RESIN INFUSION OF SANDWICH STRUCTURES - CORE/SKIN INTERACTIONS AND VOID FORMATION

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SUMMARY

This paper presents results of experimental and modelling work exploring aspects of fibre, core and resin interaction during the infusion process. In particular we observe the nature of regions of flow front convergence in areas containing various types of core, such as wood, sealed wood and closed cell foam. Data on comparative resin absorption for the various cores are presented. It is found that sealing porous core materials such as balsa does not prevent the absorption of significant quantities of resin. More importantly, completely impervious cores are unable to absorb either air or resin. The result of this is that air trapped during flow front convergence causes a higher degree of void content in the skin laminate, compared to more porous core materials. These phenomena appear to have attracted little research attention to date, and provide significant challenges for both experimentation and process simulation.

Keywords: resin infusion; core materials; sandwich structures; resin absorption; void formation.

INTRODUCTION

Sandwich construction (thin, stiff skins combined with relatively thick, low density cores) is ubiquitous in virtually all industry sectors. It has been recognised for several years that the core itself can also play an important role in enhancing and controlling the long-range flow of resin in liquid composite moulding (LCM) processes. Commercial forms of core material, such as foams and balsa, are commonly available with features such as holes drilled through-thickness, kerf cuts in one or both faces and separate blocks of rigid core held together with glass scrim. These features are all regarded as providing some degree of 'flow enhancement', allowing liquid resin to reach both faces of the sandwich laminate and to flow long distances within the part, sometimes eliminating the requirement (in resin infusion) for a surface distribution mesh.

Flow within skin laminate and core is thus complex and three-dimensional, and involves different physical domains, such as porous media and relatively large channels. The likelihood of convergent flow fronts occurring on a variety of scales is much greater than in simple monolithic laminates, and may have important implications for part quality. In resin infusion, flow is further affected by local variations in fibre volume fraction resulting from skin compression, and consequent non-linear effects on permeability.

The core material leads to several additional complications in the modelling and control

of all LCM processes due to the possibility of absorption and/or desorption of both liquid resin and air at various stages in the manufacturing cycle. The interaction between the core, liquid resin and air is complex and continues throughout the manufacturing operation. Even in notionally sealed cores, absorption of resin occurs, depending on the local processing conditions. Moreover, the exchange of residual air between the skin laminate and the core can influence the appearance of defects, and ultimately affects part quality and performance.

A porous core can act either as a sink or a source for trapped air. The presence of a large volume of porous core material plays a significant role in the commercial resin infusion processing of large components such as wind turbine blades, where a critical vacuum level must be achieved before resin flow can commence. In many cases, the time required to evacuate a complex stack of dry material can be considerably longer than the flow process itself, and has a major influence on the manufacturing cycle time.

This research is a preliminary attempt to understand some of these interactions. Here, we report some phenomenological observations of flow convergence and subsequent void formation in a variety of material combinations. Basic measurements of air and moisture transport between skin and core provide a basis for the modification of resin flow models to simulate the void formation process.

PREVIOUS WORK

Flow fronts observed in RTM appear to behave independently and in a repeatable manner before convergence [2]. If the fronts converge on a mould edge they will merge as a single front, but if the fronts meet perpendicular to each other there will be increased void content along the knit line so formed. The voids formed at this point may well remain as the driving pressure gradient is removed. Pearce *et al* [3] found that in areas where void content reached 5%, this resulted in a reduction in the maximum measured ILSS of the order 20%. It was suggested that by using sequential inlet ports, flow front convergence could be reduced. Flow fronts converging at 180° to each other was the worst case scenario [3]. However void formation will also occur at lower angles of convergence, although at a reduced level [4]. This was, however, applicable only to monolithic laminates, where flow channels are not influenced by the core material.

Work on foam cores has been conducted [5] to optimise the form of flow enhancement in terms of process efficiency, weight gain due to core absorption and material usage. No firm conclusion was reached as the resulting laminates had extensive areas of either knit lines, or dry fabric patches.

Flow convergence can be predicted qualitatively with the help of 2D and 3D resin flow models, and these simulations are useful in the design of overall injection strategy. An example is shown in Fig. 1, using PAM-RTM [6]. The scenario here is that of resin flow in 2D, having emerged from an array of holes drilled through-thickness through a core material. The holes are modelled as a constant-pressure boundary, and flow takes place in a homogeneous porous medium with constant resin viscosity.

