STRENGTH ANALYSIS OF WOVEN INTERLOCK COMPOSITES SUBJECTED TO COMPRESSIVE LOADING: EXPERIMENTS AND SIMULATIONS

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Abstract

This work aims at observing and modelling the behaviour, damage and failure of an interlock woven composite with polymer matrix under quasi-static tensile and compressive loads. The modelling is based on the Onera Damage Model for polymer matrix composites (ODM-PMC). Validity of the predictions of the model is assessed based on test results. Improvements to the model are made accordingly. The improved model is then identified. Experimental results and model predictions are compared on classical tests with satisfactory results. A last validation is proposed on a compression with pivots test.

1. Introduction

With the increasing use of composite materials in a large range of applications, new architectures of composite materials are developed. These innovative composites need to be experimentally tested in order to characterize their performances. This characterisation is completed through large tests campaigns. These experimental investigations have to be done for various loadings, such as tension, compression or bending. Additionally, models able to correctly predict the behaviour of composite materials, and thus the response of the composite structure, are required for structural design. The development of such a model has to be based on a sound knowledge of the behaviour of the material.

In the public literature domain, the woven interlock composite materials with polymer matrix have been experimentally studied by few authors only. The behaviour, the damage mechanisms, and the failure are very dependent the architecture of the material. Thus each kind of architectures requires experimental investigation to characterize the behaviour, and to observe the different damage and the failure mechanisms. Cox *et al.* [1][2][3] have studied, in the early 90's, woven interlock composites under different loadings such as tension, compression and bending,[2] and also under compression-compression fatigue solicitation. More recently, several studies have been carried out on such composites, but essentially for tensile loadings. Schneider [4] has studied behaviour and damage mechanisms of interlock woven composite in quasi-static tension solicitation. Then, Henry [5] has investigated the behaviour and damage under tension-tension fatigue. All these studies used a very rich instrumentation. Multi-instrumentation of tests allows measuring behaviour, and observing damage and failure mechanisms during the test. Moreover it is possible to cross-check the observations in order to validate them. The test campaign in this work has been completed with Digital Image stereo Correlation [6], Acoustic Emission [7], and microscopic observations [8].

In the mean time, damage and failure models have been developed for interlock woven composite. Models are developed at three scales of the material, i.e. microscopic [9], mesoscopic [10][11][12] and macroscopic [12][13]. Several authors worked on mesoscopic modelling of the behaviour of woven composite, which seems to be very promising. But, one of the major difficulties of this scale is to mesh the architecture of the woven composite, which is especially complex for interlock composites. On the contrary, at macroscopic scale there is no need to mesh the complex architecture of the composite. And this scale is more adapted to run calculations on large woven composites structures. Hochard *et al*. [13] studied the behaviour of 2D woven composite. Nevertheless, there are only few models for interlock woven composite with polymer matrix. Marcin [14] developed a specific model for interlock woven composite with polymer matrix, the Onera Damage Model for Polymer Matrix Composite (ODM-PMC). ODM-PMC describes the viscoelastic behaviour, the damage and the failure of the woven interlock composite under quasi-static tensile solicitation. Latter, the ODM-PMC has been extended to tension-tension fatigue load by Rakotoarisoa [15]. In this work, we propose to extend the ODM-PMC to compressive loadings.

Based on previous works on model development and identification, this study aims at characterizing the behaviour of an interlock woven composite under tension and compression loads. The existing model ODM-PMC is enhanced to predict response of structures under multi-axial loads. In section 2, a short description of the ODM-PMC model is provided that justifies the choices made in the experimental investigation. In section 3, the main results of the test campaign are described. The experimental results are used in section 4 to identify the ODM-PMC model. Finally, simulations and experimental data are compared on a compression with pivots test to validate both the model and the associated identification.

