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# SEMIPREGS: HOW THROUGH-THICKNESS AIR PERMEABILITY AND RESIN FLOW CORRELATE DURING VACUUM-BAG ONLY CURE

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**SUMMARY**: Non-autoclave processing of honeycomb sandwich structures generally leads to poor compaction and high porosity of the skins along with decreased skin-core adhesion. Skin air permeability was shown to be a critical parameter of low pressure processing [1]. It influences the skin porosity and controls the skin-core bonding through the pressure drop in the honeycomb cells and potential degassing of the adhesive film. This work focuses on a semipreg prone to be used in sandwich skins. Since it alternates dry and impregnated areas along the fibre bed surface, the initial pressure in the honeycomb cells might be tailored to specific needs. The through-thickness air permeability of the semipreg before cure was found to be about one and a half order of magnitude higher than that of a unidirectional prepreg impregnated with the same resin. The semipreg air permeability changed with cure due to resin flow, however with a different flow length than for the prepreg. Contrary to the prepreg and depending of the resin permeability of the adjacent layer, dry fibre areas might remain in the semipreg after cure, due to resin pouring across the fibre bed into the honeycomb cells. Sandwich skins combining prepreg and semipreg plies will be envisaged, aiming to join the homogeneity of the first with the high permeability of the second.

**KEYWORDS**: through thickness air permeability, resin flow, semipregs, sandwich structures

## INTRODUCTION

Vacuum-bag only processing of sandwich structures faces particular challenges when compared to autoclaving, a consequence of using the atmospheric pressure only 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. The optimum values of fibre volume fraction ($V_f$) and void content obtained in autoclaved composites, over 60 % and less than 1 %, respectively, are still a faraway objective for non-autoclaved composites sandwich structures, where $V_f$ is typically around 55 % and void content is between 5 % and 10 %. This refrains from using low pressure processing in the aircraft industry. 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.

The combination of a less performing adhesion with the presence of air inside the honeycomb cells may cause delaminations if the sandwich structure is exposed to pressure or temperature variations. To address this last issue, non-autoclave processing is adapted to the manufacturing of honeycomb sandwich with prepreg skins by increasing voluntary the air permeability of the prepregs. This is achieved by perforating the prepregs with a sharp tool in a patterned way [2]. One of the purposes of this procedure is to open an air path for the honeycomb cells voiding. In this way, the skin is better pressed against the honeycomb in an effort to increase the adhesion between skins and core. It is also performed in view of a better compaction of the plies and voids reduction. Despite this procedure, the adhesion between the skin and core of a sandwich structure fabricated through vacuum-only remains less performing than for the autoclaved structures [2].

In previous work the through-thickness air permeability was shown to be a critical parameter of low pressure processing of prepreg skins for honeycomb composites [1]. 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. The air permeability was characterised at room temperature and its evolution was monitored during vacuum-bag only cure. Skin air permeability was shown to influence the skin porosity and to control the skin-core bonding through the pressure drop in the honeycomb cells and potential degassing of the adhesive film.

Partially impregnated prepregs, or semipregs, are characterised by selective impregnation of the fibre bed, creating passages for gas evacuation during manufacturing. In this study, a semipreg with initially high through thickness air permeability was chosen. It is made of alternate dry and impregnated areas along the fibre bed surface. Due to this feature, the initial pressure in the honeycomb cells might be tailored to meet specific needs in the sandwich processing.

The objective of this study was to measure the initial through thickness air permeability of the semipreg at room temperature 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. The results were compared to those obtained with a UniDirectional (UD) prepreg, impregnated with the same resin. The effect of inserting an adhesive film was quantified. The advancement of the resin flow front was measured for laminate and sandwich samples made from the semipreg plies.

