) varying root-layer sizes requiring (b) segmented binders

In addition to the flanges and binders added to the molds to accommodate the “automated” manufacturing process, the intersection area between (Fig. 30a) the trough of the moulds and flanges is rounded (Fig. 30b) to prevent convergence issues that could arise as elements attempt to wrap around what would otherwise have been sharp edges as shown in Fig. 30a. To keep the curvature of the rounded edges smooth, the mesh of the mold in Fig. 30b is also refined.

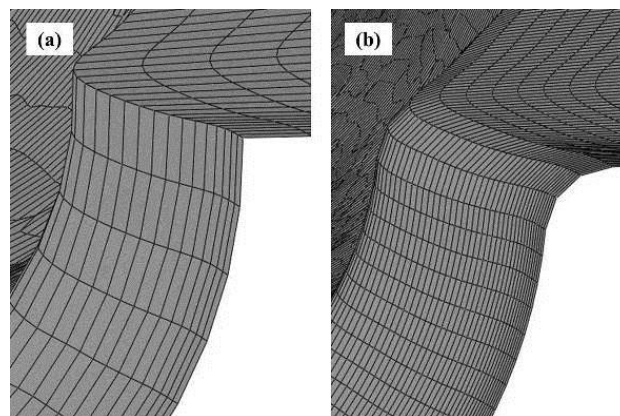


Fig. 30 Flanges added to rigid mould with (a) sharp edges changed to (b) rounded edges to allow fabrics to drape more easily

After the simultaneous forming of the root layers, the moulds with the flanges and binders are replaced by the moulds without the flanges. Pressures are applied to the surfaces of the root layers preceding the first spar cap layers to press them tightly into the molds. Once sitting firmly in the mold, the nodes of those root layers are fixed into place, as shown in Fig. 31a, and the spar-cap layers are formed using a combination of rigid cores (Fig. 31b) and additional pressure (Fig. 31c). Note that a multi-piece core is used because the thickness at the skin of the blade is much less than that at the root section and a single-piece core would not be able to press the spar-cap layers fully into the mould in the skin section. Pressure could be applied uniformly over the entire spar-cap surface or over different regions such as the root section shown in Fig. 31c, depending on how well the layers were pressed into the mold by the rigid cores.

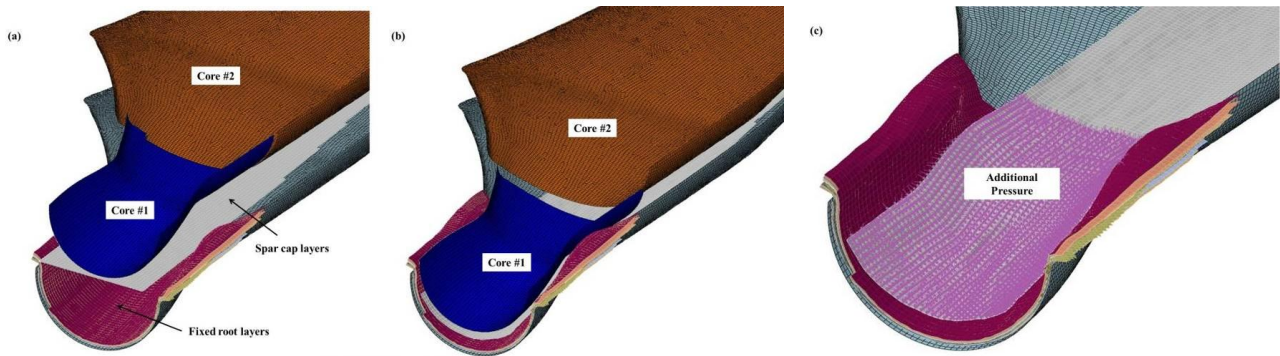


Fig. 31 (a) Forming of spar cap layers using (b) rigid cores and (c) additional pressure

In cases where the low shear stiffness of a fabric leads to the distortion of some shell elements (Fig. 32a), tensile forces can be applied to the edges of the fabric in an effort to straighten the elements (Fig. 32b). Subsequent pressures can then be reapplied to press the fabric down into the mould. This combined step of in-plane tension and downward pressure is analogous to the manipulation of the fabric done by hand by operators on the manufacturing floor and to what would need to be done if the process were to be automated.