2. Brief description of Onera Damage Model for Polymer Matrix Composite

The Onera damage model is a macroscopic model for woven composite with polymer matrix. It is developed at Onera and based on continuum damage mechanics [16]. ODM-PMC is able to predict the behaviour, damage and failure of such composites submitted to quasi-static and fatigue tension load [14][15]. The viscous behaviour is described with a spectral formulation [17][18]. The principle of a spectral formulation is to divide the viscous behaviour into several elementary viscous mechanisms. High difference between matrix and yarns mechanical properties orientates the damages along the microstructure.

Two kinds of damages are represented in the model. They are classified through their effect on the behaviour. Matrix cracks have a non linear effect on the behaviour (d_i), whereas yarns failures have a non-linear and softening effect on the behaviour ($D^{\pm}{}_k$). $D^{\pm}{}_1$ and $D^{\pm}{}_2$ represent the rupture of the warp and weft yarns respectively in tension and compression, and D_3 corresponds to the yarn/matrix debonding. The evolutions of the different damage variables are described (eq. 1 and 2).

$$d_i = d_c^i \left(1 - \mathbf{exp}\left[- \left(\frac{\left\langle \sqrt{y_i} - \sqrt{y_0^i} \right\rangle_+}{\sqrt{y_c^i}} \right)^{p_i} \right] \right) \quad \text{i=[1,2]} \qquad (1) \qquad D_k^{\pm} = \left(\frac{\left\langle \sqrt{Y_k} - \sqrt{Y_0^k} \right\rangle_+}{\sqrt{Y_c^k}} \right)^{P_k} \quad \text{k=[1,2,3]} \qquad (2)$$

where d_c is the value of the saturation, for matrix cracks only, y (Y respectively) is the driving force, y_0 (Y_0 respectively) corresponds to the damage initiation threshold, and y_c and p (Y_c, P respectively) are kinetic parameters of the damage evolution.

The effects of these damages are taken into account in the three material directions. Coupling between different directions of the material is taken into account as observed during experimental tests. The unilateral aspect of damage is represented through an activation index that activates the effects of the damage in tension only, when cracks are opened.

Based on the formulation of the model, an experimental campaign has been set up in order to validate the hypothesis on the studied material, and to determine if ODM-PMC is able to predict the behaviour of woven interlock composite under tension and compression.

3. Experimental investigation of woven interlock composite with polymer matrix

The test campaign is held at Onera and aims at observing the mechanical behaviour, the damage mechanism and the failure of a woven interlock composite [19]. Tension and compression tests are done to ensure that the hypothesis made in tension in the model are still relevant for the studied material. Observations in compression are required to assess the validity of such a model in compression.

3.1. Experimental device

Tests are run on an electro-mechanic machine ASVIC with a maximal capacity of 15T. All tests are instrumented with Digital Image stereo Correlation (with the commercial software Vic3d$^{©}$). Digital Image stereo Correlation (DIC) measures in-plane and out-off-plane displacements at the surface of the sample. Strains are calculated by derivation. For tensile test an extensometer (25mm length) is added in order to measure the strain of the material and to cross-check the measurement of the DIC. During tests, the acoustic activity of the material is recorded thanks to an Acoustic Emission (EA) device (Mistras system from Euro Physical Acoustic). Recorded acoustic events are a rich source of information about damage onset and evolution of damages during the test. Some tests are instrumented with in-situ microscopic observations on a polished free-edge of the sample. Microscopic observation gives crucial information about the kinds of damage induced during the test. Figure 1 shows photography of the experimental device for a compression test.

