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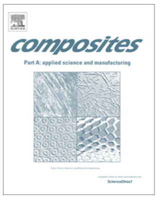

Squeeze flow in heterogeneous unidirectional discontinuous viscous prepreg laminates: Experimental measurement and 3D modeling

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ABSTRACT

The freedom of composite design can be improved by combining continuous and discontinuous prepregs. The forming of a pre-heated blank made of optimally oriented and distributed discontinuous prepreg plies may lead to unacceptable defects such as in-plane and out-of-plane wrinkles, sliding of plies over long distance, rotation of adjacent plies, bending of fiber induced by transverse squeeze flow and finally to inappropriate and inefficient fiber distribution. This arises because the individual discontinuous plies are free to move and deform in the mold during the forming step. First, this paper presents some experiments conducted to identify the behavior of a stack of unidirectional discontinuous viscous prepregs subjected to through-thickness compression. Then a model based on a heterogeneous anisotropic fluid approach is gradually developed in accordance with the experimental findings. It is shown that the various observed phenomena are retrieved by the numerical model and that the predicted values are in good agreement with measurements, but also that it requires to be solved in 3D with a relatively fine mesh in the thickness to provide good results.

1. Introduction

One of the key advantages in designing fiber reinforced composites is the freedom of design. Polymer composites can be shaped in very complex forms to meet design requirements starting from a prepreg material that is a flat sheet which combines fibers and thermoplastic or uncured thermoset matrix. To get a structural 3D part at a production rate suitable for the automotive industry, one of the available processes is to form the initially planar prepreg into a final 3D part through thermo-stamping. In order to keep the design freedom, the main concern is to control fiber orientation and reduce the remaining defects below an acceptable level, while keeping the target cycle time. The design freedom can be further developed in thermo-forming of thermoplastic or thermosetting materials combining continuous and discontinuous prepregs. Discontinuous prepregs are patches used to locally strengthen the part where necessary. Structural analysis helps to identify locations where a part needs to be particularly reinforced with continuous fiber reinforced composites and where the part is less mechanically loaded, allowing cheaper composites to be used. A multi-thickness/multi-material blank made of thermoplastic or thermosetting patches can be manufactured according to this design procedure as shown in Fig. 1. The blank is preheated and formed under press to the get the tailored composite [1]. Fig. 1b shows the flat blank designed to be formed to obtain a curved hat-shaped framing component. A discontinuous woven prepreg placed on the right-hand side of the blank is initially aligned with the component axis. After forming to obtain the hat shape, this patch experienced a rotation as shown in Fig. 1c. No in-plane shearing is observed because the forming in this region of the component consists in squeezing and folding the discontinuous prepreg. On the left-hand side of the tailored blank, a discontinuous unidirectional prepreg underwent large transformations as seen in Fig. 1c. Fibers are no longer straight and the ply dimensions are not controlled due to the large squeeze flow. Pure sliding of discontinuous prepreg are also observed in vertical zones as a consequence of the mold closing. The main advantages of this technology are the use of noble materials only where necessary, allowing for fewer scraps while achieving final weight reduction. Beyond these many advantages, there are still some difficulties to overcome as shown in the example in Fig. 1. The pre-heated blank is not held inside the tool, which lets the individual discontinuous plies free to move and deform in the mold during the forming step. This can lead to unacceptable defects such as in-plane and out-of-plane wrinkles, sliding of patches over long distance, rotation of

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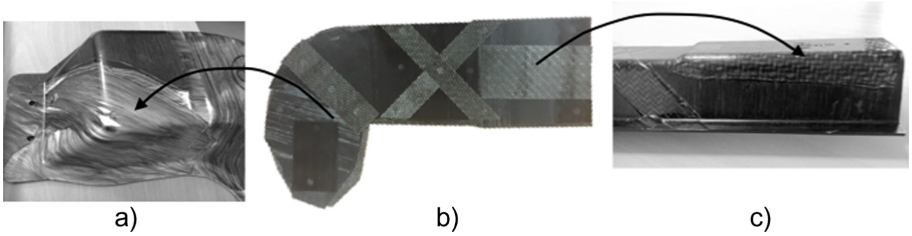

Fig. 1. (a) UD prepreg deformation and sliding, (b) flat multi-material blank before forming, (c) woven prepreg rotation [1].

adjacent plies, bending of fibers induced by transverse squeeze flow and finally to inappropriate and inefficient fiber distribution [1]. All these mechanisms are the result of stresses (compression, tension and shear) which build up during the forming process.