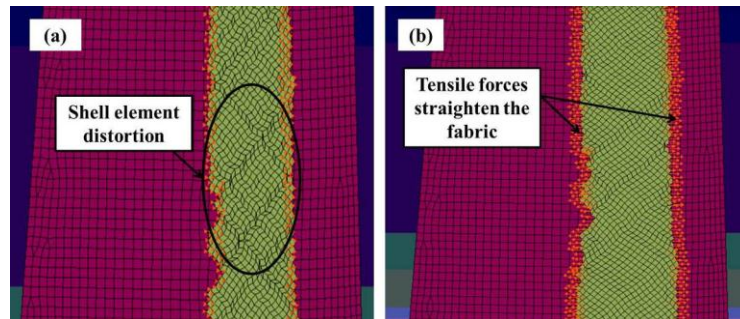


Fig. 32 (a) Forming of a double-bias spar-cap layer leading to element distortion; (b) In-plane tension is applied to straighten the fabric

For this particular 9-meter blade model, additional root layers follow the first few spar cap layers. In a similar approach, those root layers are pressed into each mould until the next group of spar-cap layers. Those spar-cap layers are then formed using the same approach presented for the first few spar-cap layers. The resulting LP and HP molds are shown in Fig. 33.



Fig. 33 Formed layers in (a) LP mould and (b) HP mould

During the forming simulations, the fabric stresses of each individual layer are examined to determine if any problematic areas exist as a result of the fiber reorientations and stretching. In particular, in-plane shear angle contours are observed to see if any yarns have trellised beyond the locking angle that might lead to out-of-plane buckling. Also, the tensile forces in the yarns are examined to indicate if any yarns are in danger of breaking. The limits of the shear angle contours are based on the locking angles determined from shear-frame tests, and the limits of the tensile force contours are based on the yarn fracture loads determined via tensile tests on individual yarns.

Fig. 34a shows the shear angle contours in a biaxial HP root layer with the maximum shear angle set to the locking angle of 36° . For the most part, the yarns remain oriented in their intended directions, as indicated by the blue regions and the annotations. However, despite little in-plane shearing, the contours still indicate that the shearing is not uniform throughout the part. Structurally, a zone-based or ply-based modeling approach could not account for the nonuniform shearing without the use of knockdown factors or by breaking the zone into many smaller zones, thereby making the defining of the property variations a very tedious task.

Note in Fig. 34b that the yarns of a double-bias fabric also did not shear significantly in the root section. While the double-bias fabrics do not necessarily have a locking angle, as defined for the biaxial fabrics, the contours in Fig. 34b show that the yarns did not deviate much from their intended $\pm 45^\circ$ orientations. However, some slight in-plane waviness is observed, as shown in the zoomed-in view of the double-bias fabric in Fig. 35.