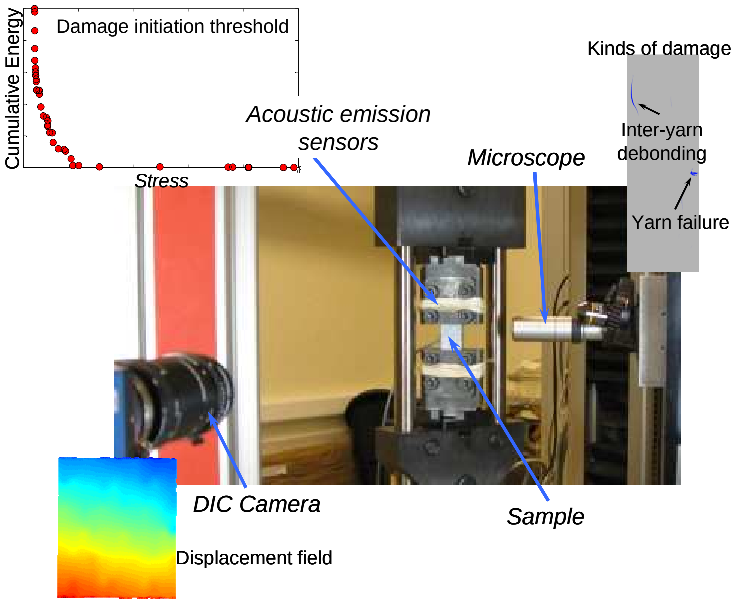

Figure 1. Multi-instrumented set up for compression test and observations for each measurement techniques.

In order to collect all the required information the material is tested in three directions, warp, weft and off-axis at 45°. In all directions, monotonous, creep and incremental tests are performed. Scattering of the measurements is analysed by repeating the different tests.

3.2. Experimental observations

The material tested is an interlock woven composite with carbon yarns and a polymer matrix. It can be observed in Figure 3 that, due to a high percentage of yarns in the warp direction, the behaviour is almost linear to rupture in tension and compression. On the contrary, in weft direction, the behaviour is non-linear due to damage for both tension and compression load. Off-axis behaviour at 45° is also non-linear, with two main sources of non-linearity, (i) the viscosity of the matrix, and (ii) the damages.

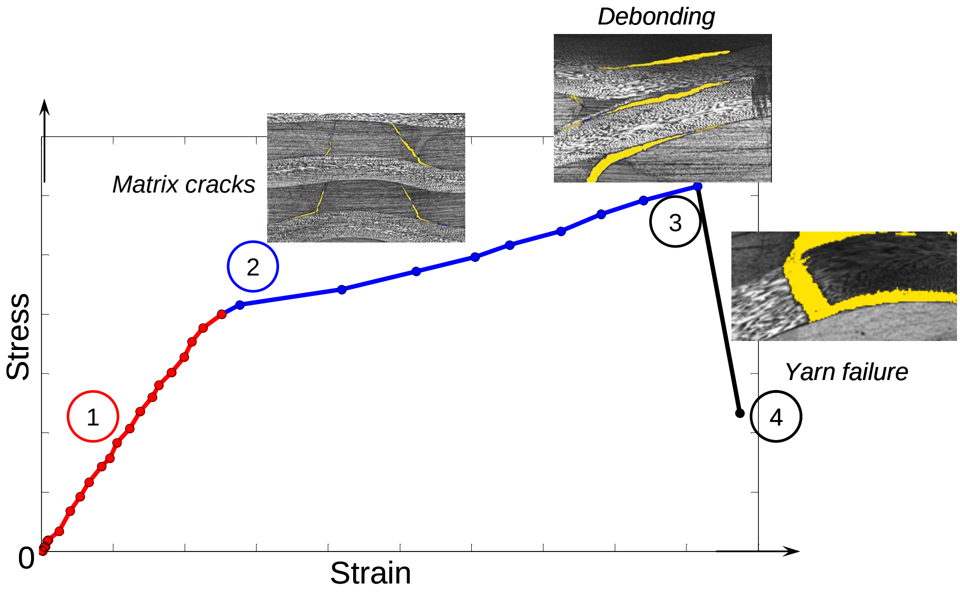

Figure 2. **Established scenario for a tensile test in the weft direction. (1) is the viscoelastic part, (2) matrix cracks occur, (3) yarns start to debond and (4) failure of the specimen.**

Induced damages depend on the type of solicitation and on the direction of the loadings. Figure 2 is an example of the established scenario for the weft direction in tension. Table 1 sums up the experimental observations, for both tension and compression. The debonding occurring in the vicinity of the yarns leads to yarn kinking. The kinking leads then to yarn failure.

