A FINITE ELEMENT MODEL CAPABLE OF PREDICTING RESIN POCKETS FOR ARBITRARY INCLUSIONS IN COMPOSITE LAMINATES

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Abstract

This work presents the progress in the development of a finite element model capable of predicting resin pockets occurring in composite structures with embedded sensors. The F.E.-model is built using standard tools in ABAQUS software, avoiding the need of specialized coding. Both progresses in material characterization as well as finite element modeling are shown. The model will eventually be used to optimize the shape of an embedded optical fibre interrogator used within the FP7 'SmartFiber' project.

1 Introduction

Extensive research is currently being devoted towards the development of structural health monitoring (SHM) systems for composite structures [1-5]. While SHM can be achieved using many different sensing technologies (fibre Bragg gratings, Raman and Brillouin scattering, piezo crystals…), the measurement of multi-axial strains – which are important in orthotropic materials – often, necessitates the embedding of the sensing system.

Sensing and detection capabilities, accuracy and speed are generally the focus-point in SHM related research. The impact of the embedded sensor on general health of the structure is rarely accounted for. However, the mismatch between sensor and host material always leads to a local perturbation of the stress/strain distribution within the host [6], affecting its strength. Additionally the draping properties of the host material, limits the capability of the reinforcements to conform to the shape of the sensing system. This in turn results in the creation of resin rich areas (resin pockets) surrounding the sensor and creating weak points within the structure (possibly promoting the initiation of certain failure mechanisms such as delamination at the boundaries of the resin pocket).

Within the domain of SHM some authors have performed experimental research to determine the influence of embedded structures on material properties [5, 7]. Others have performed finite element analysis by using microscopic images of cross section from embedded sensors as a reference for the geometric modeling of the structure[8]. A few attempts have been made to predict the resin pocket geometry for the specific case of embedded optical fibres [9, 10]. Outside the SHM area, much research is available on modeling the forming and draping behavior of fabrics [11-16]. Some of the more basic algorithms (such as the fish-net approach) have even been implemented in commercial FEM software. Unfortunately, these algorithms are only capable of capturing large scale forming behavior, and lack the necessary accuracy at low levels such as embedded optical fibres. The more advanced models can provide the required accuracy, but are most often based on proprietary code requiring large efforts to be developed.

The EU-funded FP7 “SmartFiber” project sets out to overcome the issue of fragile egress point when embedded optical fibre sensors are employed as a sensing system. In order to overcome this downside, SmartFiber will make use of state-of-the-art technology within the field of photonic chips, electronics and wireless data transmission. This will enable the interrogator unit to be miniaturized and embedded inside the composite. All data communication and power transmission will then be performed wirelessly, overcoming one of the largest issues in industrial applicability of optical fibre sensing.

Although miniaturized, the embedded interrogator in the SmartFiber project will disturb the host material. It therefor requires accurate simulation and prediction of its impact on structural strength of the host. Additionally, a model capable of predicting the resin pocket geometry will enable the optimization of the interrogator shape minimizing its impact.

This work sets out to develop a finite element model capable of predicting resin pockets associated with random inclusions, based on simple material characterization and common finite element properties (materials, elements, FE algorithms…)

2 Reinforcing material characterization

Many different parameters determine the forming behavior of reinforcing fibres (fabrics and UD reinforcements). Generally, the most important factors are tensile modulus (or moduli), shear stiffness (and the associated locking-angle), inter-ply friction (ply-ply and ply-tool friction) and bending stiffness [17]. This work focuses on uni-directional glass fibre reinforcements, reducing the parameters to tensile modulus, inter-ply friction and bending stiffness (shear stiffness reduces to almost zero).

2.1 Tensile modulus

Tensile modulus can be measured by performing a tensile test. When characterizing a fabric material, a bi-axial tensile test is required and should be performed at different ratios of tensile strain in each direction. When a UD material is used, a straightforward tensile test as illustrated in Figure 1 (left) is performed. The results from such a test are shown in Figure 1 (right). A number of different discontinuities can be seen in the force-displacement curve. These correspond to failure in the different yarn bundles. The tensile modulus is determined between the starting point and the first yarn failure.