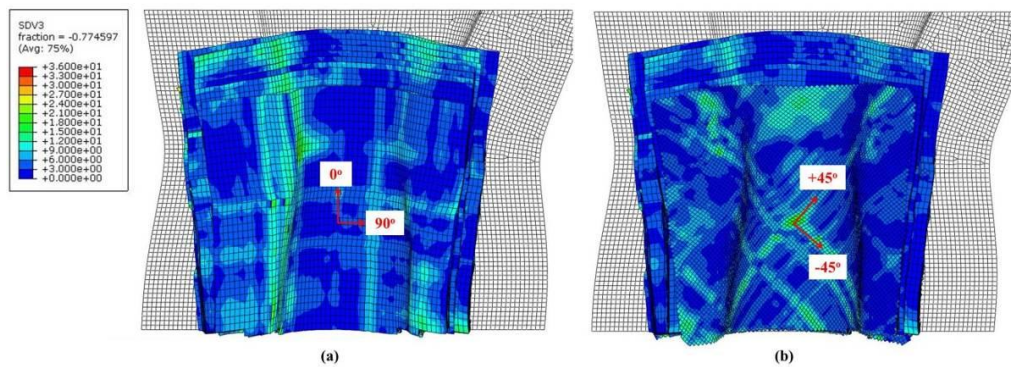


Fig. 34 In-plane shear angle contours in (a) 0/90 biaxial NCF and (b) +/-45 double-bias NCF

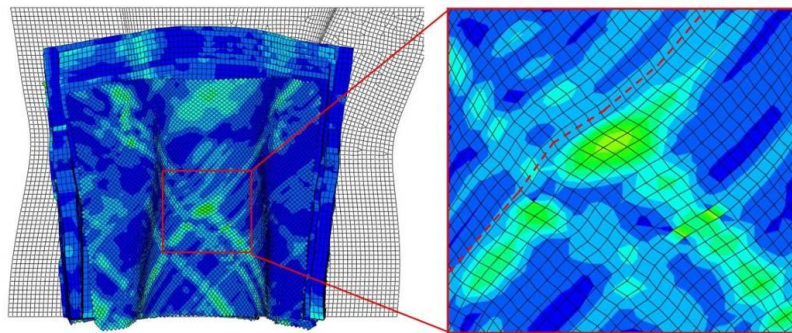


Fig. 35 Zoomed-in view of double-bias NCF showing slight in-plane waviness of yarns

Similarly, typical tensile-load contours from a biaxial root layer (Fig. 36a) and a double-bias root layer (Fig. 36b) indicate that none of the yarns have experienced tensile forces beyond their respective fracture loads. The areas annotated in Fig. 36b that show high tensile forces are in the excess fabric flange regions which are later cut from the fabric.

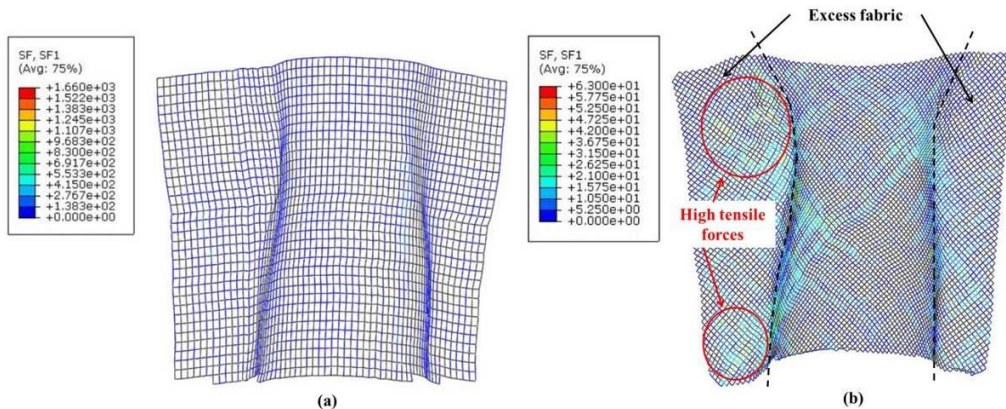


Fig. 36 Yarn tensile force contours in (a) 0/90 biaxial NCF and (b) +/-45 double-bias NCF

Fig. 37 shows the workers cutting away the excess material after the fabric has been placed in the mold. Using the forming simulation methodology of the current research, the initial fabric blank sizes, or flat patterns, can be optimized to reduce the amount of excess fabric that must be cut prior to placement in the mold in either a manual or automated composite manufacturing process. Flat pattern optimization could help reduce material costs and the time needed to cut away excess material. After first running a forming simulation with an oversized blank, the “ideal” blank geometry is extracted, as indicated by the path of nodes in Fig. 38a. A second forming simulation, shown in Fig. 38b, is done to validate the “ideal” blank size such that no excess fabric will exist after pressing the layer into the mold.