## THROUGH-THICKNESS AIR PERMEABILITY

Ahn et al. [3] developed an experimental method for in-plane prepreg air permeability measurement and a model for its prediction based on Darcy's law. Both the method and model were further refined and air permeability was studied as a function of orientation and prepreg aging time [4]. The principle can be designated as a falling-pressure method and an equivalent model was derived recently for the study of the air permeability of asphalt [5]. The falling-pressure method requires an exchange of air imposed by a pressure differential between two volumes having as separation medium the material of which the air permeability is to be determined. In 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. Typically, the valve will be opened for each permeability measurement. In view of the exclusive determination of longitudinal or transverse air permeability, it is very important to prevent air from flowing in one of the directions, which always implies some sort of sealing. The air permeability can be calculated by monitoring the pressure variation in the confined volume until both sides are in equilibrium. The boundary conditions are the constant pressure on one side and the initial pressure on the other. The model is expressed by equation (1), where $\overline{P}_2$ is the constant known pressure, $P_{1,i}$ is the initial pressure inside the honeycomb, acting on the volume $V$, $P_1(t)$ is the pressure at any instant $t$, $K$ is the permeability, $A$ is the area exposed to air exchange, $L$ is the length air has to traverse and $\eta$ is the air viscosity. The air permeability can be determined from the slope of the plot of the natural log of the function on the left side of Eqn. 1 versus time.

$$ln\left[\frac{\left(\overline{P}_2+P_{1,i}\right)\cdot\left(\overline{P}_2-P_1(t)\right)}{\left(\overline{P}_2-P_{1,i}\right)\cdot\left(\overline{P}_2+P_1(t)\right)}\right]=-\frac{KA\overline{P}_2}{LV\mu}\cdot t \qquad (1)$$

## EXPERIMENTAL

Two types of potential base materials for sandwich skins were used, a semipreg and a prepreg, both supplied by Advanced Composites Group (ACG) and impregnated with VTM 264 resin. The semipreg is a Zpreg® type, i.e., lines of impregnated regions partially covering the fabric thickness alternate with dry regions comprising the whole thickness of a continuous fibre fabric, see Fig. 1. This material will be designated as Zpreg. The fibre bed is a Non-Crimp Fabric (NCF) of T700 carbon fibre from Torayca, with a [+45/-45] configuration and areal weight of 400 g/m$^2$. The resin content is 40 wt%. The prepreg, with 34 wt% of resin content and 160 g/m$^2$ of areal weight, consists of UD carbon fibres from Zoltek, Panex 35 and is designated as Prepreg. When applicable, a supported adhesive film from ACG was used, with nylon support, resin system VTA 260, 313 g/m$^2$. For the permeability measurements, an aluminium honeycomb of 3 cm height was combined with the Zpreg and Prepreg plies, with approximately 0.4 cm of cell width and a density of 1785 g/m$^2$.

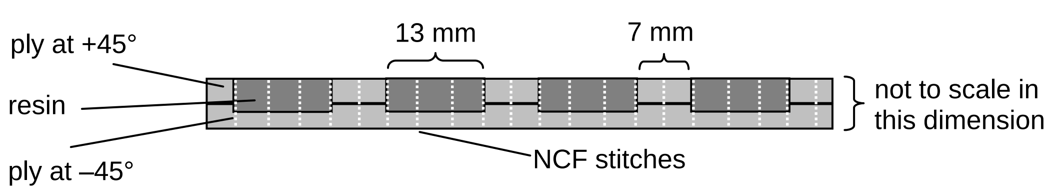



Fig. 1 Schematic representation of the Zpreg structure.

The advancement of the resin flow front was measured for the Zpreg, both on laminate samples and on sandwich type samples. For the laminate samples, one Zpreg ply was placed over a flat metal plate, while for the samples of sandwich type two Zpreg plies were stacked directly over the honeycomb. For both cases the flow was non-saturated, and the line that defines the advancement of the flow front has a wavy configuration. The values were measured along a parallel line with respect to the resin lines of the Zpreg, although the resin is advancing on the fibre bundles direction, i.e., at 45° (see Fig. 2). To compensate for the wavy configuration, the advancement was considered to be at half of the distance between the saturated front and non-saturated one.

