THE COMPRESSION BEHAVIOUR OF NON-CRIMP FABRICS COMPOSITES FOR AUTOMOTIVE APPLICATIONS

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Abstract
The automotive industry is making great effort to reduce costs and increase the productivity of composites manufacturing processes. Even if all these technologies are still emerging, it appears that Liquid Composite Moulding (LCM) processes in which there is a compression phase, as the Wet Compression Moulding (WCM) or Compression Resin Transfer Moulding (CRTM), are the best positioned. In these cases, as the dry fibre preform is compressed during the process, it is essential to know the compression behaviour of these materials in order to select and optimise the manufacturing process by simulation tools.

When dealing with the compression process, the preforms have usually been considered to exhibit an elastic linear behaviour. Nevertheless, the last publications have shown that this behaviour is mainly viscoelastic.

In this work the relaxation of a dry (no binder) 50k carbon fibre Non-Crimp Fabric (NCF) under compression has been characterised for 3 different fibre volumes and fabric layer quantities . To do so, the viscoelastic behaviour has been described by fractional models, which compared with exponential models, are able to correctly reproduce the relaxation of the material during the maximum compression stage.

1. Introduction

Vehicles lightweight is one of the most important topics considered in the automotive industry. In this sense, composite materials are an efficient alternative to metals, and therefore, the automotive industry is making a great effort in order to reduce costs and increase productivity for the manufacturing process of these materials.

The use of Non-Crimp Fabrics (NCF), in which the unidirectional (UD) fibres with several orientations are transversally stitched, facilitates the automation of manufacturing processes by increasing their productivity [1]. Furthermore, the probability of fibre orientation errors is reduced, together with the better in plane properties compared with woven fabrics (there is no fibre crimps) and better interlaminar properties (the layers are stitched together).

Due to the high manufacturing rates and reduced manufacturing cost margin needed, the best positioned manufacturing methods are the LCM processes in which there is a compression phase, such as WCM or

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CRTM [2]. In such cases, the dry fibre preform is compressed during the process, so it is essential to know the material compression behaviour in order to select and optimise the manufacturing process by means of numerical process simulation techniques.

The force acting on the mould surface is the sum of the pressure generated by the resin and the reaction generated by the preform compaction. The relative importance of each of these contributions depends on the viscosity of the resin, preform (type of fibre, roving, fabric, fibre volume), the dimensions and geometry of the part and the compression parameters. Even if the viscosity of the resin has been the subject of numerous studies, the mechanical response of the preforms has received less attention. In such cases, the most common material response has been considered as linear elastic behaviour. Nevertheless, most of the publications in recent years have shown that this behaviour is viscoelastic [3, 4].

The objective of this study is to model the stress relaxation of 50k carbon fibre reinforced NCFs while subjected to maximum compaction in function of the maximum fibre volume and the number of fabric layers. To do so, based on the experience of previous works [5], a fractional viscoelastic model is used for 3 different fibre volumes and fabric layer quantities.

2. Materials and experimetal setup

A 0/90 oriented 50k and 610 g/m^2 density carbon fibre NCF with $150 \times 140\,mm^2$ dimensions has been used to obtain the preforms. The tests have been performed in an Instron universal test machine with a 100 kN load cell. In order to compress the preform in an homogeneous way, an aluminium plate with dimensions $151 \times 140 \times 3\,mm^3$ is placed over the preforms, so that a 300 Pa pressure is applied which permits a similar initial deformation of the samples. To measure the deformation induced in the samples, the aluminium plate displacement is measured in two different locations by using 2 laser sensors, as it can be seen in the setup shown in Fig. 1 .

Figure 1. Experimental setup.

In the initial stage of the test, due to the weight of the aluminium plate, the preform has a initial thickness e_0 of 7 mm. Then, the preform is compacted at 50 mm/min until the maximum thickness of compaction is reached. The level of maximum compaction is maintained for some fixed t_c time and then the preform is completely unloaded at a constant velocity of 50 mm/min. In this study, on the one hand, 3 different compaction thickness levels have been analysed, corresponding to fibre volumes of 40 %, 50 % and 60 %, denoted vf40, vf50 and vf60, respectively. On the other hand, the effect of the number of fabric layers within the preform will also be studied.

In Fig. 2 the thickness and load profiles are shown. As stated before, in this study only the phase of maximum compression is studied, where the force decreases due to the material relaxation.

