VACUUM BAG ONLY MANUFACTURING OF HONEYCOMB SANDWICH PANELS

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Keywords: low cost manufacturing technologies, process modeling, out-of-autoclave prepreg, sandwich panels

1 Introduction
Thermoset prepregs offer a consistent, predictable manufacturing method for flight-critical structures. Applications considering lightweight honeycomb core inserts for part stiffening may encounter unique manufacturing difficulties. The differential pressure between the inside of the honeycomb core and the vacuum bag may introduce core crush or migration, blown cells, and skin pillowing or dimpling if the autoclave pressure is high (standard cure pressure is 690 kPa) [1]. These problems are usually overcome by reducing the autoclave pressure to between 280 and 350 kPa [1], but can lead to inferior bonding between the skin and core, including disbonds, and high skin porosity levels. Clearly, the honeycomb core pressure strongly influences the quality of co-cured honeycomb panels.

As low-cost vacuum bag only (VBO) manufacturing gains popularity, substandard bonding and skin porosity are prominent concerns for applications featuring honeycomb core. Manufacturing honeycomb sandwich panels is a complex activity, influenced by the following factors: reinforcement (raw material, fabric style, and weave pattern), prepreg (resin type, content, and impregnation), adhesive film (flow behaviour, carrier, and areal density), consumable materials (release film perforations, and breather density), and part manufacturing (layup, bagging arrangement, vacuum level, ambient pressure, and curing cycle). Researchers have investigated the effect of select process parameters on the quality of lab-scale honeycomb panels using both experimental [2-6], and material characterization and process modelling techniques [7-13]. Both approaches aim to identify the best manufacturing method available for the given materials and process parameters, however, they are difficult to relate. The studies of lab-scale honeycomb panels measure passive process variables, such as process temperature, vacuum bag pressure, and ambient pressure, but cannot easily measure the honeycomb core pressure. Material characterization and modelling studies focus on the constituents’ influence on honeycomb core pressure by neglecting holistic effects (such as the tool-side skin and adhesive). A link is needed between the two techniques before scaling the manufacturing process to larger structures.

Sensing techniques have been investigated for sandwich structures using capillary tubes to measure the honeycomb core pressure during autoclave processing [14,15]. Other sensing applications include optical Fibre Bragg Grating (FBG) sensors for structural health monitoring [16] and to measure process-induced strains between a composite skin and core [17,18]. However, introducing sensors without altering the properties, behavior, or creating leaks within the parent structure is challenging. Capillary tubes can be large (up to 0.8 mm in diameter [15]) and if rigid, may not conform to contoured parts. Optical fibres offer a flexible and smaller solution, but are fragile. Groves may need to be cut in the core to protect optical fibres from being crushed by the cell walls, [18], and the sensor itself may impede fillet formation between the skin and core [18] or create resin rich areas [17]. A miniature, robust solution is needed to validate process models without disturbing the process phenomenon within the host structure.

In this study, process models are combined with dual-skin lab-scale honeycomb panels by embedding micro-fabricated pressure sensors in honeycomb panels. As a result, the honeycomb core pressure is measured throughout the manufacturing process, linking the two approaches. A technique is introduced to embed the pressure sensors into honeycomb cores to minimize intrusion and to avoid creating leak paths. Once embedded, the honeycomb core pressure is measured during the vacuum hold prior to cure and during elevated temperature processing in an oven and an autoclave. The results are compared with previously developed process
models and demonstrate the ability to measure the honeycomb core pressure for bag molding processes.

2 Overview of honeycomb core pressure process models

The key analytical models used to express the honeycomb pressure are presented in the following sections for quick reference. The process models used in this paper are developed in detail in Ref. [12,13].

