MODELLING AND SIMULATING THE FORMING OF A UNIDIRECTIONAL DRY REINFORCEMENT DESIGNED FOR PRIMARY AIRCRAFT STRUCTURES

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Abstract

As a response to the weight to cost trade-off for next-generation aircrafts, Hexcel has developed HiTape® a unidirectional dry carbon reinforcement with a thermoplastic veil on each side designed for aircraft primary structures. The aim of this work is to develop a model that can simulate the forming step occurring prior to infusion or injection, in order to predict the geometry and distribution of properties of the formed stack for process optimisation and reverse engineering. Tension in the fibre direction, out-of-plane bending, along with inter-ply friction are identified as the main mechanisms controlling the HiTape® response during forming. Bending is characterised using a modified Peirce's flexometer. Inter-ply friction is studied using a "pull-through"-type equipement. A large deformation continuous approach at ply-scale is selected. The reinforcement is modelled in the Zset framework with 3D quadratic elements representing the fibrous layer and governed by a hyperelastic behaviour; together with cohesive zone elements describing the specific inter-ply behaviour due to the presence of the thermoplastic veil. Experimental tests are simulated both to verify the robustness of the models and to identify the constitutive laws.

1. Introduction

As a response to the weight to cost trade-off for next-generation aircrafts, Hexcel has developed HiTape®: a unidirectional (UD) dry carbon reinforcement with a thermoplastic veil on each side designed for aircraft primary structures (Fig. 1). One privileged high volume automated production route consists in Dry Fibre Placing of flat reinforcements stacks with an Automated Fibre Placement machine, forming them using specific processes, and infuse or inject the resin to yield the final composite part (Fig 2).

The aim of the project is to produce a numerical tool that can simulate this whole production route for primary aircraft structures, in order to reduce development costs due to the inherent trial and error approach. More specifically, this PhD work focuses on the forming of the flat stack, with the aim of modelling and simulating the forming to predict the geometry, distribution of properties (permeability, *etc.*) and appearance of defects (wrinkling, misalignments, *etc.*) on the formed stack for process optimisation.

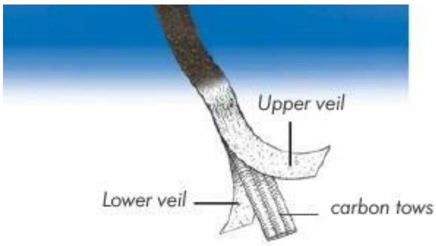


Figure 1. HiTape® structure [1]

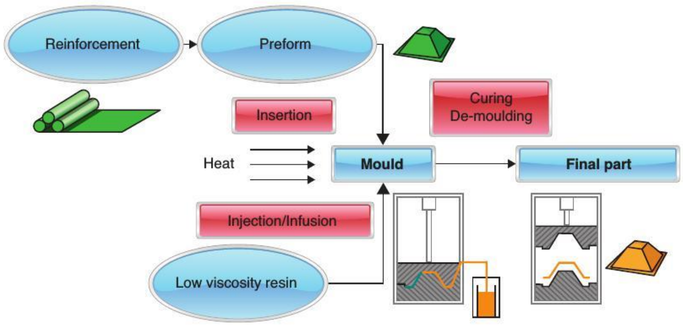


Figure 2. Direct processes schematics

2. State of the art

2.1. Reinforcements forming simulation specificities

The main specificity of the reinforcements is their multi-scale structure inducing various approaches. Some approaches look down at fibre scale with the aim of studying fibre interactions but simulations are limited to tows of a few dozens of fibres due to large computation times. Other approaches focus on a tow (3K to 80K fibres) and aim at studying local reinforcement properties such as permeability or mechanical properties. Macro-scale approaches look at the whole ply stack and aim at predicting macroscopic properties such as wrinkles or bundles formation. For this study, one ply-scale has been selected in order to be as close as possible to the process scale involving ply-by-ply deposition as well as to respond to a trade-off between computation time and realistic description.

This multi-scale structure of the preforms (with possible movement between fibres or tows) induces specific deformation mechanisms which depend on the reinforcement structure, fibres properties, and fibre volume content, and which are largely determined by the fibres orthotropic elastic behaviour and their arrangement. Possible deformation mechanisms are shown in Fig. 3: they involve traditional deformation mechanisms from continuous mechanics *i.e.* traction/compression in the three main directions and shears (in-plane and through-thickness), and additional ones more specific to reinforcements *i.e.* out-of-plane bending and inter-ply sliding. Predominant deformation mechanism vary with fabric type. For crimped fabrics such as wovens, predominant deformation mechanisms are elongation in the fibre directions, in-plane shear since tows can rotate around their crossing points, and out-of-plane bending. For thicker reinforcements, such as non crimp fabrics (NCFs) and interlocks, additional deformation mechanisms are required to represent the through-thickness behaviour: transverse shears and compaction.

Extensive work has been carried out on prepreg and dry woven fabrics forming behaviour and simulation, however the interest for dry non-woven reinforcements has emerged more recently. Some work has been achieved on NCFs but studies on the forming behaviour of UDs are seldom and deal with UD prepregs only. The predominant deformation mechanisms of a UD prepreg stack have been highlighted [2-4]: in-plane shear, bending, and inter-ply sliding. Deformation mechanisms of the considered HiTape® material will be introduced in a next section.

