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MULTISCALE HOMOGENIZATION OF A GLASS-PA66 FABRIC COMPOSITE BEHAVIOR FOR CRASH STUDIES

P. Rozycki¹, M.A. Mbacke² and A.T. Dau^{1,2}

¹Ecole Centrale de Nantes, Institut de Recherche en Génie Civil et Mécanique (GeM), UMR CNRS
6183, BP 92101, 44321 Nantes Cedex 3, France

Email: patrick.rozycki@ec-nantes.fr

²IRT Jules Verne, ERT Simulation des Structures et des Procédés, Chemin du Chaffault, 44340
Bouguenais, France

Email: mamadou.mbacke@irt-jules-verne.fr

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Abstract

In the automotive industry, the taking into account of different environmental conditions is a major key because it assures the cars to be well designed for quite all over the world. The introduction of some composite materials such as woven thermoplastic composites then complexifies the task of the engineers because due the sensitivity of the matrix to both temperature and hygrometry; they have to manage long and expensive experimental testing. The aim of this paper is to present a numerical study based on a double homogenization in order to alleviate the constraints of experiment and let the engineers to quickly find some mechanical characteristics for their designs. First, we present the methodology and the constitutive laws (fiber and thermoplastic matrix) adapted to the first homogenization in relation with the tows. The matrix has been characterized for several environmental conditions (temperature and Relative Humidity). In a second step, we suggest the methodology to extract the behavior of the woven composite material using the numerical results of the tows and the behavior of matrix. The obtained numerical results are compared to the experiment done on the woven thermoplastic composite at different RH. It allows to expose our future prospects.

1. Introduction

The experimental characterization of a composite material leads to more tests than metallic due to their orthotropy. In tension, the experiment must include at least 3 orientations [1]: one in the direction of the fibers (UniDirectional composite) or in the warp (woven composite) – often called 0°, one in the transverse direction of the fibers (UD) or in the weft (woven composite) – often called 90° and one in the shear direction – often called 45°. If for metallics 5 specimens are needed to assure the repeatability, the composite materials need 15 specimens. If now, we turn into the dynamic loadings in order to check the influence of the strain rate, it is necessary to test at least 4 different strain rates. A common characterization from quasi-static to dynamic in tension leads then to at least 75 specimens.

In the automotive industry, the introduction of woven thermoplastic composite materials points out a problem concerning the materials characterization because the matrix of the composites can be sensitive to the environmental conditions (temperature and the Relative Humidity). In order to take into account different types of climate all over the world, the automotive engineers must assure the behavior of some structural parts for a range of temperature from -40°C to $+80^{\circ}\text{C}$ and for a range of humidity going from a dry climate (Relative Humidity of 0% - RH0) to a wet climate (upper or equal to Relative Humidity of 85% - RH85). This constraint imposes, if 3 temperatures and 3 RH have to be carried out, to multiply the number of experimental tests by 9, so 675 specimens! This is the main reason which has pushed the IRT Jules Verne and their automotive industrial partners to bring a numerical solution

which aims could be, first, to identify quickly the main mechanical characteristics of a woven Glass/PA66 composite material for different environmental conditions and, second, have a reliable methodology to achieve the same goal in the case of change of the matrix nature.

To achieve the previous goal and in regard of the literature review [2]-[6], we decide to base our work on a multiscale homogenization method. This methodology is using a double homogenization (Fig. 1): one at microscale to obtain the tows behavior and one at mesoscale to obtain the composite behavior. Usually, the Representative Volume Element (RVE) for the tows corresponds to the one of a unidirectional composite material while the RVE of the composite represents as accurately as possible the one of the composite material.