2.1 Honeycomb core pressure evolution prior to cure

The honeycomb core pressure is predominantly governed by the air permeability of the honeycomb skin, \( k \), which can be characterized if a decrease in honeycomb core pressure can be measured [7-11]:

\[
\ln \left( \frac{P_{Bag} + P_{Cell,i}}{P_{Bag} - P_{Cell,i}} \right) = -\frac{K A P_{Bag}}{L \mu V_{Cell}} t
\]

where \( P_{Bag} \) is the pressure in the vacuum bag side of the skin and \( P_{Cell} \) is the pressure in the honeycomb core measured at time \( t \), \( P_{Cell,i} \) is the initial honeycomb core pressure, \( V_{Cell} \) is the volume of air on the honeycomb core side of the skin, \( L \) is the skin thickness, \( A \) the area through which flow occurs, and \( \mu \) is the viscosity of the permeating fluid. The left hand side of Eq. (1) is linearly dependent on time \( t \), and for this reason when the left hand side of Eq. (1) is plotted versus time, the slope of the straight line is the air permeability [19].

In the case of elevated temperature air permeability characterization, Sutherland’s law was used to compute the viscosity of air as a function of temperature

\[
\mu(T) = \mu_0 \left( \frac{T}{T_0} \right)^{\frac{3}{2}} \left( T_0 + S \right) \left( T + S \right)
\]

where \( T \) is the temperature in Kelvin, \( S \) is the Sutherland constant, and \( T_0 \) and \( \mu_0 \) are reference values.

Eq. (1) can be solved for \( P_{Cell} \) to predict the pressure evolution in the core during the vacuum hold prior to cure [12]:

\[
P_{Cell}(t) = P_{Bag} \frac{c + e^{-\beta t}}{c - e^{-\beta t}}
\]

where \( c \) and \( s \) are:

\[
c = \frac{P_{Cell,i} + P_{Bag}}{P_{Cell,i} - P_{Bag}}, \quad s = \frac{K A P_{Bag}}{L \mu V_{Cell}}
\]

2.2 Honeycomb core pressure during cure

The honeycomb core pressure at the end of the vacuum hold can be used to predict the pressure differential between the honeycomb core and vacuum bag during cure if both the air permeability and gas (within the honeycomb) core are known. The ideal gas equation of state can be used if moisture is negligible within the core, but if non-metallic cores are used, a more complex model capturing the moisture desorption is needed to describe the honeycomb core pressure during cure. A model describing the honeycomb core pressure during VBO co-curing of honeycomb panels is presented in Ref. [13]. The model requires an input of initial masses of air and water vapor, and the moisture content of the honeycomb core. The initial masses of air and water could be calculated from Eq. (3) and the ambient relative humidity. Assuming no drying of the core during the vacuum hold (the core moisture content remained constant) the honeycomb core pressure, \( P_{Cell} \), could be predicted by

\[
P_{Cell} = \frac{R_v T}{V_{Cell}} \left[ \frac{m_{Air,i} + (m_{Vapor} + \dot{m}_{Honeycomb} \Delta t)}{\omega_{Air} + \gamma_{Vapor}} \right]
\]

where \( R_v \) is the universal gas constant, \( T \) is the temperature, \( V_{Cell} \) is the empty volume of the honeycomb core, \( m_{Air,i} \), is the initial mass of air in the honeycomb core, \( m_{Vapor} \) is the total mass of water vapor in the honeycomb core, \( \dot{m}_{Honeycomb} \) is the mass flow from the paper cell walls into the honeycomb core, \( \dot{m}_{Bag Skin} \) is the mass flow rate of gas within the honeycomb core through the bag-side skin, \( \gamma \) is the mass fraction of air and water vapor in the cell, and \( \omega \) is the molar mass of air and water vapor.

The models presented in Eq. (1), Eq. (3), and Eq. (5) neglect the tool-side skin since vacuum is applied asymmetrically. In large parts, most air evacuation from the core will travel through only the bag-side skin. Volatiles entrapped within the tool-side skin
may flow into the into the honeycomb core during the vacuum hold prior to cure and during elevated temperature processing. The volume of volatiles within a honeycomb skin may be negligible compared to the honeycomb core volume, but validating these process models in honeycomb panels featuring both a bag and tool-side skins is an important step towards reducing the uncertainty between modelling and realistic composite parts.