The interlaminar shear effects play a significant role in the forming of multi-layered composite parts, especially when discontinuous patches made of continuous fibers are introduced in the lay-up. A resin rich layer exists in between prepreg plies, where the two resin rich layers on either side can represent about 5% of the total thickness [2], with the thickness depending on the technology used. It has an impact on the behavior of the plies [3–5]. Due to its important lubrication function, the thermoplastic or thermosetting matrix decreases interply friction and therefore facilitates large amount of slippage, deformation and rotation of discontinuous plies. Interply-slip helps to alleviate the in-plane stresses due to compression, and fiber waviness. Fiber buckling can then be avoided.

The production of quality parts without extensive experimental investigations is needed. It is therefore important to predict where issues may occur during forming and how they can be alleviated. Designing the process through a trial and error procedure may lead to an acceptable product, but it always brings additional labor and tooling costs, machine time and scraps. Due to the complexity of the problem, the numerical simulation of the forming of complex blanks is necessary. Numerical tools can simulate the production processes and provide to the subsequent Finite Element Analysis (FEA) a material-scale description of the as-manufactured part. The in-plane loading and slippage of a UD prepreg ply has been modeled in [6]. This situation can arise when a prepreg patch is dragged by the tooling in the downward direction during the deep drawing of a blank.

This paper investigates the through-thickness compression of laminated fiber-aligned prepreg patches and its numerical modeling. The flow of the viscous matrix between and along the fibers is not considered. The continuous fibers in each ply prevent any extensional flow in the fiber direction [7], although a too low viscosity might lead to bleeding [8] [5]. Owing to the wide range of prepregs, to the various and complex mechanisms reported in [1], a detailed analysis is required to capture each mechanism individually. To do so, Section 2 presents dedicated experiments with instrumented specimens to measure large-deformation including changes in fiber orientation and inter-ply rotation. Experimental findings will be used to build a preliminary multi-layer heterogeneous 3D model presented in Section 3. Section 4 addresses its numerical solution. Section 5 presents some numerical tests linked to experiments run in Section 2. The numerical predictions are compared to experimental findings to refine the proposed model and make it more realistic.

2. Experimental observations

Compaction experiments are run on uncured unidirectional prepregs.

The material used in the experiments is a unidirectional carbon fiber-reinforced epoxy prepreg (Hexply M21/35.5 M%/268/T700GC from Hexcel) of 56.9% nominal fiber volume fraction. As it is a material of industrial grade, the given properties are subjected to statistical variations. The experiments are conducted on uncured thermoset unidirectional prepregs because the principal desired characteristic being the material to be a linear viscous fluid. As a monomer is very likely to stay in its linear domain regardless of the rate of shear, this assumption is considered reasonable. Futhermore, considering that the fillers added in the material are of small dimension compared to the ply, the resin rich layer can be considered an homogenized fluid which viscosity is the one provided by the manufacturer. Individual plies have a nominal cured thickness of 0.262 mm. $150 \times 150\ \text{mm}^2$ samples with 3 stacking sequences (UD, cross-ply and angle-ply) were considered. The ply edges are left unconstrained which allows them to expand and rotate freely. Thin copper threads of 0.1 mm in diameter were added at some interfaces between plies to probe the interface flow. An array of parallel threads aligned with adjacent UD plies is inserted at the interface. To form a grid, a second array of parallel threads can be placed at another interface between adjacent UD plies aligned in the second stacking direction. The two arrays of tracers are not inserted at the same interface as they would significantly increase the interface thickness and possibly interact with each other. A visual description of the configuration is presented in Fig. 2.

The dimension of the tracers is higher than the average thickness of the resin interface, however it does not have an impact on the flow as their stiffness is very low compared to the viscosity of the matrix. Futhermore they will be convected by the resin in the same fashion as the fibers are, considering that the flow is induced by the through-thickness compression. While their exact position in the thickness cannot be controlled, they will penetrate the sheet of fibers with which they are aligned. They therefore remain an interesting solution to inspect the configuration of the fibers.

As these tracers are dragged by the viscous polymer at the interface between two plies they provide useful experimental data to be compared to model predictions. After placing these tracers in the prepreg assembly, mold plates are pre-heated at 260 °C then the stack is debulked in the press under 100 kN during five minutes. Both the initial and final 2D geometry of the grid are obtained from a high-resolution X-ray computed tomography (CT) scanner (X-Radia Carl Zeiss). The high contrast between the copper threads and the carbon fiber polymer composite allows for a fast scanning with a very high accuracy.

The application of a compaction force produces a pressure gradient within the material that induces transverse flow. This transverse flow allows fibers to spread sideways under normal compressive load. Because the fibers are inextensible, the sample ply cannot expand along their axis but resin can be squeezed out in that direction if the resin viscosity is low enough. The viscosity evolves with the temperature and the degree of cure, but as the thermo-stamping is a fast process there is no evolution of these