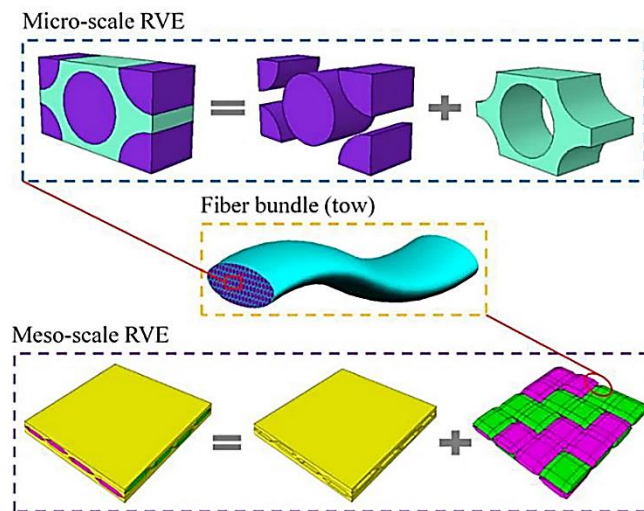


Figure 1. Simplified representation of the multiscale modelling strategy [2].

As far as the authors know, it is difficult to find in the literature, some researches really including the effects of both temperature and hygrometry using the multiscale methodology. However, the review of literature [2]-[5] shows that for composite materials made up of a thermoplastic matrix PA66, the level of humidity is acting on the composite behavior differently in function of the loading direction: while for the 0° or 90° the rupture constants are only affected, the action of RH plays a role, in shear direction, on the elastic domain, the ductility of the composite and the rupture constants. This sensitivity is mainly due to the fact that RH is moving the glass transition temperature (T_g) of the matrix (and of course of the composite). There is less papers regarding the influence of temperature on composite made up of PA66. However, the review [6] shows once again that the influence of the testing temperature on this type of composite is similar to the RH: indeed, as the RH is moving the T_g from negative values to positive (and high) values, the testing temperature leads to change the state of material (rubbery, transition or glassy). It is then important to be able to take into account as well the temperature as the RH in the multiscale methodology; this is the objective of this paper.

In a first part, we expose the experimental results obtained for both woven Glass/PA66 composite material and PA66 matrix for several couple of temperature/HR. In a second part, we focus on the numerical methodology of homogenization including the type of constitutive laws we chose for each component. In a final part, we present the comparison between the experimental results for our composite and the one coming from the double homogenization. We also offer the future prospects relative to this methodology, highlighting the key points.

2. Experiment

2.1. Woven Glass/PA66 composite

Tensile tests have been done on specimens of 250 x 25 x 2 mm dimensions for 3 main orientations: 0° (the woven is balanced), 45° and 30°; the chosen size of specimens allows to contain at least 1.5 to 2 the RVE size (depending on the composite orientation). Each time, the tests have been done for 3 different temperatures (-40°C, +23°C and +80°C) and 3 different RH (RH0, RH50 and RH85). The procedure to ageing the specimens was firstly to dry them using a vacuum drying system and secondly to change their state to RH50 and RH85 using a climate chamber. In both cases, the time to achieve the RH0 state or both RH50 and RH85 states was identified using a weighing procedure. The tests correspond both to rupture tests and cyclic tests (with a maximum of 6 hysteresis loops to measure the damages). The results (Fig.2 and Fig.3) show the same observations than for others types of composite material in the literature: quite no sensitivity to the environmental conditions in longitudinal direction except for rupture constants and a strong influence on the shear direction. For each test, data have been extracted, characterizing then the elasticity, damage states and irreversible strains and will allow comparisons with our virtual tool.