### 3 Experimental procedure

A lab-scale solution is developed in the following sections to simulate co-curing of large composite structures. First, the sensors are described. Second, the embedding procedure is developed. Finally, the materials and processing conditions are presented.

#### 3.1 Sensors

A piezoresistive silicon micromachined pressure sensor from Measurement Specialties (model number: MS5407-AM) was selected to measure the pressure inside the honeycomb core. A picture of the sensor is shown in Figure 1. The actual pressure sensor is 2 mm x 2 mm, but the associated packaging increased the total size to 6.4 mm x 6.2 mm. This sensor was chosen because it offered high sensitivity, 0.2 % linearity between the 0 to 7 bar operating pressure, and a maximum operating temperature of 125 °C.

The sensor has a Wheatstone bridge wiring configuration, and therefore required 4 wires to be soldered to the back side of the carrier. Enamel coated copper magnet wire was used to connect the sensor to the data acquisition system to avoid introducing leaks along the wire into the panel or vacuum bag. Twenty-eight gauge wire was found to offer the best balance of handling, durability and size; thirty-two and thirty-six gauge wires were evaluated, but those sizes readily became entangled and broke at the solder joints even with careful handling.

These pressure sensors offered temperature compensation by embedding a fluorocarbon polymer coated thirty-gauge K-type thermocouple wire beside the pressure sensor within the honeycomb. The temperature compensation required a four-point calibration at two temperatures: 22 °C and 125 °C, and two pressures: 0 and 1000 mbar.

#### 3.2 Embedding sensors in a honeycomb core

A simple solution was sought to embed the pressure sensor and pass the wires through the panel without introducing a leak path and subsequently disrupting the pressure behaviour. A schematic of the embedding technique is presented in Figure 2. To avoid in-plane air flow at the perimeter of the core, a 150 mm x 150 mm x 20 mm aluminum frame was fabricated from 12 mm thick square tubing. Six slots (3 mm wide x 4 mm deep) were machined on one side to allow the wires to pass through the frame. A blind 3 mm diameter hole, 3 mm deep, was drilled in the center of the slot to provide extra an anchoring point. The wires were potted with a room temperature vulcanizing silicone rubber (RTV silicone) that was temperature resistant up to 200 °C after seven days at room temperature.

The quality of the wire potting was evaluated using a flow meter and a hot water bath. The frame with embedded wires was sandwiched between two aluminum plates with rubber o-rings, and a flow meter was connected between one plate and a vacuum pump. If the flow rate fell to zero after evacuating the core, the panel was assumed to be sealed. This confirmed that the embedded wires did not create any leak paths through the edges of the frame. If the assembly failed the leak test, atmospheric pressure was vented into the frame, and the assembly was submerged into a water bath at 50 °C to identify the location of the leaky wire(s). Once the leak was identified, it was repaired with additional silicone. This evaluation procedure was repeated until both the flow meter registered zero flow and no bubbles appeared when the frame was submerged in the hot water bath.

The pressure sensor was located in the centre of the frame, but the pressure sensor did not fit into a single 3.1 mm honeycomb core cell. A 12 mm diameter blind hole was drilled 8 mm deep into the centre of the honeycomb core, connecting a total of five cells. The six wires (four for the Wheatstone bridge and two for the thermocouple) were encapsulated between 2 layers of adhesive film between the pressure sensor and the edge of the frame, as shown in Figure 3a. Alternative solutions that were considered included cutting a groove in the core for the wires, but this would allow air migration between the edge and centre of the panel. Air migration could be eliminated by potting the wires in the groove with silicone, but this would introduce a foreign material near the sensor, possibly skewing
the measured pressure. Sealing the wires between 2 layers of adhesive film between the sensor and panel edge offered a solution that could be scaled to larger parts without adding foreign materials or additional weight to the panel.