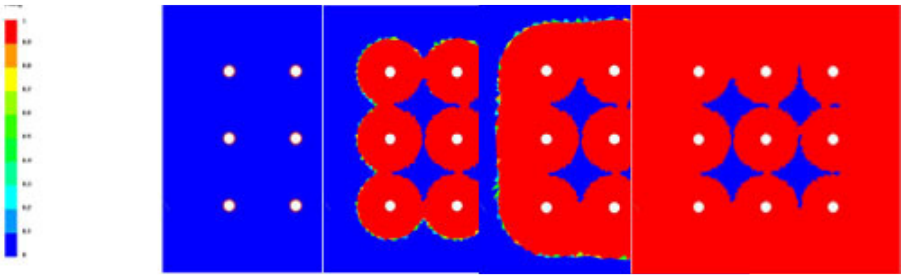

Fig. 1. PAM-RTM 2D simulation of resin flow from an array of circular holes, showing schematic flow front convergence.

In Fig. 1, flow ceases once the locked-off regions have been isolated. This paper is concerned with the subsequent behaviour of these regions of trapped air, and how they interact with porous cores.

EXPERIMENTAL

Knit Line formation and core porosity

An infusion experiment (using a development epoxy resin) was conducted to recreate knit lines resulting from flow front convergence [7]. The experiment used five different types of 25mm thick core (Table 1), with two different through-thickness flow channel arrangements. A single skin of EBX936 (Saint Gobain) biaxial non-crimp E-glass fabric was placed on either side of the core. The impermeable Perspex core was covered in flash breaker tape to allow for later skin removal and analysis. The skin plies were extended beyond the panels to enable calculation of resin absorption in the core materials.

Table 1. Core materials used in flow experiments.

	material	*density (kg/m^3)*	*Supplier /designation*
1	end grain balsa	130	Baltek. Contoukore, Lamprep D100 (1 inch)
2	surface sealed end grain balsa	135	Baltek. D100, AL600-10, (1 inch)
3	PET foam	150	Fagerdala. Non commercial trial sample
4	PVC foam	60	Airex.
5	Solid Perspex	-	n/a

The experiment produced the required knit lines (visible as surface porosity) resulting from through-thickness flow, in a pattern similar to Fig. 1. It was immediately apparent that the surface porosity was significantly worse in the panel containing the impermeable Perspex core.

A photographic technique was used in an attempt to quantify surface porosity as detailed in [7]. ImageJ software [8] was used to measure the percentage area of the image that was occupied by the knit lines (Fig. 2).

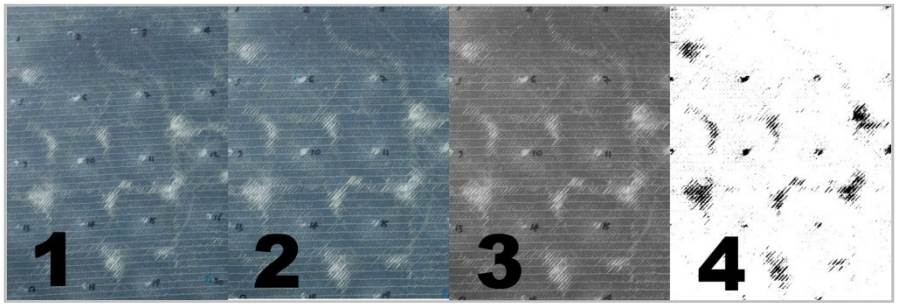

Fig. 2. Stages in image enhancement for quantification of surface voids.

The percentages of the total area occupied by knit-line voids are shown in Fig. 3. These results are an average of three measurements from each image. The image analysis is unavoidably subjective, but the difference between the different core types is very obvious.

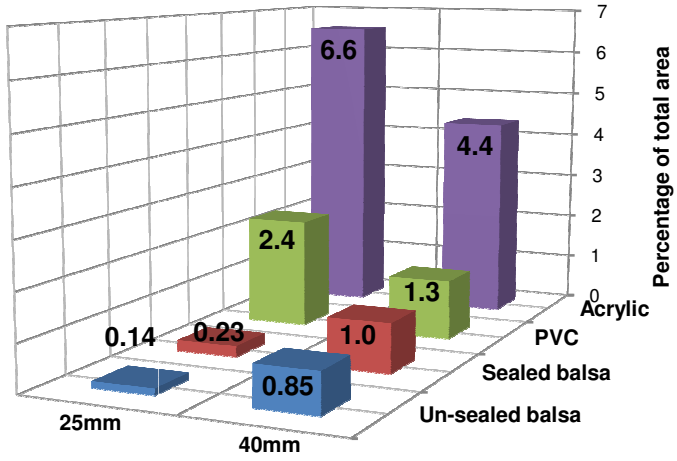

Fig. 3. Area percentages of knit line surface voids.