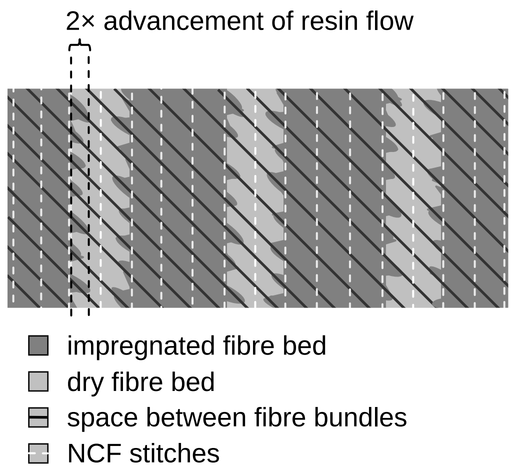
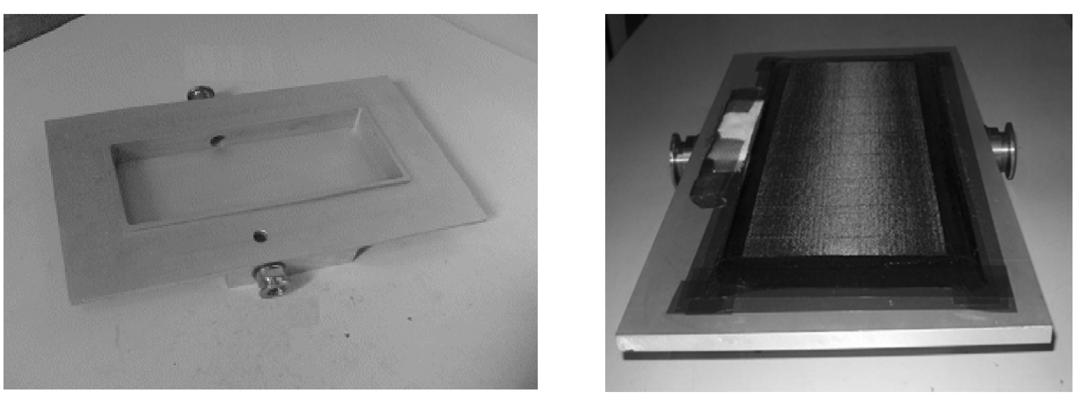



Fig. 2 Schematic view of the advancement of the resin flow front of the Zpreg.

The through thickness air permeability was determined using a leak tight mould, see Fig. 3 a). The Zpreg and Prepreg plies, sustained by the honeycomb, were placed over the mould cavity. Two Zpreg configurations were tested, each using two plies. One, designated as [90,90], indicates that both plies were placed over the mould in such way that the resin lines are at 90° with respect to the length of the cavity. Also, the resin lines of the two plies were superposed, originating alternated stripes of impregnated fabric with dry ones, across the stack thickness. The other configuration, designated as [0,90], indicates that the top ply had the resin lines along the length of the cavity and the ply in contact with the honeycomb has the resin lines at 90°. This configuration formed a checked pattern, where the area of dry fabric was reduced to small squares resulting from the intersection of the dry lines. The fibre bed stacking sequence was the same for both configurations, i.e., [+45/-45/+45/-45]. The prepreg had a stacking sequence of $[0_2/90_2]_S$.



a) b)

Fig. 3 a) Mould for the permeability measurements; b) mould after sample preparation.