After the wires were sandwiched between two layers of adhesive film (Figure 3b), the tool-side skin, consisting of prepreg and surfacing film, was laid-up directly onto the adhesive. A layer of Airetech’s Flashbreaker® 2 polyester film tape was applied around the perimeter of the skin to prevent in-plane gas flow during processing (Figure 3c). The frame was then placed tool-side down onto a non-perforated release film covering 12 mm thick aluminum tool. The bag-side adhesive film and prepreg layers were applied (Figure 3d) over the core. Again, Flashbreaker® tape was placed around the perimeter of the panel to prevent in-plane flow, reproducing the pressure behaviour in a large panel. The embedded wires were sealed at the exit point of the aluminum frame and the vacuum bag between two layers of sealant tape.

3.3 Materials and processing

A plain weave out-of-autoclave prepreg material was used in this study. The prepreg was impregnated with Cytec 5320 by Cytec Engineered Materials. The reinforcement fabric had a nominal areal weight of 196 g/m² and an initial resin content of 36 % by weight. The honeycomb core was Nomex, 20 mm thick, with 3.1 mm cell diameter, and a density of 96 kg/m³. A structural film adhesive from 3M, AF 163-2K with a 294 g/m² weight, was used to bond the skin to the core. A surfacing film from Cytec, SM 905 with a 171 g/m² weight was used to minimize surface pitting on the tool side skin. The consumable materials were FEP release film (non-perforated and perforated with 0.38 mm perforations staggered by 6.35 mm), breather, vacuum bag, and sealant tape.

Elevated temperature processing was performed in an atmospheric pressure oven and an autoclave. The test matrix is presented in Table 1. The oven experiments (trials 1–3) runs were used to identify the effect of absorbed moisture in the honeycomb core on the measured and predicted core pressure. The autoclave experiments (trials 4–7) were used to identify the effect of consolidation pressure application and pressure magnitude on the measured and predicted core pressure. The consolidation pressure exerted on the honeycomb skin was equivalent in Trials 1 through 5. Trials 1 through 3 were conducted under 1000 mbar of vacuum pressure, and trials 4 and 5 were performed with a total of 1000 mbar of positive pressure – the vacuum bag was vented to atmosphere (roughly 1000 mbar) and the autoclave pressure was roughly 2000 mbar. In trials 6 and 7, vacuum pressure was maintained in the vacuum bag and the 2000 mbar autoclave pressure effectively doubled the compaction pressure applied to the honeycomb skin.

The same cure cycle was used for both oven and autoclave curing. The temperature was ramped at 1.7 °C/min from ambient to 121 °C and held for 4 h. This cure cycle was chosen from the manufacturer’s material data sheet [20]. The bag-side skin temperature was measured using a separate K-type thermocouple to the one described in section 0. The measured temperature is plotted in Figure 4 alongside the corresponding resin and adhesive film viscosity models taken from Ref. [21] and Ref. [13], respectively. The adhesive and resin are both thermoset polymers, but have different cure and viscosity behaviour during cure. Both materials decrease in viscosity as the temperature rises, however the adhesive viscosity remains significantly higher than the resin viscosity throughout the cure cycle. The resin reaches minimum viscosity at the same time as the adhesive gels, which occurs an hour before the resin gels.

The air permeability of this skin, bagging configuration, and cure cycle was previously characterized in Ref. [13] and the results are presented in Figure 5. During elevated temperature processing, resin mobility increases and the pore space within the skin decreases. As a result, the air permeability decreases at the beginning of heating as the resin softens, becoming tackier and closing macro-pores that were open after the room temperature vacuum hold. As the skin temperature continues to rise past 40 °C, the resin viscosity decreases sufficiently for connected pores to form, allowing air to flow through the skin with less resistance until the fibre tows are saturated (0.75 h into cycle) and the adhesive gels (1.25 h into cycle), followed by resin gelation (2.25 h into cycle). Once the resin has gelled, the air permeability remains constant. Two permeability curves are shown in Figure 5 because of the experimental variability in air permeability measurements.