Fig. 37 Manual cutting of excess fabric during the manufacturing process

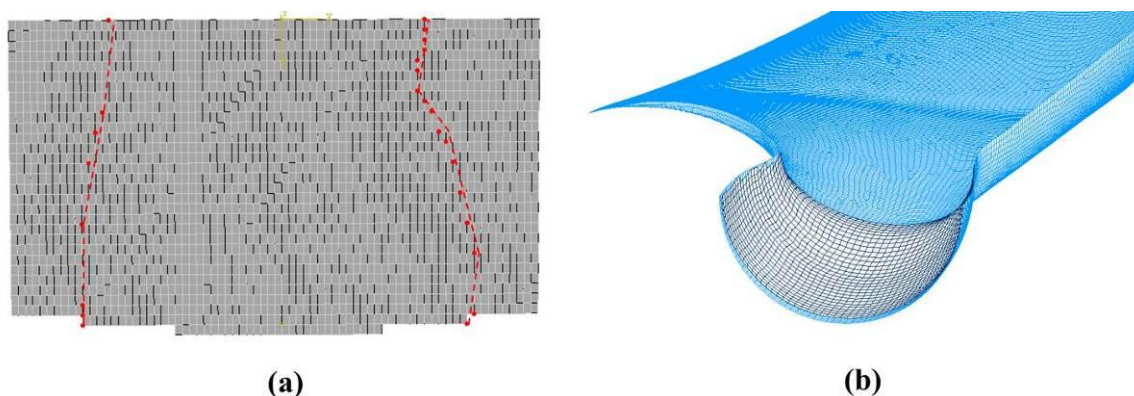


Fig. 38 Flat pattern with (a) node path from deformed fabric to determine where to cut the fabric for (b) minimal excess material after forming

Out-of-plane wave defects:

After the forming simulations and draping analyses are complete, a pressure equivalent to atmospheric (101 kPa) is applied to the top-fabric surfaces to simulate the compaction of the layers during the manufacturing process via a vacuum bag. It is during this stage that layers of fabric can potentially bunch together to form out-of-plane waves that are later filled with resin to form resin-rich pockets. Composite wind turbine blade manufacturers have been challenged as to avoid the formation of wave-defects. Manufacturers have expressed the desire for a high-fidelity simulation such as the discrete mesoscopic approach presented in this chapter that can provide insight into where defects may form and what mechanisms are responsible for their formation. To demonstrate the usefulness of such a process simulation for predicting wave defects, variations in the bending stiffness and interlaminar friction were made in the spar-cap layers of the 9-m blade LP mould. The simulations are summarized in Table 1. Note that EI represents the bending stiffness of the fabric and μ_s , μ_d and β represent the static coefficient of friction, dynamic coefficient of friction and exponential decay constant, respectively.

TABLE 1 PARAMETRIC STUDY ON WAVE DEFECT FORMATION IN 9-M BLADE SPAR CAP

Simulation No.	EI (N-mm ²)	μ_s	μ_d	β
1	300	0.93	0.57	1.0
2	3	0.93	0.57	1.0
3	300	0.30	0.25	0.7
4	3	0.30	0.25	0.7

Simulations no. 1 and 2 varied the fabric bending stiffness while maintaining the static and dynamic friction coefficients equal to those measured between fabrics with a tackifier sprayed between them. Simulation no. 1 used the actual bending stiffness of a carbon NCF (300 N-mm²) while Simulation no. 2 used the lowest measured bending stiffness value of 3 N-mm² (double-bias NCF). After the application of atmospheric pressure, the spar-cap layers remained undeformed using these combinations of bending stiffness and friction. The contours in Fig. 39 represent out-of-plane displacement in units of mm. The upper contour limit of displacement (4 mm) was based on the amplitude of typical defects found in wind turbine blades [11]. Note the lack of any significant out-of-plane displacements when using the 4 mm max as a reference.