The plies were oversized compared to the honeycomb in order to accommodate a sealant between the first ply and the mould, so that air was forced to pass across the plies in the through thickness direction. Also, polyimide tape was used to seal the edges of the skin, as depicted in Fig. 3b). Consumables were disposed above the plies in the following order: peelply, perforated film, absorber, breather and vacuum-bag enclosing the ensemble with a sealant against the metallic tool. The curing cycle, performed inside a Heraeus furnace, UT 6200, consisted of two dwells, an initial one of 2 h at 65 °C followed by a second dwell of 4 h at 80 °C. The heating and cooling rates were of 0.5 °C/min. A primary vacuum pump was connected to the vacuum-bag side. The pressure inside the volume isolated by the plies and enclosing the honeycomb was recorded during cure, as well as the temperature, using a LABView interface. The pressure inside the vacuum-bag was also recorded. The pressure sensors were from Leybold, measurement range from 1 mbar to 2000 mbar and from $5\times10^{-5}$ mbar to 1000 mbar, respectively.

## RESULTS

### Advancement of the resin flow front

The advancement of the resin flow front is summarized in Fig. 4, for laminate and sandwich samples. There is a large difference between the flow front advancement for each case. Indeed, when the Zpreg plies are stacked directly over a honeycomb the resin does not impregnate totally the dry fabric regions and the two flow fronts originating from consecutive resin lines do not meet. This is due to action of gravity on the resin while viscosity is low enough. As a result, a small quantity of resin gets poured into the honeycomb cells. This occurrence will have an influence on the permeability measurements of the Zpreg, i.e., the permeability will not decrease as much as it would if all dry regions would finish impregnated.

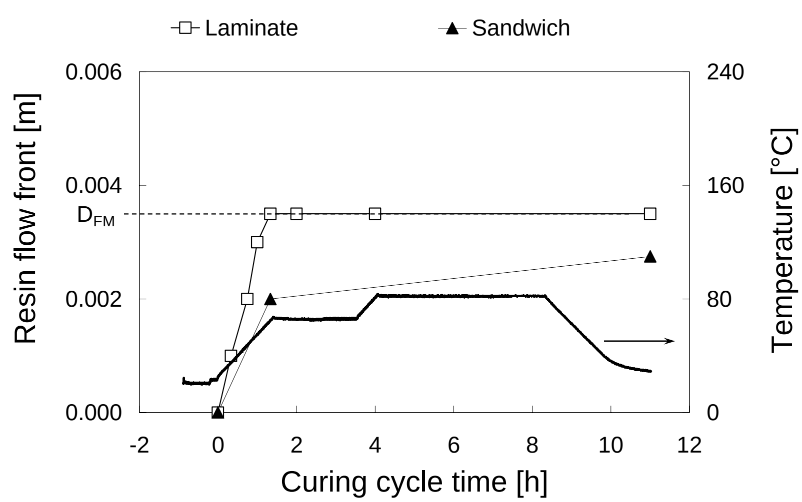



Fig. 4 Advancement of the resin flow front of the Zpreg with the curing cycle: laminate vs sandwich. The line at $D_{FM}$ indicates the distance at which the two fronts meet.

## Evolution of the Through Thickness Air Permeability

The evolution of the through thickness air permeability of the Zpreg with the curing cycle is summarized in Fig. 5. It was obtained with four similar samples, each with two Zpreg plies, with the resin lines at [90,90]. The initial permeability is $2.6\times10^{-10}$ $cm^2$. During the curing cycle the permeability decreases with respect to the initial value, mainly during the first two hours of the cure, until achieving a rather stable value of approximately $2.1\times10^{-11}$ $cm^2$. As discussed above, this value should be lower in case all dry fabric becomes impregnated.

Fig. 6 summarizes the results obtained for Zpreg samples with resin plies at [0,90]. Two types of samples were prepared, one with the plies directly over the honeycomb, as previously for samples [90,90] and other with an adhesive film between the Zpreg plies and the honeycomb. The evolution of the permeability of the adhesive film alone is plotted for comparison. The sample with resin lines at [0,90] and without adhesive film has an initial permeability very similar to the one of the sample with the resin lines at [90,90], i.e., $2.4\times10^{-10}$ $cm^2$. Although there is a reduction of the dry fabric through thickness path, the air flow is not affected. During cure the permeability decreases and stabilizes at about $1.7\times10^{-12}$ $cm^2$, approximately one order of magnitude lower than for the sample with resin lines at [90,90].

