Compressibility and relaxation models for fibrous reinforcements in Liquid Composites Moulding.

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ABSTRACT : Liquid composites moulding processes are now widely used in the aeronautical and the aerospace fields. For the automobile sector, this type of processes is more and more used and still has very high potential. Optimizing moulding parameters, particularly the time cycle and improving the quality of the obtained parts, are key to increasing use of this type of process.

When closing the mould in the LCM processes, the compression phase followed by the reinforcements' relaxation are important stages that influence all process parameters.

This work presents a theoretical modelling based on two approaches. The results are compared to the experimental ones obtained within our laboratory.

In the experimental results, the compressibility behaviour of the reinforcements according to their type; number of ply, lubrication and compression speed were studied. The test results highlight the influence of these parameters on the compressibility and the relaxation of the reinforcements and identify the nesting and the anisotropy as being two important factors.

For the theoretical modelling, two approaches are proposed. In the first one, based on the equation of continuity, Darcy's law and the Terzhagui model; the total stress in the mould is equal to a viscous stress due to the fluid flow and an elastic stress due to the fibers response. The equation of Chen and Al, used to model elastic stress allows us to predict the compressibility of the impregnated reinforcements. The second approach is a rheological one where the models of Zener, Burger and Maxwell are used.

The results analysis highlights the influence of some moulding parameters and fibrous reinforcement's compression rules. A good agreement is noted between the experimental and the theoretical compression curves of the fibrous reinforcements. The rheological model of Maxwell gives the best prediction of reinforcements behaviour in both compression and relaxation phase.

Keywords: Liquid composite moulding, compressibility, relaxation, rheology.

1. INTRODUCTION

The liquid composites moulding, which include the RTM, the VARTM, the CRTM and the RFI processes, is a manufacturing method largely used in the advanced technology industries and has still a great potential of application. From a practical point of view, all the LCM processes have a more or less long phase of compression of the reinforcement. This step is done completely before the injection of the resin (RTM), or at the same time as in the CRTM or the infusion processes. This step also influences the compression rate of reinforcement and consequently the process of filling of the mould. This has a direct impact on the profitability of the process and the performances of the parts obtained.

This work on the compressibility of the reinforcements presents a modelling using a micromechanical and a rheological approaches. The first model of compressibility of the reinforcements is that of Chen [1] represented by a power law between the stress and the fiber volume fraction. It is written :

$$\sigma = A V_f^B \qquad (1)$$

A and B are parameters of adjustment of the models. Several authors underlined the large dispersion of the results obtained for these two parameters and some modifications of this model has been proposed [2,3] in order to better fit the experimental results. Chen et al. [4] proposed a model using physical parameters. These models applies only to the phase of compression and do not allow to describe the phase of relaxation. Gutovski & Al proposed a model based on the beams theory [5]. This model, in spite of his micromechanical aspect, does not permit to model the phenomena observed in the experiments. Several authors used the rheological models but the phases of compression and of relaxation are described separately [6,7]. These models give good results thanks to the use of the coefficients of adjustment.

For the experimental part, several authors were interested in the study of the compressibility of the reinforcements. An abundant literature exists on this aspect in particular the study of the effect of the type of reinforcement, the rate of compression, the number of plies or the impregnation [8-10]. The experimental studies highlight at the same time the phase of compression and the phase of relaxation which are represented on the same figures [11]. Kelly [12] proposed interesting model inspired from the work of Saunders [13] which treats simultaneously the phases of compression and of relaxation.

The objective of this work is to propose two approaches for the modelling of the compressibility. The first one is based on the model of Chen and the second uses the rheological models of Zener, Burger and Maxwell. The results obtained are compared to the experimental curves obtained within our laboratory. The experimental curves present simultaneously the phase of compression and of relaxation. The effects of the process parameters, such as the architecture of the reinforcement, the number of plies, the rate of compression and the impregnation on the compressibility of the reinforcements have been studied.

2. MICROMECHANICAL APPROACH

For the modelling of the viscoelastic behaviour of the fibrous reinforcements, the approach by equation of continuity and Darcy's law are used. The viscous stress is generally well modelled. This is not the case for the elastic stress. We propose in this work to use the micromechanical model of Chen et al. It is written :

$$P=\frac{1}{C_b}\left(1-\frac{V_{f0}}{V_f}\right) \qquad (2)$$

C_b represents the compressibility coefficient of the reinforcement. It is a function of the fiber fraction before and after compression. This equation is used with the equation of continuity, that of Darcy, the boundary conditions and the law of Terzaghi to obtain the following equation :

$$\overline{P}_{totale}=\frac{1}{C_b}\left(1-\frac{h(t)}{h_0}\right)-\frac{1}{6}\frac{\mu}{K}\frac{V_c}{h(t)}a^2 \qquad (3)$$

This relationship represents the viscoelastic response of the saturated reinforcement and can be written as a viscous part $\left(-\frac{1}{6}\frac{\mu}{K}\frac{V_c}{h(t)}a^2\right)$ and an elastic part $\left(\frac{1}{C_b}\left(1-\frac{h}{h_0}\right)\right)$. The model of Carman-Kozeny [14] is used to determine the axial permeability of the fibrous reinforcements.