	Warp	**Weft**	**Off-axis 45°**
Tension	(1) Matrix cracks (2) Debonding (3) Yarns failure	(1) Matrix cracks (2) Debonding (3) Yarns failure	(1) Matrix cracks
Compression	(1) Debonding (2) Yarns failure	(1) Debonding (2) Yarns failure	(1) Debonding

Table 1 Different kinds of damage observed during tests classified by order of occurrence (i).

All observations and data collected during the tests are used to establish damage scenarii. Results from experiments are then used to identify the model ODM-PMC.

4. Confrontation between simulations and experiments

4.1. Model identification

The various experimental observations are used to identify the different parts of the model. Creep tests give information on the viscous behaviour of the materials. Monotonous tests are used to identify the elastic and the damaged part of the behaviour. They give data on the effects of damages in each direction, meanwhile the kinds of damages are observed with the microscope. Creep tests are used to identify the viscous behaviour. These tests have long creep step in order to emphasis the viscous behaviour. Moreover to distinguish viscosity from damage, creep steps are done with a magnitude below the stress threshold for damage onset. Failure of the material, mainly yarn failure, is identified as a strain threshold. This point is addressed in section 4.3. Thus, most parts of the model can be identified, especially the in-plane parameters. Figure 3 shows the result of the identification, on monotonous tests and for an off-axis creep test. It can be observed that there is a good agreement between the results of the model and the experiments.

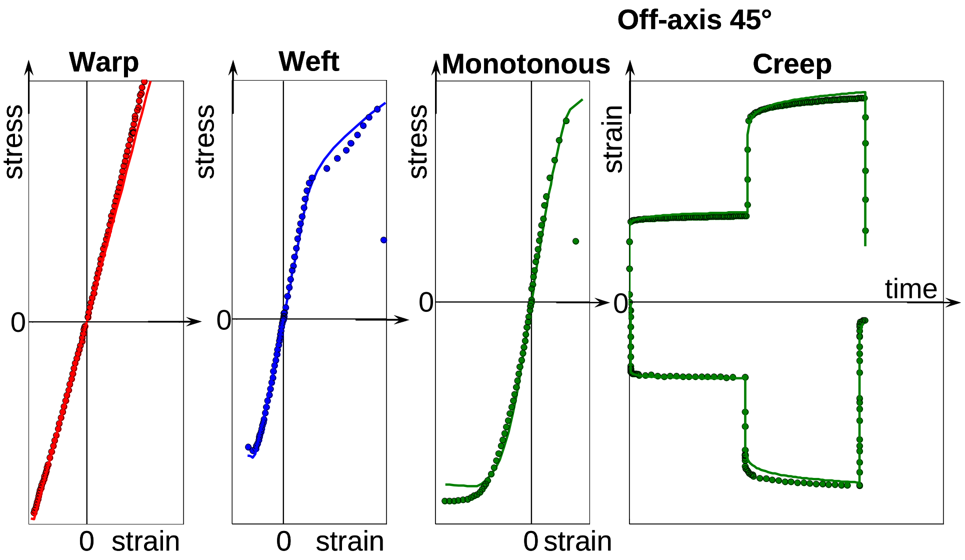

Figure 3. Comparison between results from experiments (points) and from simulations with ODM-PMC (line), (a) warp monotonous, (b) weft monotonous, (c) off-axis 45° monotonous and (d) off-axis creep tests.

4.2. Validation of the model

In order to validate the identification made on monotonous tests on sample without stress gradient, it is relevant to compare results from experiment and Finite Elements (FE) simulation on a more complex loading case. FE simulations are done with an implicit code, ZeBuLoN. Here, the choice of a compression with pivots has been made. Compression with pivots is an alternative to four-point bending tests. Its main advantage is that there is no contact between cylindrical bars and the sample and thus no local indentation. Moreover, it is easier to model a test without contact. Figure 4 gives a schematic explanation of the test, and a comparison between the simulation results and the experimental observations. First, the response of the structure is observed. Then, the damage area is analysed. It can be observed that the predictions of the model are in good agreement with the experimental observations. However there are still improvements to make to be able to predict the progressive failure of the structure more accurately.