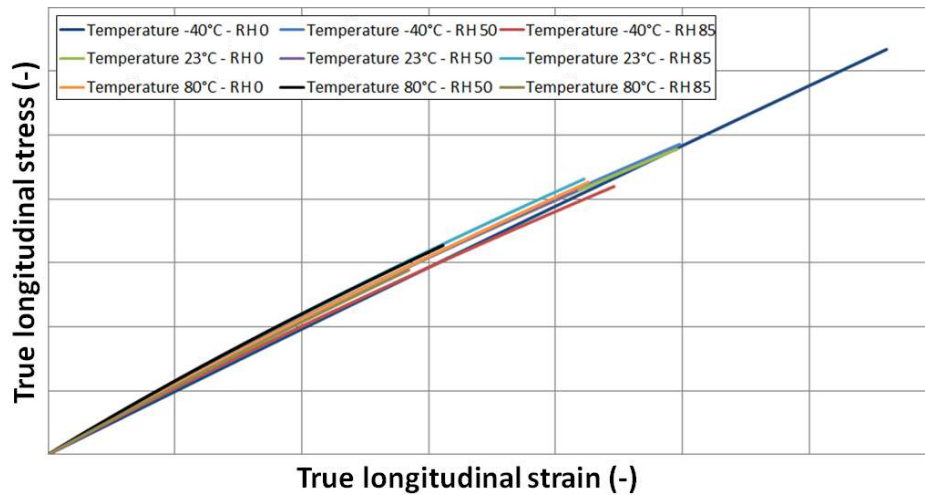


Figure 2. Behavior of Glass/PA66 woven composite in longitudinal direction.

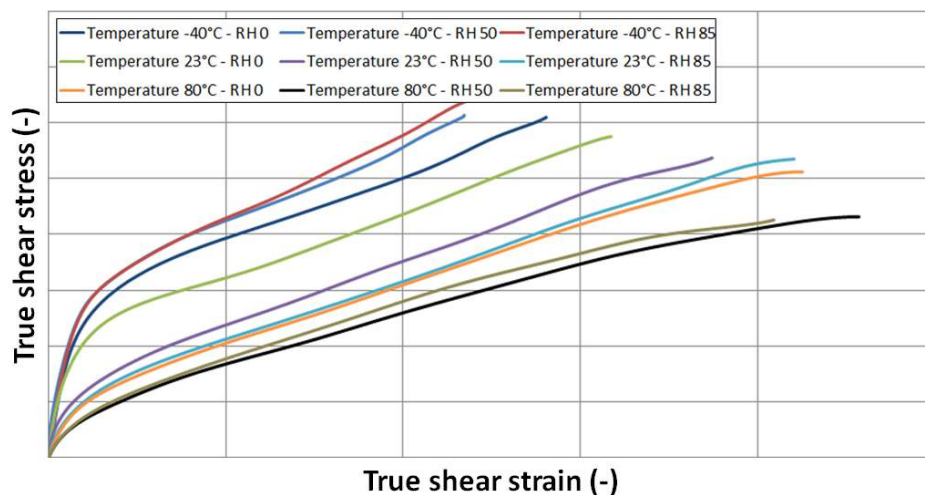


Figure 3. Behavior of a Glass/PA66 woven composite in shear.

2.2. PA66 matrix

Tensile tests have been carried out on specimens of 170 x 10 x 2 mm dimensions. Only several couples of temperature/RH have been chosen in accordance with the principle of temperature/RH equivalence [7]. An identical ageing procedure than for composite material has been applied. A DMA experiment has also been done for RH50 and RH85 to determine the glass transition temperature of the matrix. The tests correspond both to rupture tests and cyclic tests (with a maximum of 6 hysteresis loops to measure the damages). The results (Fig.4) well demonstrate that the humidity is acting as a plasticizer (due to the increasing mobility of the polyamid molecules chains) and then modifies its behavior. For each test, data have been extracted, characterizing then the elasticity, damage states and irreversible strains: these data will be used for the model developed used by the double homogenization.