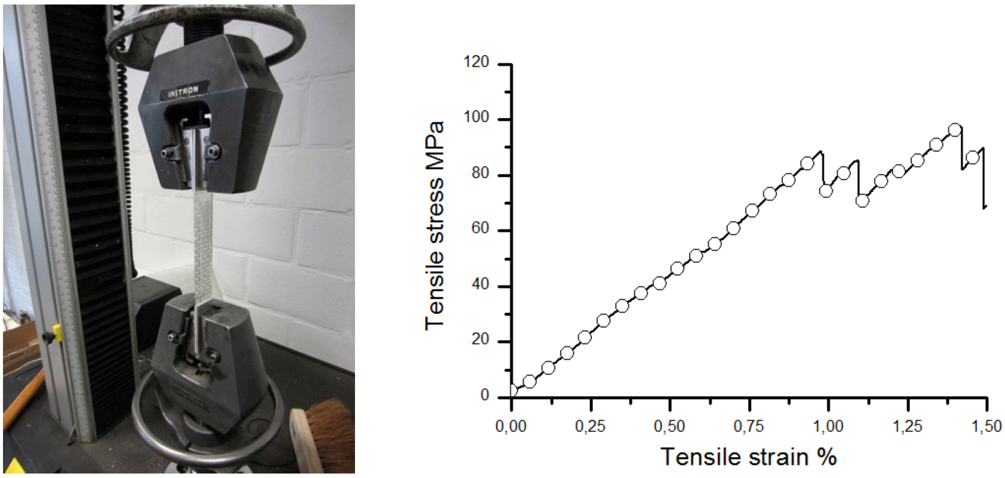

Figure 1. (left) Tensile test set-up for a UD glass-fibre material. (right) Stress-strain curve from a tested sample

A total of 5 samples were tested and the average E-modulus was found to be 99.7 $\pm$ 1 GPa. The rather large spread on the determined modulus is due to the use of the tensile bench displacement recording as a reference for strain. Slippage in the clamps or flexing of the bench frame can cause additional displacements, which do not translate into actual strains. Higher accuracy can be achieved by using an optical technique to measure strains on the sample.

2.2 Ply-ply and tool-ply friction

When measuring ply-ply friction, the determined friction is strongly dependent on the amount of normal pressure/force applied. With increasing pressure, the reinforcing fibres in both plies will redistribute themselves and both plies will progressively be pushed into each other, changing the amount of friction.

In order to measure ply-ply friction, a new tool was designed (based on [18]), as illustrated in Figure 2. In this tool, two separate plies can be clamped (one in the top part, the other in the bottom part). Both plies contact each other (one folder around the other one) in the central part, which is clamped by spring-loaded bolts. These bolts can be tightened to control the amount of normal pressure on the plies. The entire tool fits within a tensile bench, which can register the required tangential force to separate both plies. The tooling material can replace one of the plies in order to measure tool-ply friction.

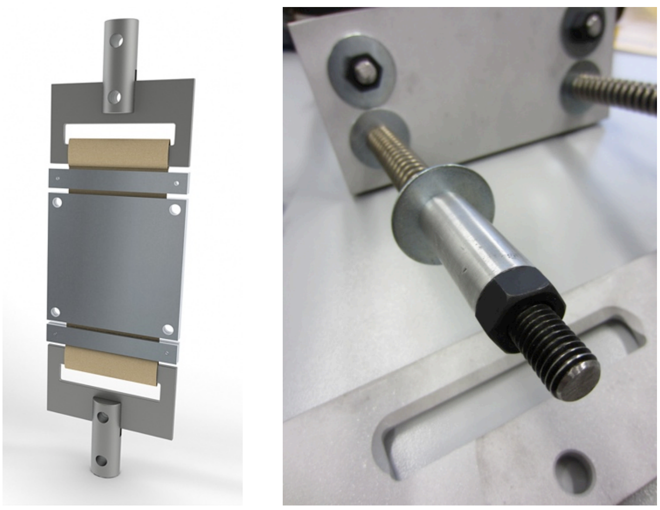

Figure 2. Illustration of ply-ply friction tester design

In the near future, the required friction measurements will be performed on the selected UD glass-fibre material.

2.3 Bending stiffness

Bending stiffness in fibre bundles cannot be determined solely on the basis of tensile modulus (as is the case for traditional materials such as steel). Since fibre bundles are a collection of many thin fibres, relative sliding will reduce the bending stiffness far below what would be calculated based on the ply area and tensile modulus. A separate measurement of bending stiffness is thus required in order to accurately simulate the draping behavior. Since bending stiffness is relatively low in these materials, normal bending tests will not provide adequate results. The technique and formulas to determine bending stiffness in fabric materials (a cantilever test) was proposed by Pierce, and is shown in Figure 3. Within this test, a piece of fabric is allowed to bend under its own weight, until a certain angle is reached. The overhanging length can then be used to calculate the bending stiffness.