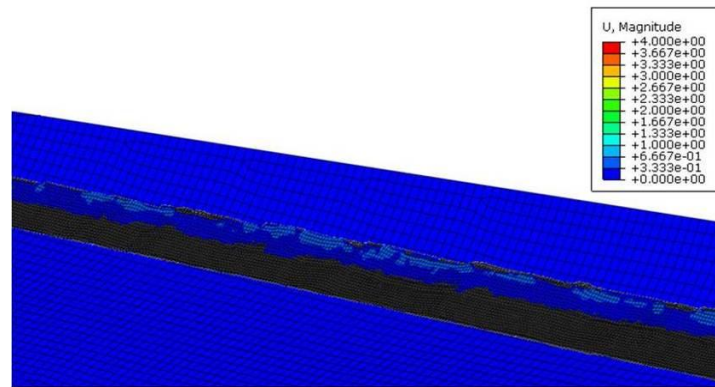


Fig. 39 CX-100 spar cap without out-of-plane deformation (Simulation no.1)

Simulations no. 3 and 4 used the same bending stiffness values as were used in the first two simulations, but used lower coefficients of friction representing the Coulomb friction measured without the tackifying spray between the carbon and E-Glass spar-cap fabrics. When defining lower friction coefficients with the stiffer fabric in Simulation no. 3, no out-of-plane deformation was observed, but the combination of low bending stiffness and low friction coefficients in Simulation no. 4 led to the formation of a wave at the 6.7 m spanwise location. The wave did not propagate across the entire width of the spar cap (as illustrated in Fig. 40).

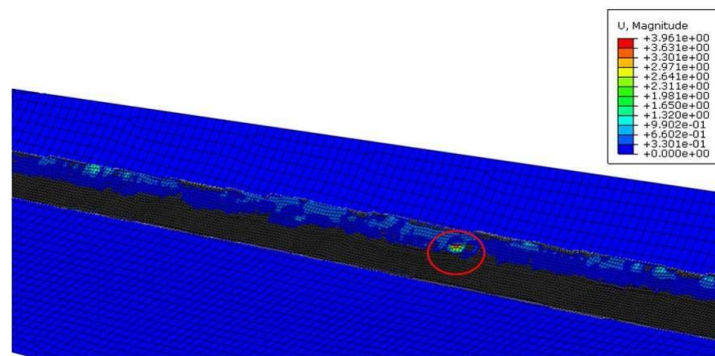


Fig. 40 Blade spar cap with out-of-plane deformation (Simulation no.4)

According to the contour plot in Fig. 40, the height of the wave defect was 3.96 mm, which falls within the range of typical defect heights found in wind turbine blades. However, because the mesh density of the fabric layers in the blade model are chosen to allow for reasonable computational times, too coarse a mesh can compromise the resolution and thereby compromise the ability of the model to predict accurately the size, location and severity of a defect. Fig. 41 shows the out-of-plane displacement contours in the spar cap in units of mm. These contours are the result of applying a vacuum pressure using the same parameters as that in Simulation no. 4, but with a coarser mesh. Although some out-of-plane deformation is still observed at the 6.7 m location, the contours indicate that the wave height is over two times the height (7.983 mm) cited in Fig. 40. Furthermore, out-of-plane deformations that are most likely singularities as a result of poor mesh resolution are shown in multiple areas along the spar-cap length. Fig. 41 shows the importance of having a sufficient mesh either prior to performing simulations of the manufacturing process.