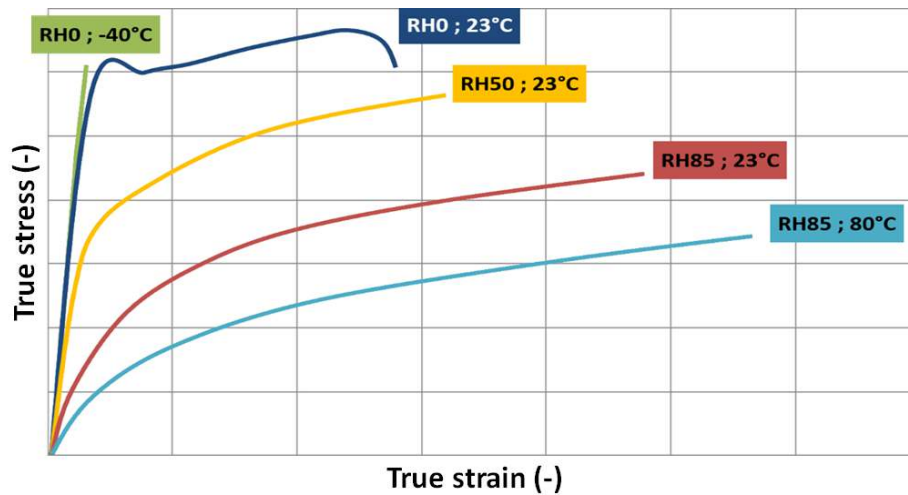


Figure 4. Behavior of a PA66 matrix.

3. Double homogenization methodology

3.1. First homogenization: the tows

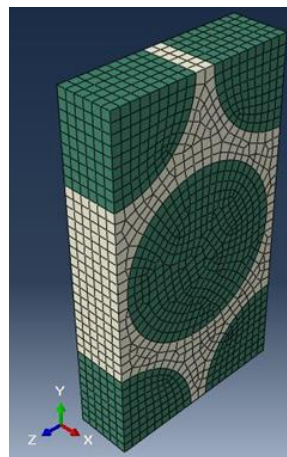


Figure 5. Geometry of PA66 RVE.

The RVE to obtain the tows behavior is the one coming from a UD composite material (Fig. 5). This is the most common way we can find in the literature to model them. The constitutive law of the Glass fibers is linear elastic (with standard values for the Glass); the constitutive law of PA66 is an isotropic elastic-plastic with damage law. This law has been developed introducing isotropy in some composite behavior laws developed within our research team [9]-[10]. The parameters of this constitutive law have been identified using the experimental data for each available couple of temperature/RH.

For the homogenization, we assume to have a perfect contact at the interface of tows/matrix (as first assumption because of lack of information). We have applied periodic boundary conditions which can be adapted to some direction such as shear and we carried out numerical tests to obtain both principal and shear behaviors. The results provide an elastic fragile behavior in the direction of the fibers belonging to the tows and nonlinear behavior in the others directions (Fig. 6).

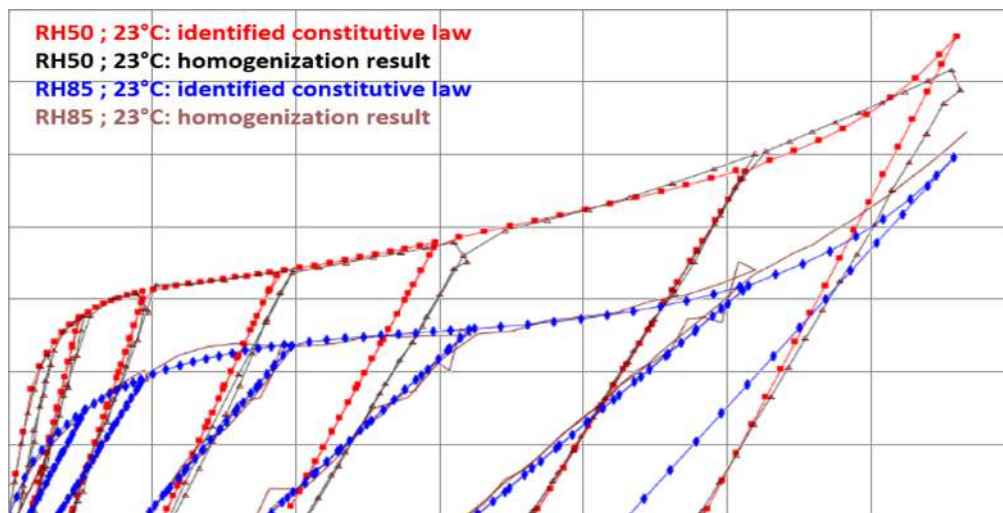


Figure 6. Shear behaviors obtained after homogenization for the tows.