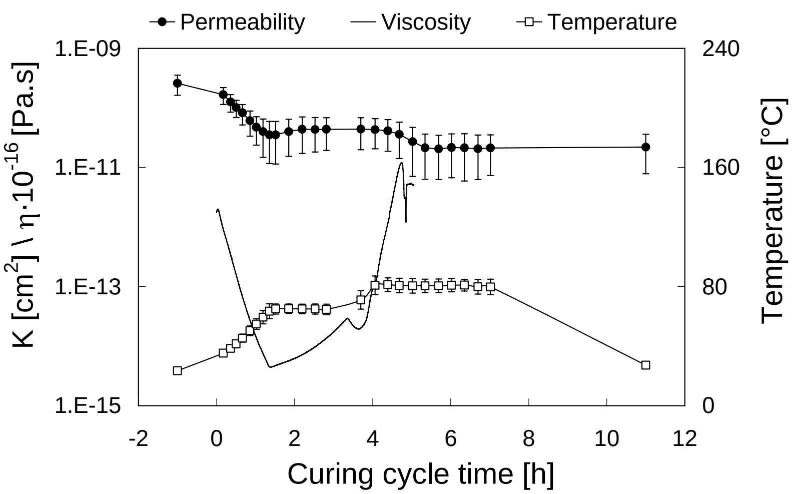



Fig. 5 Evolution of the through thickness air permeability of the Zpreg during cure. Average of four samples, each with 2 plies, resin lines at [90, 90].

The adhesive film has the particularity of being very impermeable, i.e., it has an initial permeability of about $2.2\times10^{-15}$ $cm^2$. Therefore, the sample with adhesive film has an initial air permeability approximately two orders of magnitude lower than the one without adhesive film. During cure the permeabilities of the samples with and without adhesive film reach similar values. Indeed, the adhesive film degasses during cure and acquires a porous texture causing its permeability to increase about two orders of magnitude.

The evolution of the through thickness air permeability was also monitored on plates made with the Prepreg, see Fig. 7. The initial through thickness air permeability of the Prepreg is about one and a half order of magnitude lower than that of the Zpreg, due to its uniform and complete impregnation with resin. During the two first hours of cure the permeability decreases for both materials, due to the same mechanism, but at a different scale. The resin viscosity decreases significantly during this period, see Fig. 5, allowing for resin flow. In the case of the Zpreg, it will flow between and through the fibre bundles of the NCF until the latter becomes fully impregnated. Although uniformly impregnated, the resin distribution in the Prepreg is not totally homogeneous; there are some air passages before cure that will be covered with resin as it becomes fluid, making the permeability decrease. The reason why the Prepreg permeability increases afterwards after this initial decrease is not yet fully understood, however it could be due either to resin microcraking or to degassing of the resin, much as it occurs with the adhesive film, but to a smaller extent. Investigations are still ongoing to understand this increase. After cure, the Prepreg will reach a through thickness air permeability lower than the Zpreg. However these values cannot be directly compared due to the existence of dry fabric at the end of the Zpreg cure.