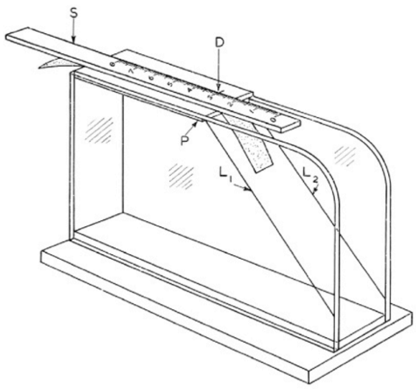

Figure 3. Schematic drawing of Pierce cantilever test

The selected glass fibre UD material has a bending stiffness, which is higher than what can be measured by the Pierce cantilever test device. In order to measure the bending stiffness for this material, a larger test device has to be built, or measurement should be performed at smaller angles. This work will be performed in the future.

2.4 Shear stiffness

When using fabric materials, an additional test using either a trellis frame or a bias extension test has to be performed to determine the (in-plane) shear stiffness and locking angle. These test are not required for the selected UD material, and shear stiffness can be selected as an arbitrary low value.

3 Numerical simulations

Using the experimental data from material characterization should allow the creation of a finite element model capable of capturing the most important phenomena occurring during a forming process. Within the scope of this work, an attempt is made to build an accurate model using standard tools available in F.E.M. software.

3.1 Finite element challenges

Finite element modeling of fabric and fibre bundle behavior poses a couple of significant problems.

The default frameworks used in finite element software (Jaumann and Green-Naghdi in ABAQUS/Standard and ABAQUS/Explicit respectively) are incapable of accurately determining stress-states in fabric materials under certain circumstances (e.g. shear under tension). A specific framework is required to correctly track stresses and strains during forming. Within ABAQUS, this can be resolved by using the FABRIC-keyword, which utilizes a correct framework. These errors become significant in large strain deformations. Secondly, simulating forming of fibrous materials is usually achieved by using shell or membrane elements, being more computationally efficient than 3D solid elements. However, membrane elements possess no bending stiffness, while shell elements have a bending stiffness determined by its elastic modulus. Both are incorrect when modeling fibrous materials. This is usually overcome, by creation of a UMAT (user material) or UEL (user element) in ABAQUS. However, this is outside the scope and goal of this work.

3.2 Hybrid membrane-shell approach

A different approach was explored by using a combination of membrane and shell elements. Two outer membrane layers and one central shell layer model a single ply. The total thickness is fixed to the physical thickness of the ply. By changing the thickness of shell and membrane parts, the bending stiffness can be tuned to the desired value, without affecting in-plane properties or total thickness of the ply. This is important to achieve accurate results. Using a genetic algorithm (or any other optimization technique) enables the determination of the required heights in order to achieve the measured bending stiffness.

3.3 Finite element model

Based on the approach described above, a finite element model has been created in accordance to a resin-infused sample with embedded steel part (50x50x2.5mm). Both the numerical model and corresponding RTM plate are shown in Figure 4.

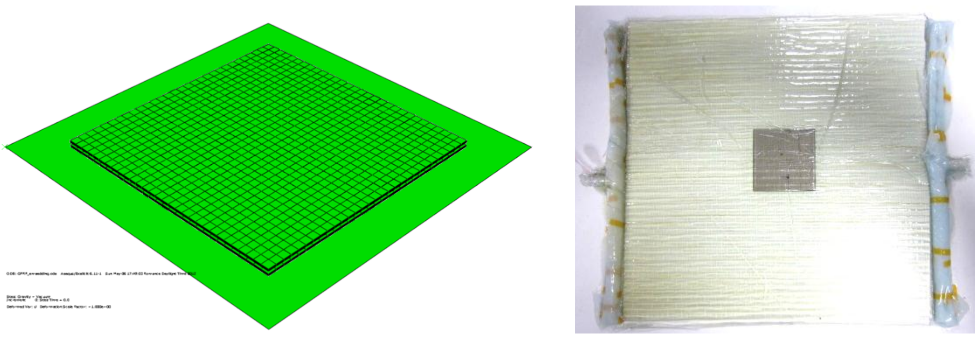

Figure 4. (left) F.E.M. model (right) RTM infused plate

4 Future prospects

This paper has presented some preliminary results towards the creation of a finite element model capable of capturing the most important forming mechanisms in forming of fibrous materials, using only standard tools available in ABAQUS F.E.M. software.
A finite element model has been built corresponding to a RTM infused plate. Future work will entail the further mechanical characterization of the selected glass fibre material (friction and bending stiffness). This will allow to finalize the F.E.M. model and compare the accuracy with microscopic cross-sections of the RTM plate.

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