Once the behavior is obtained using this first homogenization, we identify from the numerical results the parameters of our constitutive law that we implemented within Abaqus (VMAT). This constitutive law is an extension to the 3D of a UD composite material law we previously developed [11]. It is an elastic-plastic with damage in transverse and shear directions. The parameters identification is done for different temperature/RH couples (Fig. 6).

3.2. Second homogenization: the Glass/PA66 woven composite

Instead of using a generic software which creates a RVE, we chose to build a parametrizable RVE on CATIA V5. This choice allows us to act on the periodicity dimension (lengths of RVE), the distance between the tows, both width and height of tows and the thickness of the RVE. Such as for the tows, the contact is assumed to be perfect between the tows and the matrix. For a numerical simulation at one given RH, we also assume that both tows and matrix are in the same state of RH. This assumption is strong because the water diffusion in the composite material is a complex process and naturally leads to an overall average RH even if the matrix, tows and the interface tows/matrix and fibers/matrix possess different level of RH. The constitutive laws used for both tows and matrix are the ones issued from the first homogenization.

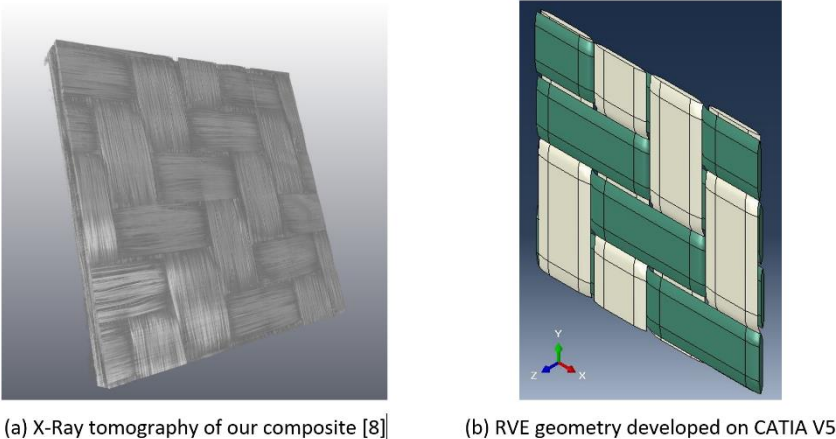


Figure 7. Developed geometry of Glass/PA66 RVE.

4. Comparisons between experiment and the virtual tool

The results that we present in this part, are the shear behavior of the composite at +23°C and RH50 (Fig. 8) and at +23°C and RH85 (Fig. 9). The first observation is that there is a good agreement between the experiment and the homogenization results even if the tows behavior cannot be validate in regard of experimental data. The assumptions we supposed (perfect contact in both homogenizations and same state of humidity level in both tows and matrix) allow to predict the composite behavior in stress with a maximal error about 30% on a large scale of shear strain. However, these assumptions has a strong impact on the shear damage evolution: the slopes of homogenization prodecure are different from the experimental hysteresis. We can also observe that there is a stiffening on the beginning of the numerical results at RH50 and a softening at the center of behavior at RH85. The explanation of this phenomena can be associated to the assumption of homogeneous humidity level both in tows and composite. As we mentioned previously, this assumption is a strong assumption because the diffusion process of water within the composite material is complex. It leads (from the literature review) to the apparition of some humidity level gradient (the water has less ability to migrate within the tows).