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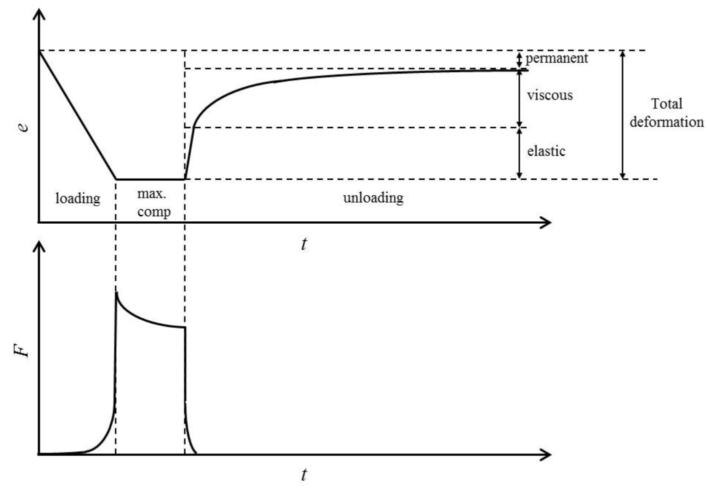

Figure 2. Preform thickness and compression force profiles

3. Fractional viscoelastic model

In order to characterise the viscoelastic material behaviour of a preform submitted to a constant compaction level, fractional models have been used [5–7]. These models generalise the classical models based on elastic elements (linear springs) and viscous elements (linear dashpots), which model the elastic and pure viscous character, respectively, by the use of Scott-Blair elements of α order. For $\alpha = 0$ and $\alpha = 1$, perfectly elastic an viscous elements are obtained, respectively. Thus, extending the method used for clasiccal mechanical models, based on springs and dashpots, the following fractional standard linear solid (FSLS) model is used to establish the relationship between the force in time $F(t)$ with the thickness in time $e(t)$:

$$F(t) + \tau^{\alpha} \mathrm{D}_t^{\alpha} F(t) = k_\infty e(t) + k_0 \mathrm{D}_t^{\alpha} e(t) \quad (1)$$

where τ, k_0, k_∞ are material parameters and D_t^{α} is the fractional derivative operator of order α with respect to time [8]. The relaxation force $F_{\mathrm{rel}}(t)$ corresponding to a constant maximum compaction thickness $e_0(t)$, imposed at $t = 0$ is obtained by integrating Eq. 1, which yields:

$$F_{\mathrm{rel}}(t) = F_\infty + (F_0 - F_\infty) E_\alpha \left[-\left(\frac{t}{\tau}\right)^{\alpha} \right], \quad t \geq 0 \quad (2)$$

where τ is the material relaxation time and E_α is the α-order Mittag-Leffler function, which is defined as [8]:

$$E_\alpha(z) = \sum_{k=0}^{\infty} \frac{z^k}{\Gamma(1 + \alpha k)} \quad (3)$$

For the particular case where $\alpha = 1$, Eq. 2 yields the exponential classical relaxation response:

$$F_{\mathrm{rel}}(t) = F_\infty + (F_0 - F_\infty) \mathrm{e}^{-t/\tau}, \quad t \geq 0 \quad (4)$$

4. Numerical-experimetal correlation

In Fig. 3, the experimetal curves corresponding to the compression tests for 3 different maximum compression levels. For all these tests, the maximum compression has been maintained for 20 s. For the

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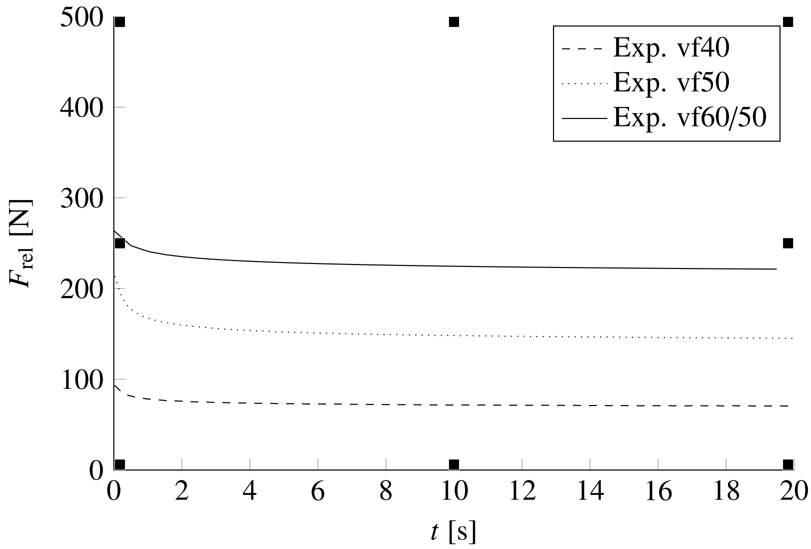

Figure 3. Experimental relaxation curves for three different compaction levels.

minimum, intermediate and maximum compression levels (vf40, vf50 and v60), the force relaxation levels obtained are 24 %, 32 % and 34 %, respectively.

Fig. 4 shows the experimental curves for the relaxation for 3 different fabric layers quantities within the preform, where the maximum compression time has been maintained for 20 s. The force relaxation levels are 27 %, 27 % and 18 % for preforms with 2, 4 and 6 layers, respectively.