Core resin absorption

The overall resin absorption during the infusion experiment was calculated for each sample from weight measurements. The results for three of the cores are shown in Fig. 4 (the Acrylic is non-porous and the PET foam was found to contain defects that led to erroneous results).

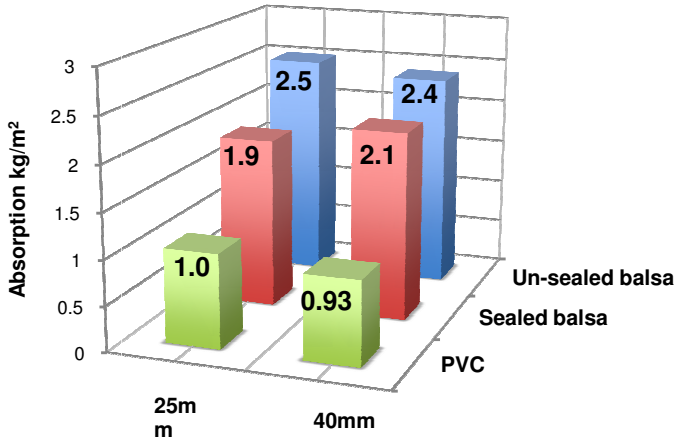

Fig. 4. Resin absorption per unit area of core.

Core air absorption/desorption
A pilot experiment has been designed to investigate the capacity of balsa to absorb/desorb air, and the rate at which exchange takes place.

Two vacuum chambers were connected via a 4mm i.d. pipe with a ball valve inserted to allow isolation of the small chamber from the large (Fig. 5). An Edwards E2M18 high vacuum pump was used to evacuate the chambers.

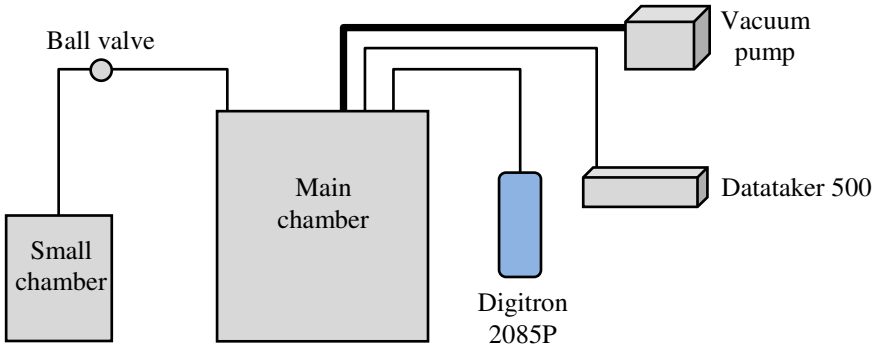

Fig. 5. Absorption experiment schematic

Pressure was monitored with a Datataker 500 and DeLogger 4 software, using a Plastech PV(5801) pressure sensor. A Digitron 2085P (± 2 mbar) digital gauge was used as a reference, to calibrate the Plastech sensor before each run. Both sensors were attached to the main reservoir chamber. The pressure measuring equipment was considered adequate for the pilot experiments whilst the procedure is being established, but it is recognised that more accurate equipment may be required for future experiments. The main chamber volume is 21.62 litres, including all ancillary pipes. The small material chamber has a volume of 1.522 litres including the link pipe before the valve.

Methodology
Both chambers were evacuated and the pump was then physically disconnected from the equipment and the pressure was monitored for 1 hour. The leak rate was measured as 6 mbar/h (1.67×10^{-3} mbar/s), and appeared to be constant over multiple runs.

Calibration Run 1 - Desorption
The first run was to establish the change in pressure when the small chamber was evacuated into the first. This would give an equilibrium pressure of the two empty chambers for the desorption experiments.

1. Ball valve closed, with both chambers at atmospheric pressure.
2. Main chamber evacuated to < 1 mbar absolute.
3. Pump disconnected from the main chamber.
4. Valve opened between chambers.
5. Pressure change and rate of change recorded.

Calibration Run 2 – Absorption
Experiment 2 was then conducted in a similar manner, but to simulate absorption tests. Here the main chamber was at atmospheric pressure and vented into the evacuated material chamber.