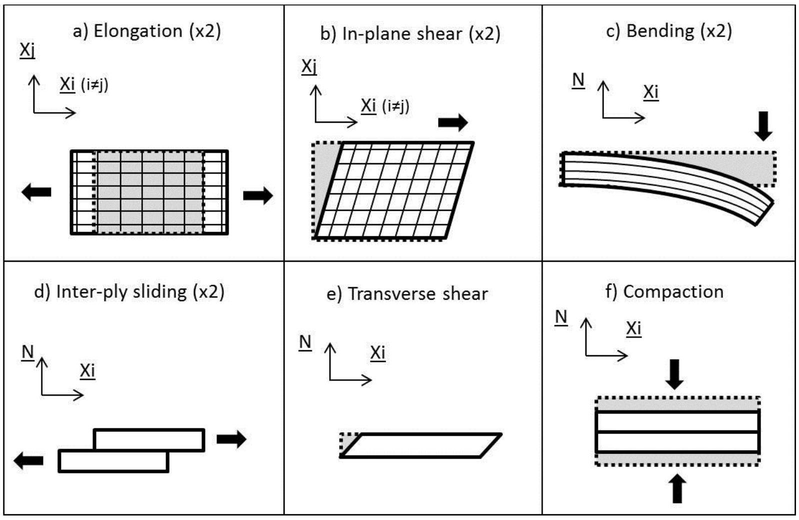


Figure 3. Possible deformation mechanisms of reinforcements with (X1, X2) being the reinforcement plane and (X1, X2, N) a cartesian basis

2.2. Modelling approaches

The selected model fro forming representation should account for geometrical nonlinearities due to large displacements and large rotations, as well as possible material nonlinearities (in the case of bending for example [5]) As a response to take into account all those specificities, several approaches have been developed in the literature. On one hand, discrete approaches model the reinforcement as a set of springs and nodes; such a model has been developed for non-technical dry reinforcements for example [6]. On the other hand, continuous approaches consider that the reinforcement is an elastic homogeneous continuous medium which can be described by the general theory of continuum mechanics with either hyperelastic or hypoelastic constitutive models. Hypoelastic formulations relate the objective derivative of the Cauchy stress tensor to the deformation rate; such models have been used for the mesoscopic modelling of woven and knitted [7] reinforcements. Hyperelastic formulations assume that a strain energy density W exists and is a function of the deformation gradient only. By application of the principle of objectivity, W is a function of the right Cauchy-Green tensor **C**, this yields the general hyperelastic constitutive model [8]:

$$\boldsymbol{S} = 2\,\frac{\partial W}{\partial \boldsymbol{C}} \tag{1}$$

where **S** is the second tensor of Piola-Kirchhoff. This type of formulation has been used to model woven fabrics at macro-scale [5], and a carbon tow at meso-scale [9] for example. Besides, the inter-ply friction behaviour can be described with a Coulomb's law (solid-solid contact) which may be associated with a hydrodynamic law (solid-solid contact with a lubricating film in between) [2].

3. Experimental characterization

3.1. HiTape® structure and resulting assumptions

HiTape® is a UD dry carbon reinforcement with thermoplastic veil on each side [1] as shown in Fig. 1. The UD structure brings optimal behaviour in fibre directions; the veil allows automatization and improved impact resistance compared with state-of-the-art dry materials. Compared with state-of-the-art reinforcements, HiTape® is neither an entirely dry material nor a prepreg: one ply behaves as a dry reinforcement but when considering multi-plies the influence of the veil may be predominant.

One HiTape® ply is very thin (approx. 0.1-0.3mm) which justifies the assumption that deformations occurring through-thickness are negligible compared with deformations occurring in the ply plane: therefore transverse shear and compaction are not considered. UDs very little deform by shearing because out-of-plane bending is largely predominant [4]; therefore in-plane shearing is not taken into account as a first approximation. Inter-ply friction is *a priori* predominant and is a function of temperature (due to the thermoplastic veil). Eventually, tension in the fibre direction, out-of-plane bending and inter-ply friction are considered as predominant. Their importance is to be confirmed through experimental testing, but in any case the modelling strategy must be adapted to this specific behavior.

Elongation in the fibre direction is dictated by the one of carbon fibre (1-3%). However out-of-plane bending and inter-ply sliding behaviours cannot be predicted and need proper characterisations.

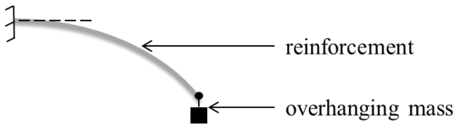
.3.2. Out-of-plane bending characterisation

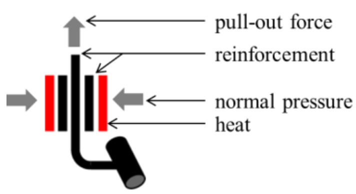
Reinforcements bending behaviour has been showed to be nonlinear [5], hence a bending bench is developed with the aim of characterising this nonlinear relationship between curvature and bending moment at high temperature (relatively to the polymer involved). Accordingly to Liang's method [5] adapted from Peirce's flexometer [10], a piece of reinforcement is clamped at one tip and a mass is hanged down at the other tip to force the sample to bend (Fig. 4a). The whole deformed profile is recorded and using image processing the relationship between the bending moment and curvature is identified using a Voce's model. This relationship is to be implemented in the hyperelastic model. Mono-plies are first considered; then multi-plies are tested with the aim of identifying the coupling between bending behaviour and ply number, which means understanding the influence of the interface.