3. RHEOLIGICAL APPROACH

Two phases are to be distinguished in the compression tests of the reinforcements; 1. The step of compression ($t\leq t_r$) where the rate of compression is maintained constant ($\dot{\gamma}=\frac{d\gamma}{dt}=\dot{\gamma}_0=Cte$). 2. The step of relaxation ($t>t_r$) where the strain is maintained constant ($\gamma=Cte$).

Table 1 summarizes the rheological equations of the models of Burger, Zener and Maxwell corresponding to the phases of compression and of relaxation.

Models	**Compression** $\dot{\gamma}=d\gamma/dt=\dot{\gamma}_0=Cte$
Burger	$\sigma(t)=k_1\left(e^{t/\tau_{1c}}-\frac{\tau_{2c}}{\tau_{1c}}e^{t/\tau_2}+\frac{\tau_{2c}}{\tau_{1c}}-1\right)$
Zener	$\sigma(t)=k_1\left(e^{-t/\tau_{1c}}+\frac{1}{\tau_{1c}}t-1\right)$
Maxwell	$\sigma(t)=k_1\left(e^{t/\tau_{1c}}-\frac{1}{\tau_{1c}}t-1\right)+k_2\left(e^{t/\tau_{2c}}-\frac{1}{\tau_{2c}}t-1\right)$

Models	**Relaxation** $\gamma=\gamma_0=Cte\ et\ \dot{\gamma}=\ddot{\gamma}=0$
Burger	$\sigma(t)=k_1\left(e^{-(t-t_r)/\tau_{1r}}-e^{-(t-t_r)/\tau_{2r}}\right)+\sigma_r e^{-(t-t_r)/\tau_{2r}}$
Zener	$\sigma(t)=k_1\left(e^{-(t-t_r)/\tau_{1r}}-1\right)+\sigma_r$
Maxwell	$\sigma(t)=k_1\left(e^{-(t-t_r)/\tau_{1r}}-1\right)+k_2\left(e^{-(t-t_r)/\tau_{2r}}-1\right)+\sigma_r$

Table 1: Models of Burger, Zener and Maxwell.

4. EXPERIMENTAL PROCEDURE

Dry and saturated reinforcements are used in the experiments. The testing machine used is a universal press of a maximum capacity of 50 KN controllable in displacement. The software of the driving machine allows the tracing of the curves representing the evolution of the compressive force or the compressive stress according to time. The reinforcements in the form of rectangular plates of dimensions 150*100 mm^2 are compressed between two rigid plates up to a constant level of strain. The deformation is then maintained constant to make it possible the relaxation of the reinforcement. The tests made it possible to study the effects of the architecture of the reinforcement, the rate of compression and impregnation of the reinforcements by glycerin diluted to meet viscosities of 0,105 and 0,165 Pa.s.

5. RESULTS

5.1 Micromechanical model

Figures 1 and 2 respectively present the compression of a random mat 624 and twill reinforcements at 3 mm/min and impregnated by a glycerine of viscosity 0,105 Pa.s. The approach by equation of continuity and Darcy's law associated to the model of Chen et al. gives results in agreement with the experimental data for a fiber volume fraction lower than 45% for the mat and lower than 55% for Twill. Knowing that the fiber volume fraction usually used in the LCM processes is about 50%, the predictions are thus in agreement with the experimental results.

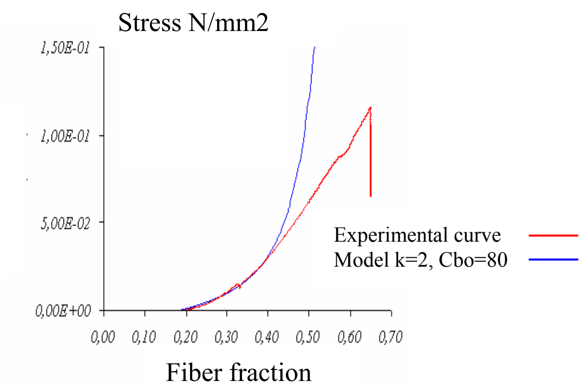

Figure 1: Validation of the model based on the equation of continuity and Darcy law for mat 624.