1. Main and small chamber evacuated to < 1mbar.
2. Ball valve closed.
3. Main chamber vented to atmosphere, and allowed to stabilise.
4. Ball valve opened allowing equilibrium pressure to be reached between the two chambers.

The pressure traces from the two calibration runs are shown in Fig. 6. Pressure rises rapidly, until equilibrium is reached in about 10 s. No compensation for the leak rate is required on this short time scale. The absorption record shows an initial overshoot, but this gradually falls back to a stable state. This appears to be a sensor effect, as on this time scale the leak rate has almost no effect.

Assuming isothermal conditions the gas law gives the equalisation pressure, according to the chamber volumes. For an atmospheric pressure of P_{atm}:

$$P_2 = P_{atm} \times \frac{1.522}{(1.522 + 21.61)} \qquad (1)$$

The calculated values for desorption and absorption were 65.8 mbar and 66.5 mbar respectively (experiments were undertaken at different atmospheric pressure), and satisfactory agreement with Fig. 6 is observed.

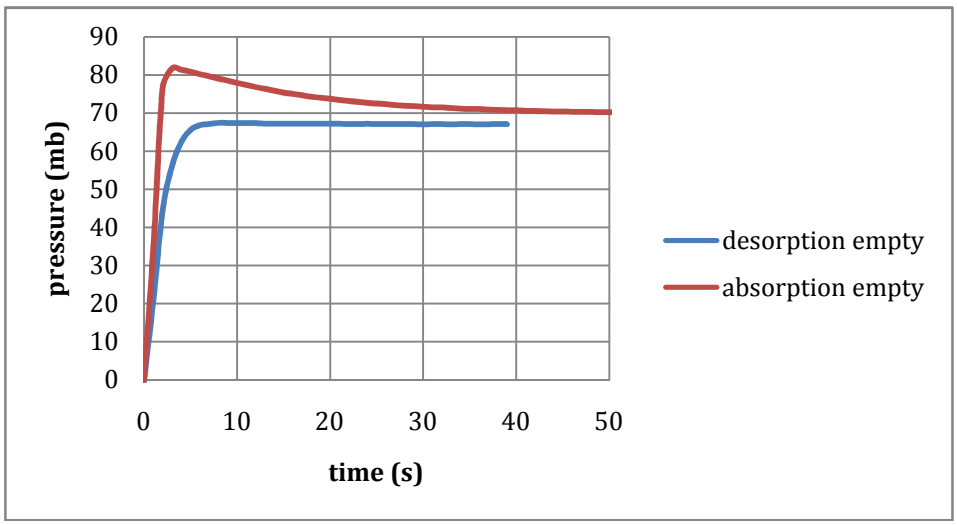

Fig. 6. Calibration run (empty chambers) for absorption/desorption

The calibration experiments were repeated with Baltek AL600 [9] unsealed balsa in the small chamber (measured nominal density 133kg/m^3). Six 25mm thick discs were stacked with negligible free air between them and around the periphery of the chamber.

Run 3 – Balsa absorption
The experimental procedure was identical to experiment 1. It is assumed that the small amount of free air in the material chamber will enter the main chamber very quickly, and that the curve represents a remarkably slow evolution of air from within the balsa structure. A steady pressure of about 40 mbar was reached after some 6.4 hours; this value differs from the empty chamber calibration runs by 27.2 mbar.

