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Assessment of semi-impregnated fabrics in honeycomb sandwich structures

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ABSTRACT

Semi-impregnated fabrics, or semipregs, are fabrics alternating dry and resin impregnated areas along the fibre bed surface. Due to their increased initial through thickness permeability to gas flow, these could constitute an alternative to prepreg in the skins of vacuum-bagged honeycomb sandwich structures, reducing the pressure in the honeycomb. The semipreg through thickness air permeability before cure is measured and is approximately three orders of magnitude higher than that of a unidirectional prepreg impregnated with the same resin. A model is proposed for the air permeability change during cure, as dry areas get infiltrated. Due to resin pouring inside the honeycomb cells, this type of semipreg is viable as a skin only if combined with a material that has low permeability to resin, e.g., a prepreg.

1. Introduction

Vacuum-bag only processing of sandwich structures faces particular challenges when compared to autoclaving, a consequence of using a pressure gradient of one atmosphere at most for manufacturing. In particular, the adhesion of the skin to the honeycomb core is reduced, as well as the compaction of the prepreg plies within the skins [1]. The combination of a weak adhesion with the presence of air inside the honeycomb cells may cause delaminations if the sandwich structure is exposed to pressure or temperature variations. Nonetheless, autoclave processing is expensive, in particular for large structures, and a growing interest has been observed for vacuum-bag only processing of sandwich structures.

In previous work, the through thickness permeability to gas flow – hereafter called air permeability, following soil science nomenclature – of the upper sandwich skin was shown to be a critical parameter for low pressure processing of honeycomb sandwich structures [2–4]. The air permeability was varied by perforating the skin or the individual elements, prepreg plies and adhesive film, aiming to reach a range of pressures inside the honeycomb [3]. The air permeability was characterised at room temperature and its evolution was monitored during vacuum-bag only cure. Skin air permeability was shown to control skin–core bonding through the pressure drop inside the honeycomb cells and potential degassing of the adhesive film [4].

An alternative to prepregs are partially impregnated prepregs, or semipregs, characterised by a selective impregnation of the fibre bed, enhancing resin flow during cure, but creating passages for gas evacuation during manufacturing [5]. There are several types of semipregs available in the market. Depending on the manufacturer, the strategy of resin distribution varies, some promoting the increase of the in-plane air permeability, others of the through thickness air permeability. Semipregs in laminate configuration were studied for applications in the automotive industry and aircraft [6–9]. Jonson and Smith [6] and Frost et al. [8] compared the available systems in the market to investigate if lightweight automotive body panels could be manufactured without the use of an autoclave. The panels were lighter, their surface finish better and overall costs were reduced when compared to manufacturing of panels with prepregs. However, the impact resistance was lower than that of the prepreg panels. Turner et al. [9] compared the cost performance between semipreg processing, a fibre preforming resin transfer process and stamped steel processing. The semipreg system offered the lowest process for low levels of mass production, i.e., below 500 parts per year.

Certain types of semipregs are made of alternate dry and impregnated areas along the fibre bed surface, Fig. 1. The fibre bed is a Non-Crimp Fabric (NCF) with two layers and the resin lines are only deposited on one of the layers. Due to this particular resin distribution, the initial through thickness permeability to air is expected to be high, and pressure in the honeycomb cells might be tailored to meet specific needs in sandwich processing. The objective of this study was thus to investigate the potential use of semipreg materials as skins in honeycomb sandwich structures. First, we measured the initial through thickness air permeability of the semipreg at room temperature (RT) in vacuum-bag only processing conditions, as well as its evolution during the resin curing cycle. Two configurations of the semipreg plies were tested, leading to distinct evolutions of permeability with cure. These results were compared to those obtained with a unidirectional (UD) prepreg, impregnated with the same resin. The effect of introducing an

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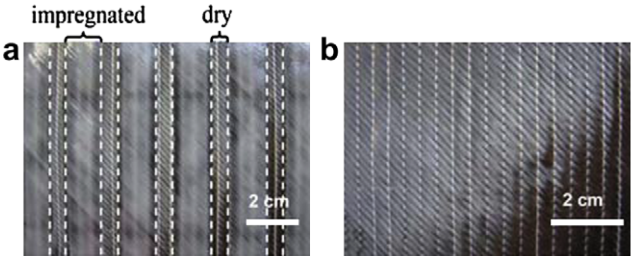

Fig. 1. Structure of the studied semipreg: (a) impregnated side; (b) dry side.

adhesive layer was also quantified. The advancement of the resin flow front was measured for laminate and sandwich samples made from the semipreg plies. An analytical model was developed to correlate the advancement of the resin flow in the semipreg with the evolution of the through thickness air permeability. Finally, solutions to use semipregs in honeycomb sandwich structures were proposed.

2. Through thickness air permeability measurement

Thorfinnson and Biermann [10,11] studied the impregnation of prepregs and its impact on the quality of autoclaved laminates, however the air permeability was not quantified. According to this study, the degree of impregnation in a prepreg is a key process variable. The in-plane prepreg air permeability was identified as determinant to the manufacturing of void free laminates, as air and volatiles tend to flow along the fibre direction. They also concluded that partial impregnation of the fibres promotes paths for the volatiles to escape. According to Harmon et al. [12], prepreg manufacturers, based on Thorfinnson's study, have purposely left air channels in the prepreg to guarantee successful air removal during consolidation. Air permeability measurement was introduced in composite manufacturing by Seferis et al., who measured the permeability to air in the in-plane direction of laminate prepregs with a falling-pressure method [13–16]. Prepreg air permeability was studied as a function of fibre orientation and prepreg aging time. Even though industry has approved and introduced the knowledge relative to prepreg air permeability, very few studies mentioned the permeability to a gas phase of the material comprising fibres and resin.