Two vacuum ports were used for each tool. One was connected to the vacuum pump, the other was
connected to a pressure transducer (range: 0 to 3000 mbar) to record the vacuum bag pressure using the same data acquisition system as the embedded sensors. The autoclave vessel pressure was measured using a separate pressure transducer (range: 0 to 10,000 mbar) connected to the autoclave data acquisition system.

4 Results and discussion

The evolution of honeycomb core pressure during the vacuum hold prior to cure is plotted in Figure 6. The vacuum hold was performed at atmospheric pressure for both oven and autoclave co-cured panels. The lower vacuum bag pressure measured in the autoclave vacuum hold (Figure 6b) occurred because a portable vacuum pump was required overnight. Both vacuum holds were intended for 12 h, but the autoclave panels were held under vacuum for an additional 3.5 h because extra time was needed to pass the pressure sensor and thermocouple wires between the autoclave door and ring lock without damaging the wires.

The measured honeycomb core pressure is plotted alongside the model predictions from Eq. (3). A constant air permeability value of 1.0 x 10^-18 m² and 1.7 x 10^-17 m² were used to generate the upper and lower pressure bounds. The honeycomb core pressure measured using the embedded sensors shows significant variability. The same observation was made during the experimental characterization of bag-side skin air permeability; the air permeability measurements at time t = 0 h in Figure 5 span an order of magnitude. The measured honeycomb core pressure decrease during the vacuum hold follows the upper pressure curve, indicating that the skin air permeability is closer to the lower bound in Figure 5. The honeycomb core pressure at the end of the vacuum hold is within the predicted pressure range for six of the seven panels.

Even with model bounds spread by nearly an order of magnitude, the core pressure was outside the model predictions for one of seven panels. This observation reinforces the variability that exists with out-of-autoclave prepreg air permeability. End-users of these materials need to be aware of this reality, and need to protect themselves by inspecting incoming materials.

The dynamics of the honeycomb core pressure change during the vacuum hold was noticeably different for all panels, and unlike the model predictions, demonstrated abrupt changes. Fluid flow through a porous medium depends on the interconnectivity of the pore space [21]. The measured pressure drop indicates that the pore space within the honeycomb skin continuously evolves throughout the vacuum hold. As pores become connected or isolated, the change in honeycomb core pressure is affected. More erratic behaviour was observed with the embedded sensor panels than the air permeability measurements [11]. This was likely caused by the localized area where pressure was measured. The embedded pressure sensor is located within a 12 mm diameter cell section, and was therefore more sensitive to the local changes in honeycomb core pressure than the large surface area in material characterization studies (the honeycomb core pressure was measured in a 150 mm x 150 mm cell area in Ref. [13]).

The elevated temperature processing results for the oven cured panels are presented in Figure 7. The embedded pressure sensor measurements are plotted alongside the vacuum bag pressure, and the model predictions from Eq. (5). All panels show a similar trend during elevated temperature processing. As the temperature increases the honeycomb core pressure increases. This is caused by pressurization of entrapped volatiles (air and water vapour). Additional water vapour is desorbed from the honeycomb cell walls, mixing into the air and moisture already present within the cell void space. The majority of the pressure increase within the honeycomb core occurred during the temperature ramp because increasing temperature has the strongest influence on diffusion kinetics; a lower cure temperature would have lower honeycomb core pressure, but also longer cure time.