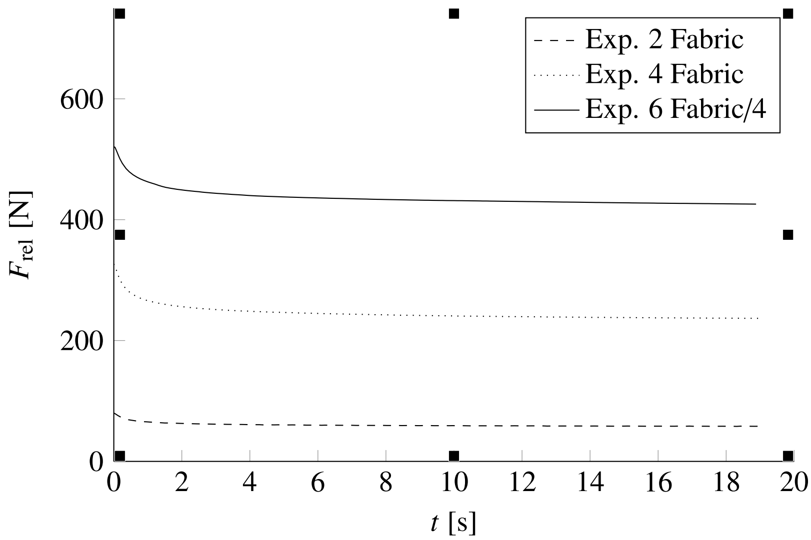

Figure 4. Experimental relaxation curves for three fabric layer quantities.

As it has been previously stated, fractional models are able to model relaxation phenomena in a more accurate way than classical exponential models. The comparison between exponential and fractional models is shown in Fig. 5. It can be observed the ability of fractional models to fit to experimental results in a very accurate way.

Table 1 gathers the fractional models parameters after identification from the experimental tests for dif-

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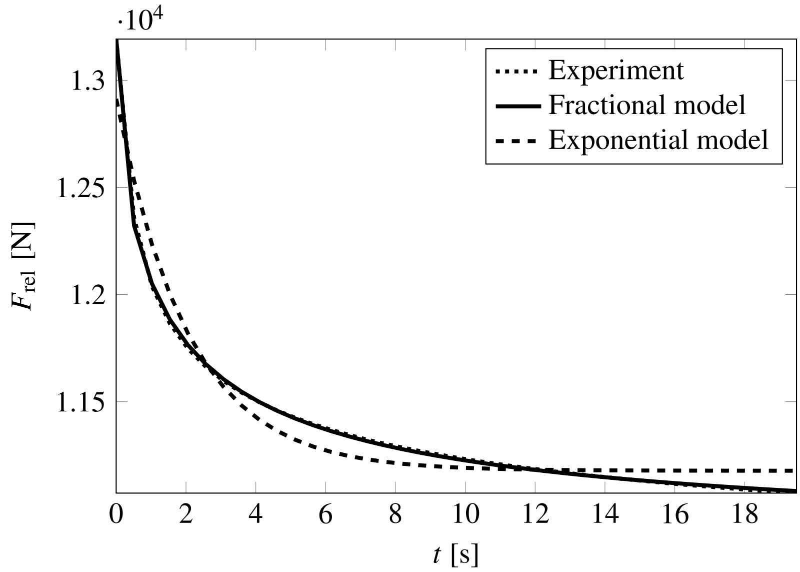

Figure 5. Relaxation curves numerical-experimental correlation for exponential and fractional models.

ferent v_{f} fibre volumes and n_ℓ number of fabric layers. The model's parameters, F_0 and F_{inf} represent

Table 1. Model parameters.

Test number	v_{f} [%]	n_ℓ	F_0 [N]	F_∞ [N]	τ [s]	α
T1	40	6	94.92	68.18	0.95	0.57
T2	50	6	207.46	144.68	1.05	0.78
T3	60	6	13196.39	10788.74	1.95	0.60
T4	41	2	81.89	57.30	0.80	0.69
T5	46	4	338.30	220.42	1.01	0.51
T6	40	6	2099.43	1676.58	1.13	0.64

the compression force at the beginning and end of the maximum compression stage, respectively. The relaxation time τ indicates the way in which the force decreases due to material's relaxation. In this sense, it can be observed an increase in the relaxation time as the final (maximum) fibre volume increases. Finally, the derivation order α varies with the maximum compaction level, which suggests that the derivation order is not an intrinsic material parameter and thus depends on the initial compression force level on the preform.

5. Conclusion

In this work, the relaxation of a dry 50k carbon fibre reinforced NCF has been modelled by fractional models while it is subjected to maximum compaction in function of the maximum fibre volume and the number of fabric layers.

For all the cases, compared with classical exponential models, the fractional model is able to correctly predict the material relaxation. Nevertheless, the fractional derivative order dependence on the maximum compaction level suggests this model parameter is not a material intrinsic one, and therefore depends on

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factors such as the preform's initial thickness, maximum compaction level, number of layers, etc.

As a future work, based on the ability of fractional models to correctly predict the material relaxation during the preform compression process, a model for the material recovery after the unloading stage will be developed, in order to optimise the manufacturing of LCM processes in which there is a preform compression phase.

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