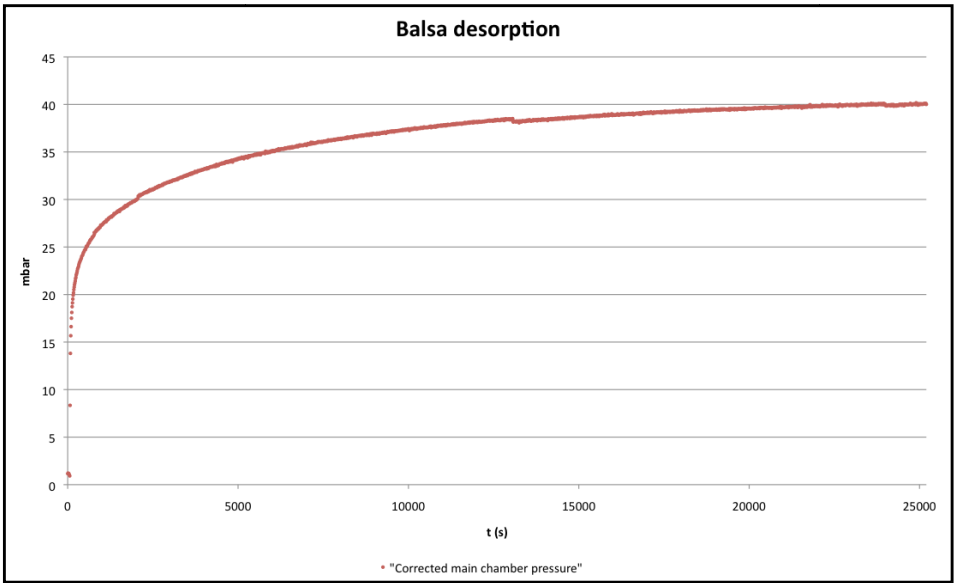

Fig. 7. Balsa air desorption.

Run 4 – Balsa desorption
This experiment is a repeat of experiment 2, with balsa in the small chamber. From previous experience it was known that a long period of evacuation would be required – in this experiment, the balsa was held under vacuum for 22 hours. The pressure record is presented in Fig. 8, and shows stabilisation at 38 mbar, in close agreement with the previous experiment. Of striking difference, however, is the relatively short time scale for air absorption to occur.

Again using the isothermal gas law (pV=constant), we can estimate the effective volume of the balsa. From the desorption experiment:

$$V_1 = V_2 \frac{P_2}{P_{atm}} = \frac{21.61 \times 40}{1000} = 0.864 \text{ litres}$$

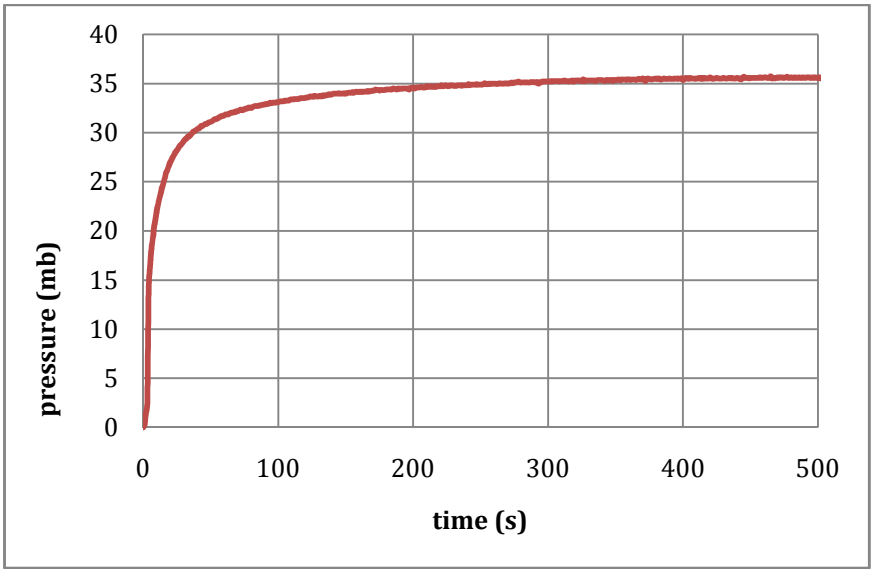

Fig. 8. Balsa air absorption.

This result suggests an effective balsa porosity of 0.57. It is interesting to compare this with the theoretical porosity. Given the measured density of 133 kg/m^3, and assuming that balsa is primarily composed of cellulose/lignin with a combined density of 1650 kg/m^3 [10], we obtain a porosity of 0.9.

The smaller value represents the volume of free space that air/gas can move in and out of freely, and not all the air that is contained within the balsa structure. This is the volume of air that needs to be evacuated during infusion to prevent air entering the resin. It can also provide a storage volume for any air or volatile diluants that become trapped due to flow front convergence, whilst a pressure differential exists between the core and void.

CONCLUSIONS

- Results show a high incidence of flow convergence and hence void formation due to through thickness flow in cored laminates. Void regions are dependent on the detailed geometry of flow enhancement modifications to the core.

- Void formation is significantly greater in cores of lower permeability/absorbance with the highest in solid acrylic core. Although sealed cores are often specified for reduction of resin absorption, it is clear that significant absorption occurs in these materials.

- The amount of free space available for air exchange in balsa is only about 2/3 of the expected porosity.

- Rates of air absorption into balsa appear to be much faster than desorption. The latter process can take several hours to stabilise, and this has important implications for commercial processing.

- Further experiments are required to investigate how absorption/desorption rates are related to geometric aspects, and to derive appropriate algorithms to describe gas exchange.

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