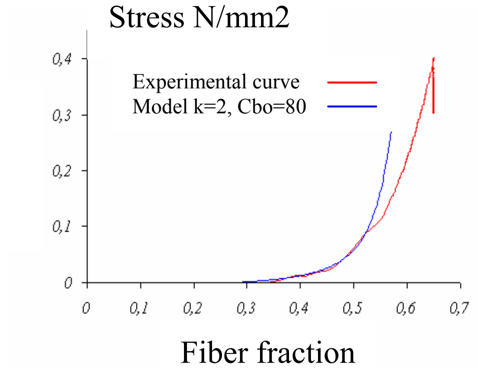

Figure 2: Validation of the model based on the equation of continuity and the Darcy's law for twill.

5.2 Rheological models

The studied rheological models can be classified in two categories: the Zener model that has one relaxation time and Burger and Maxwell models with two relaxation times. The results obtained are presented respectively for the three models in figures 3 at 5. For the rheological approach, the software Gnuplot which employs Levenberg-Marguadt method has been used [15]. The best results, particulary concerning the relaxation time, are obtained with the model of Maxwell. The relaxation time decreases with the impregnation and increases with the grammage.

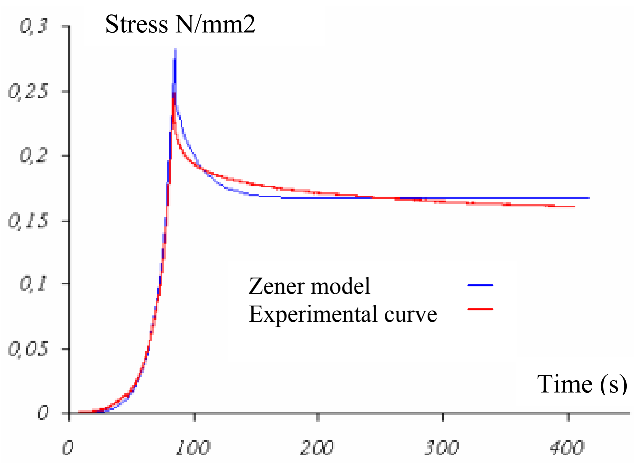

Figure 3: Validation of the rheological model of Zener in the case of a mat 450 of 20 plies.

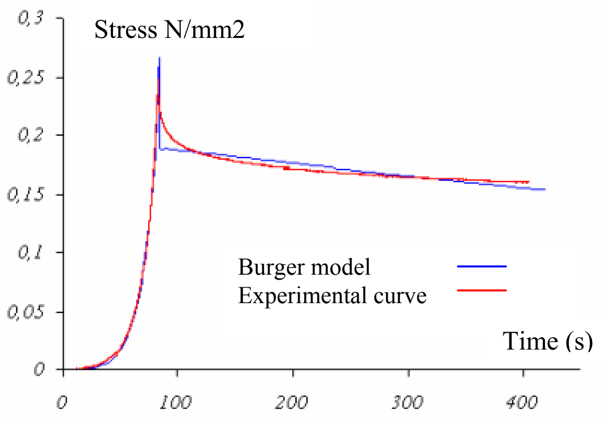

Figure 4: Validation of the rheological model of Burger in the case of a mat 450 of 20 plies.

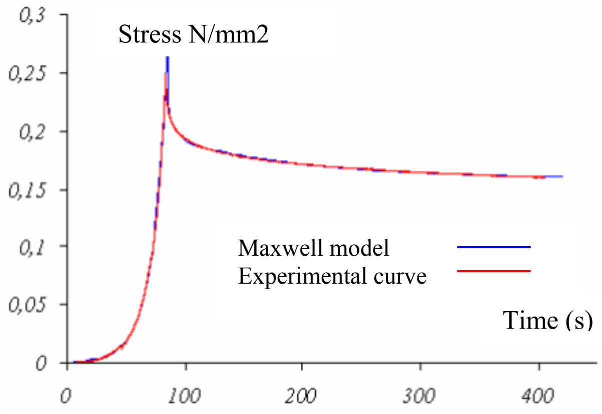

Figure 5: Validation of the rheological model of Maxwell in the case of a mate 450 of 20 plies.

6. CONCLUSIION

In this work, we used two approaches for the modelling of the compressibility. The first one is based on the equation of continuity, the Darcy's law and that of Terzhagui. The second is a rheological approach where the models of Zener, Burger and Maxwell are studied. For the tests of compressibility, results show a good agreement for fiber volume fraction less than 50%. This is very acceptable considering the rates of reinforcements usually practised in the LCM processes. For the approach by the rheological models, the Maxwell model gives the best results in particular concerning the relaxation time. The last one decreases with the impregnation and increases with the grammage.

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