However, air permeability has been, since decades, extensively analysed in the context of soil science and hydrology [17–21]. Analytical solutions based on Darcy's law have been thoroughly developed [22–24] and permeability has been experimentally determined, mainly by measuring a steady state air flux through a partially water saturated soil sample. Recently, a falling-pressure method was proposed to determine the air permeability of asphalt and a model to describe the process was developed [25]. The falling-pressure method is easier to implement if the investigated range of permeability is large. It was adapted to measure the permeability of prepregs and adhesive films [2,3], and is used in the present work for evaluating semipregs.

The falling-pressure method requires transport of air molecules imposed by a pressure difference between two volumes, seperated by the material for which the air permeability is to be determined. On one side of the medium the pressure must be constant, e.g., by means of a vacuum pump, and the volume may be unknown. The other side of the medium is connected to a known volume, leak free, inside which an initial pressure is imposed, e.g., by opening a valve connecting the volume to the exterior. The model, for the configuration used when curing samples with a vacuum-bag, is expressed by Eq. (1), where $P_{1,i}$ is the initial pressure inside the honeycomb, acting in the volume V, $P_1(t)$ is the pressure in V at any instant t, $\overline{P_2}$ is the average pressure inside the vacuum-bag across the selected time range, K_a is the permeability to air, A is the area exposed to air exchange, Z is the length air has to traverse and μ_a is the dynamic air viscosity. The air permeability can be determined from the slope of the function on the left side of Eq. (1) versus time.

$$\ln\left[\frac{(P_{1,i}+\bar{P}_2)(P_1(t)-\bar{P}_2)}{(P_{1,i}-\bar{P}_2)(P_1(t)+\bar{P}_2)}\right] = -\frac{K_a A\bar{P}_2}{ZV\mu_a}\cdot t \qquad (1)$$

The derivation of Eq. (1) implies an isothermal condition, which, forcedly, does not occur during the curing cycle, in particular during the temperature ramps prior to a dwell. Provided the heating/cooling rates are small enough such that a series of $P(t)$ values may be collected within a small temperature variation, the isothermal state can be considered for each value of permeability. The variation of temperature affects the value of the air density in the ideal gas law, used in the derivation of Eq. (1). A variation of ±2 °C is generally admitted during the dwells, corresponding to a maximum error of 1.3% in air density. In order to obtain enough data to determine the permeability value during the ramps in temperature, a variation of ±5 °C is exceptionally accepted, corresponding to a maximum error of 3.2% in the air density. Gas viscosity is pressure and temperature dependent, nevertheless, for the range of interest, the pressure correction is small enough to be ignored [26]. Eq. (2) describes the dependence of the viscosity for ideal gases with the temperature, where μ_a is the viscosity of air at a temperature T and $\mu_{a,0}$ and T_0 are reference values, e.g., $\mu_{a,0} = 1.81\times10^{-5}$ Pa s at $T_0 = 293$ K, and C is the Sutherland constant, 117 K [27].

$$\mu_a = \mu_{a,0}\left(\frac{T_0+C}{T+C}\right)\left(\frac{T}{T_0}\right)^{3/2} \qquad (2)$$

As part of the manufacturing, several consumables are placed on top of the upper sandwich skin and will consequently contribute to the measured permeability. The permeability of the consumables can be deducted by considering Darcy's law and the mean permeability of parallel porous layers, for the case where the flow perpendicularly crosses the pile. The average permeability is given by Eq. (3), where e is the total thickness of the layers, e_i is the thickness of each layer and K_i their respective permeability in the direction of flow [28]:

$$\bar{K}_\perp = \frac{e}{\sum_{i=1}^{n}\left(\frac{e_i}{K_i}\right)} \qquad (3)$$

3. Modelling the resin flow front kinetics and resulting evolution of permeability to air

During cure, the resin in the semipreg resin lines starts to flow and impregnate the dry parts of the fabric, until two flow fronts meet. The resin flow front is modelled considering saturated flow of resin within a rigid fibre bed. This represents a simplified model, since the flow is non-saturated and the fibre bed is not rigid. The evolution of the through thickness air permeability is then calculated considering the two distinct areas of the semipreg system, which can be simplified to alternating impregnated and dry lines. Three simplifications are made, with respect to the semipreg structure: (i) the resin flow front is considered to fill the whole thickness of the fibre bed, although in reality it initially covers the thickness of the top layer, as schematized in Fig. 2; (ii) despite the NCF fibre bed structure, UD flow of the resin will be considered, progressing perpendicular to the border of the resin line; finally, (iii) an infinite resin supply is assumed and flow stops when both fronts meet, not when the initial quantity of resin has been depleted.

Combining the mass conservation equation and Darcy's law, the advancement of a saturated UD flow front, L, into a rigid fibre bed