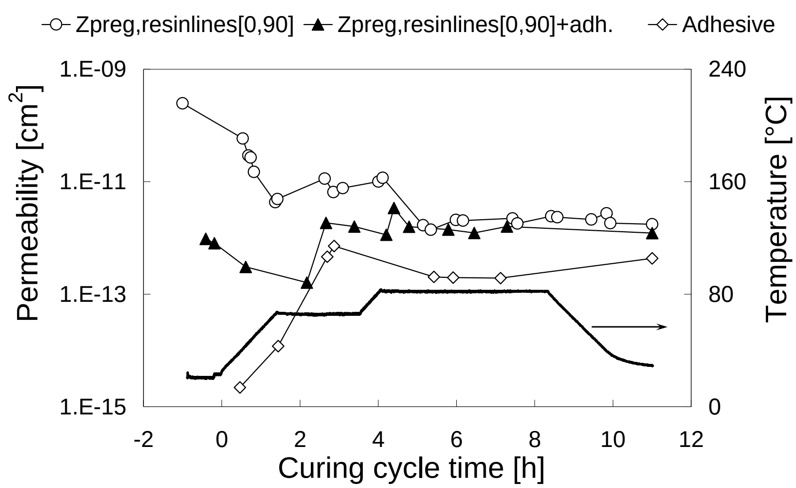



Fig. 6 Evolution of the through thickness air permeability of the Zpreg, samples with resin lines at [0,90], with and without adhesive film. The air permeability of the adhesive film is plotted for comparison.

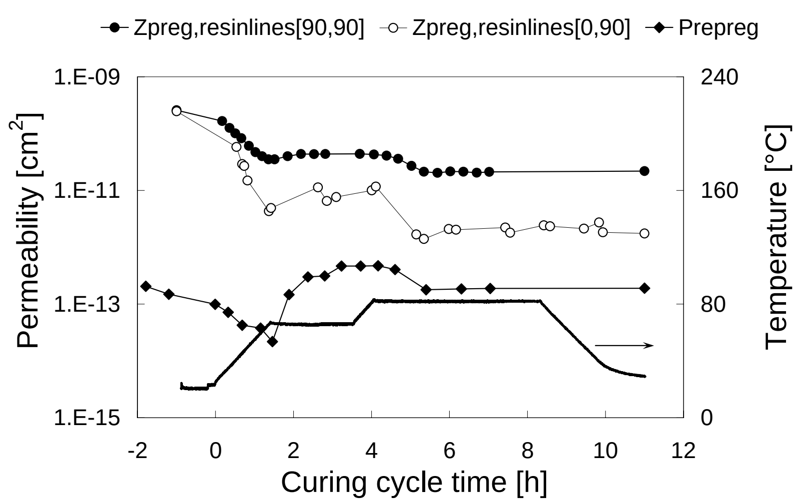



Fig. 7 Prepreg vs. Zpreg, resin lines [90,90]: evolution of the through thickness air permeability with cure.

## DISCUSSION AND CONCLUSIONS

The initial Zpreg through thickness air permeability was quantified and compared to that of a Prepreg, both impregnated with the same resin. The Zpreg has an initial air permeability of about one and a half order of magnitude higher than the Prepreg. This makes it an interesting element to use on the skins of a sandwich structure, since it allows reduction of pressure in the honeycomb, and as a consequence, increase of the effective pressure to compact the skins.

The Zpreg through thickness air permeability changes with the resin curing cycle, mainly due to resin flow. The resin, however exceeding in the resin lines, can pour through the honeycomb cells due to the combined action of gravity and hydraulic pressure. The outcome is the existence of dry fabric areas at the end of cure, due to resin shortage. All Zpreg becomes impregnated when cured over a continuous metal plate. This suggests the use of a layer that prevents vertical movement of the resin, beyond the supporting fabric. The use of an adhesive film could prevent part of this effect. Nevertheless, the through thickness air permeability of the sample having an adhesive film is not conclusive since the value after cure matches the one of the sample without adhesive film.

In the future, a membrane with selective permeability will be used monitor the Zpreg through thickness air permeability during cure. The membrane, though impermeable to resin will be permeable to air. It is also foreseen to study sandwich skins which combine both Zpreg and Prepreg plies, so that the Zpreg is not in contact with the honeycomb. Such system can combine the initial high permeability of the Zpreg with the homogeneity of the Prepreg.

## ACKNOWLEDGMENTS

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