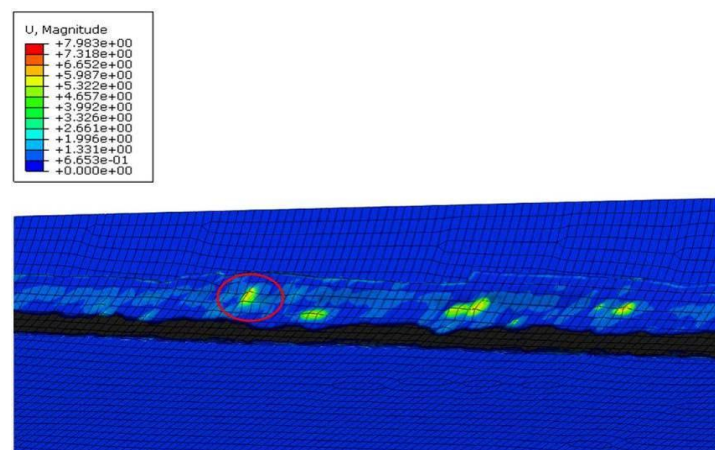


Fig. 41 Coarse spar-cap mesh showing out-of-plane deformation with insufficient mesh refinement

V. CONCLUSIONS

A discrete mesoscopic approach using 1-D beam and 2-D shell elements was used in the commercially available finite element software, Abaqus, to model the mechanical behaviour of non-crimp fabrics (NCFs) used in a 9-m long wind turbine blade. The mechanical behaviour of the NCFs was defined in terms of the in-plane shear stiffness, yarn tensile stiffness and bending stiffness, as well as the friction between contacting layers. A shear-frame test was used to characterize the in-plane shear behaviour of each fabric, and uniaxial tensile tests were performed on individual yarns to quantify the tensile stiffness of the fabric yarns. The bending stiffness was characterized by hanging fabric samples vertically and applying a horizontal load to displace the tip of the samples. The deformed profile was plotted digitally and the moment-curvature relation was determined.

The static and dynamic coefficients of friction between contacting layers of fabric were characterized using a load-control friction-test apparatus. The friction was studied between dry layers of fabric and with an adhesive, called a tackifier, sprayed onto the fabric surfaces. This tackifier simulated the conditions during the manufacturing process. The results of the various mechanical experiments were implemented into finite element models of the fabrics using the Abaqus/Explicit user-supplied material subroutine, VUMAT, to capture the mechanical behaviour of the non-crimp fabrics.

With the mechanical behaviour of each NCF defined, simulations were performed to mimic the hand-layup of the several plies during the manufacturing process. Contours of in-plane shear and tensile loads were observed to analyze the deformation of the fabric layers while conforming to the moulds of the blade. A parametric study was conducted to show that the bending stiffness of the material as well as the friction between layers were some parameters that could influence the formation of out-of-plane wave defects. The modeling approach presented in this chapter allows for the reorientation of the fabric yarns to be tracked during the manufacturing process.

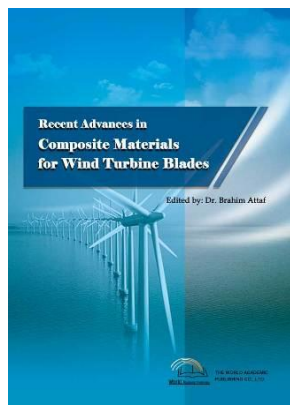
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This book of science and technology provides an overview of recent research activities on the application of fibre-reinforced composite materials used in wind turbine blades. Great emphasis was given to the work of scientists, researchers and industrialists who are active in the field and to the latest developments achieved in new materials, manufacturing processes, architectures, aerodynamics, optimum design, testing techniques, etc.. These innovative topics will open up great perspectives for the development of large scale blades for on- and off-shore applications. In addition, the variety of the presented chapters will offer readers access to global studies of research & innovation, technology transfer and dissemination of results and will respond effectively to issues related to improving the energy efficiency strategy for 2020 and the longer term.

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