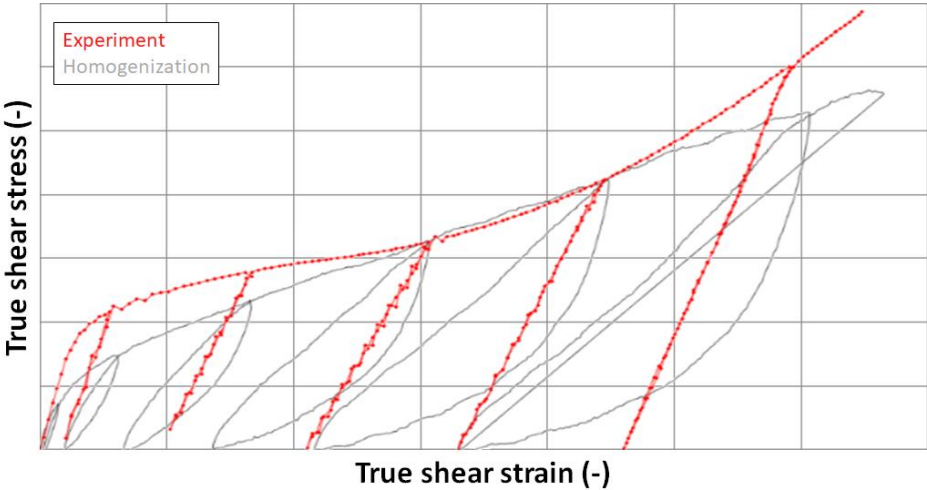


Figure 8. Comparison at RH50 and T=+23°C.

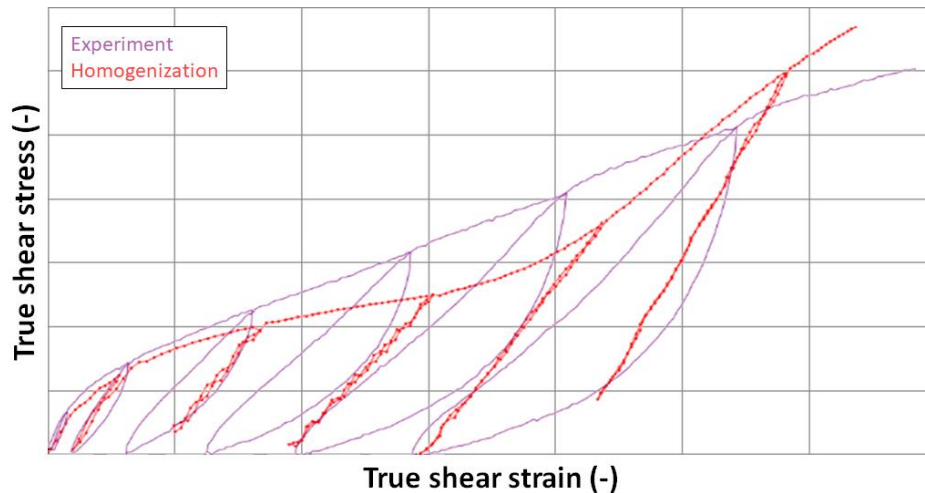


Figure 9. Comparison at RH85 and T=+23°C.

5. Conclusions

We suggest in this paper a methodology based on a double homogenization to predict the behavior of woven composite materials which matrix is sensitive to the temperature and level of humidity. This double homogenization is made up of a first UD RVE homogenization in order to determine the behavior of the tows and of a second composite RVE homogenization. Even if we postulate some strong assumptions such as the type of contact between fibres/matrix or tows/matrix or such as the homogeneity of the RH within the composite, the first numerical results leads to be able to mainly reproduce the behavior of the composite on large strain scale with a good agreement in respect of the experiment. It achieves one of our main goal: the identification of main characteristics of the composite for different environmental conditions to provide quick design. It allows also to substitute the experiment and thereby decrease its costs because this virtual tool requires only the characterization of the matrix.

Now, if some accurate information are needed, it is required to focus on both important aspects: the first one is the quality of the interface of the fibres/matrix or tows/matrix. In this case, the evaluation of the damage state within the composite (and the tows) could be better evaluated. The second aspect is in relation with the assumed homogeneous humidity level of the composite material. Some studies must be done as well experimentally as numerically in order to evaluate the approximative level of HR of each composite part. It will helps to tend the numerical behavior obtained by the homogenization method to the experimental one.

Acknowledgments

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