.3.3. Inter-ply sliding characterisation

Inter-ply sliding is characterized using a "pull-through"-type equipment (similar to [11]) mounted in a standard traction machine (Fig. 4b). A piece of reinforcement to be pulled is placed between two fixed pieces of reinforcement. A normal pressure is applied as well as heat. The pull-out force is recorded as a function of time and displacement. The Coulomb friction coefficient is obtained and the influence of forming parameters such as normale, displacement speed and temperature is assessed.

Preliminary tests at room temperature show that the friction coefficient of two HiTape® plies tested in fibre direction is independent from normal pressure and displacement speed (in the range of pressures and displacement speeds occurring during forming process) and equals approximately 0.15. Furter tests at hight temperature are to be conducted.





(a) (b)

Figure 4. Schematics of experimental tests: out-of-plane bending (a) and inter-ply sliding (b)

4. Modelling

Recalling the structure presented in Fig. 1, HiTape® is modelled as shown in Fig. 5 with two distinct materials (carbon tape, thermoplastic veil) considered as homogeneous continuous media with their own behaviours.

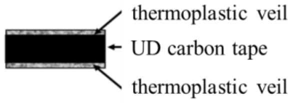


Figure 5. Model of HiTape® structure

4.1. Carbon tape modelling

The carbon tape is modelled as a transversely isotropic medium with a hyperelastic behaviour (Eq. 1). The selected formulation assumes a transversely isotropic medium exhibits four independent (decoupled) deformation mechanisms called elongation, compaction, distorsion and shear, allowing the strain energy density to be written as the sum of the contribution of those mechanisms. Each contributions is written as a function of a so-called physical invariant which is a function of the right Cauch-Green tensor **C** invariants (more details in [9]). The formulation yields to the following expression for the strain energy density *W*:

$$W = W_{elong}\left(I_{elong}\right) + W_{comp}\left(I_{comp}\right) + W_{dist}(I_{dist}) + W_{shear}(I_{shear}) \tag{2}$$

For each contribution, a polynomial form is given (Eq. 3) whose coefficients (a_i, n) are identified using experimental results when appropriate.

$$W_{\dots}(I_{\dots}) = \sum_{i=2}^{n} a_i \; I_{\dots}{}^{i} \tag{3}$$

4.2. Thermoplastic veil modelling

As the thickness of the thermoplastic veil is very small compared to the one of carbon tape, it is neglected, and a cohesive zone approach is selected : the inter-ply is considered to be of zero thickness but exhibits a proper behaviour, possibly complex, describing adhesion between plies. The formulation of Lorentz [12] finite element is selected.

5. Simulation

The hyperelastic formulation presented in Eq. 1-3 is first implemented in the finite element framework Z-set [13]. Each contribution (Eq. 2) is tested by simulating each independant deformation mechanism individually. The carbon tape is modelled using quadratic volumic elements exhibiting the hyperelastic behaviour presented in Eq. 1-3; the thermoplastic layer is modelled using interface elements exhibiting a specific behaviour. After validation of this constitutive law, the experimental tests (out-of-plane bending and inter-ply sliding) are simulated in order to identify material parameters (Fig. 6). Finally, first forming simulations based on a omega stringer geometry can be performed (Fig. 7).

(a) (b)

Figure 6. Simulation of the experimental out-of-plane bending (a) and inter-ply sliding (b) tests

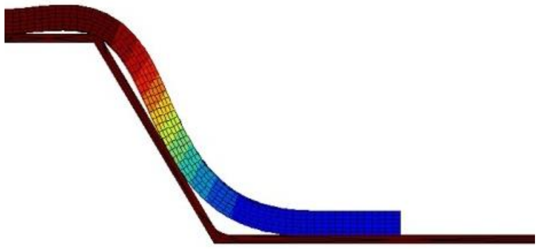


Figure 7. Forming simulation of a two-ply stack on a omega stringer under low pressure

6. Conclusion

Several approaches have been proposed in the literature for dry or prepreg reinforcements modelling. However, HiTape® – a UD with thermoplastic veil on each side – has a unique structure requiring a specific modelling strategy. Experimental tests allow a better understanding of the material predominant deformation mechanisms, and are used to determine the model parameters. A continuous approach at ply-scale is selected. A transversely isotropic hyperelastic behaviour for the carbon tape is implemented. The HiTape® is then modeled using 3D elements associated with the implemented hyperelastic behaviour for the carbon tape, and cohesive elements for the veil behaviour. Simulations are performed in the Z-set finite element code [13]. Experimental tests are first simulated, then forming simulations are performed.

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