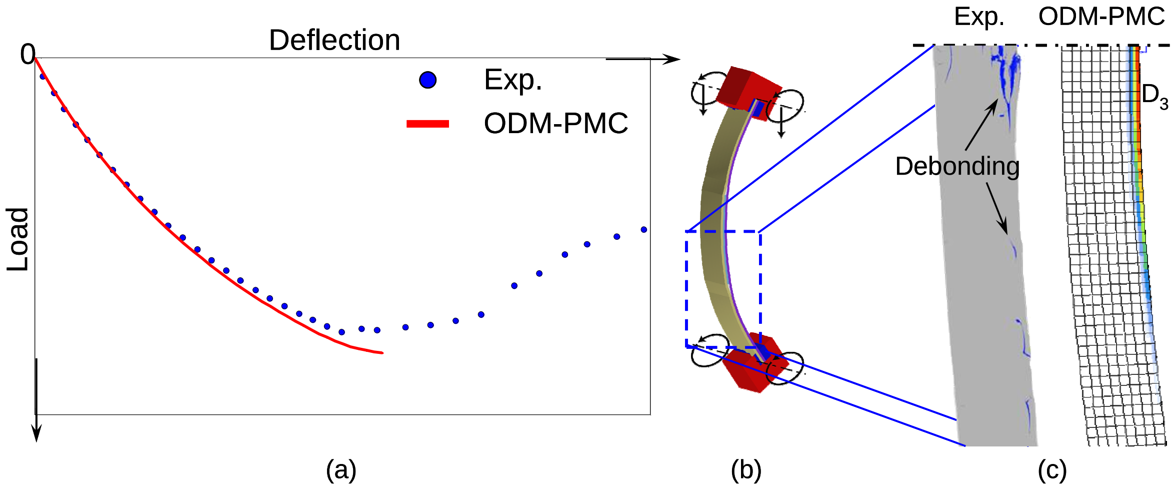

Figure 4. **(b) Schematisation of the compression with pivot test, (a) and (c) simulation/experiment comparison, (a) global response of the structure and (c) comparison of the damage area, D_3 is the variable representing the debonding.**

4.3. Model add-ons

As it can be seen in the comparison between the model and the experiment some points can be improved in the model. First, the experiments show that the material is slightly stiffer in tension than in compression. This is due to the waviness of the yarns that tends to reduce in tension. The phenomenon is not taken into account in the model. However, it could be easily added to improve the quality of the prediction for structures which undergo simultaneous tension and compression, such as bending specimens. Another lack of the identification is related to the progressive failure of the sample (observed in compression with pivots test). As a matter of facts, the identification of the progressive failure has not been done yet. To complete the identification of this part of the model, open-hole compression tests will be run. Indeed, the open-hole in the sample will induce stress gradient, and thus will lead to a progressive failure of the yarns within the sample.

5. Conclusion

This works aims at understanding the behaviour of an interlock woven composite for both tension and compression load. An experimental tests campaign has been held at Onera. The observations made thanks to multi-instrumentation and various kinds of tests have led to a better understanding of the behaviour, the damage and the failure mechanisms of such a material. The whole experimental campaign has been used in order to assess the ability of the Onera Damage Model for Polymer Matrix Composite (ODM-PMC) to predict the behaviour of the material under both tensile and compressive load. To do so the model has been identified and it appears that it is able to properly predict the behaviour, the damage and failure occurrence. The identification has been validated on a more complex loading case, compression with pivots, and the simulation results are in good agreement with the experiments.

Following up this work, other experimental tests are run at Onera in order to identify and predict the progressive failure of structures with stress gradients. In the mean time, the ODM-PCM is improved in agreement with the experimental observations. At the end, the main objective is to have a unique model able to predict response of structure for multi-axial quasi-static loading cases. In parallel, the model is also extended to low velocity/low energy impact, in order to predict after impact residual performances, in tension, compression, bending or even fatigue [20].

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