Once the skin temperature reaches the dwell temperature (roughly 1.25 h into the cycle), moisture diffusion slows, and the air permeability of the honeycomb skin dominates the honeycomb core pressure evolution in Eq. (5). During the temperature dwell (from 1.25 to 5 h) the honeycomb core pressure decreased according to the model predictions. The variability in honeycomb core pressure is reduced during elevated temperature processing. The three VBO experiments were close to the model predictions. The measured honeycomb core pressure in Figure 7a was within the model bounds, Figure 7b was higher, and Figure 7c was lower. The model developed using material characterization on bag-side skins was able to...
reproduce the measured pressure in representative panels featuring moist honeycomb core.

An unexpected experimental factor was the sub-standard vacuum level in the vacuum bag for Trials 1 and 3. A vacuum bag required eight tucks for each part, used to create extra slack in the bag to avoid breaking or bridging the vacuum bag during cure. Trials 1 and 3 were cured simultaneously on the same tool, and Trial 2 on the same tool but a different oven run. The bag for Trials 1 and 3 was more complicated, and as a result, required more tucks, which lead to a lower vacuum level Trial 2. The vacuum level achieved during the material characterization was similar to the level in Trial 2 (16 ± 4 mbar), not that of trial 1 and 3 (118 ± 23 mbar). Vacuum bag pressure is a model input, and an encouraging result was that the model is robust enough to predict honeycomb core pressure with a 100 mbar reduction in vacuum level during cure.

The results from the autoclave co-cured panels are presented in Figure 8. All panels were cured simultaneously, but Trials 4 and 5 were on separate tools from trials 6 and 7. The autoclave pressure was ramped to the 2000 mbar set-point in 1 min, and the vacuum bag was vented 5 min after the pressure set-point was reached. The fluctuations observed in the autoclave pressure signal during cure are an artifact of the controller, which is tuned for normal autoclave operation between 4000 and 8000 mbar, not the target set-point of 2000 mbar used in this study.

In Figure 8a, the pressure differential between the inside and outside the vacuum bag is similar to the air permeability characterization, and the trials in Figure 7. Once the vacuum bag was vented, the measured honeycomb core pressure followed the model predictions towards the vacuum bag pressure. The measured honeycomb core pressure followed the upper bound of the model predictions until the dwell temperature was reached. During the dwell, the measured honeycomb core pressure in Trial 4 decreased as those of VBO trials 1 through 3. The honeycomb core pressure in Trial 5 remained above the model predictions.

In Figure 8b, the vacuum bag pressure was maintained throughout the cure cycle, effectively doubling the consolidation pressure applied to the skin, when compared to Figure 7 and Figure 8a. The measured honeycomb core pressure increased faster, and peaked well above the model predictions. Doubling the consolidation pressure created a higher honeycomb core pressures during the ramp than predicted by the model. This would imply that doubling the consolidation pressure decreased the air permeability of the skin, however, the model does capture the honeycomb core pressure decrease during the dwell. This could be an artifact of the volume of gas that flowed through the skin to release the pressure in the honeycomb core. The gas flow could have created large pores within the skin, increasing skin air permeability. This however, requires further investigation.

Comparing the oven and autoclave experiments, identified that the process models are accurate when the total consolidation pressure is equivalent. This correlation offers end-user the flexibility to characterize the honeycomb skin air permeability in an oven using a vacuum bag in order to find the necessary process model parameters for light positive pressure curing in a vented vacuum bag.

All panels cured in this study (Figure 7 and Figure 8) were submerged in a hot water bath (described in section 0) after co-curing to verify that the panel was sealed at the edge and where the wires exited the frame. No leaks were caused by the wires before or after curing. If leaks were present during cure, the measured pressure would be expected to fall below the predicted pressure, which was not the case in Figure 7 or Figure 8. Although effective, a wireless pressure and temperature measurement solution that fits into a single honeycomb cell would be preferred in the future as an alternative to sandwiching wires between adhesive film and potting the wires in silicone at the edge of the panel.

5 Conclusions

Miniature pressure sensors were successfully embedded into lab-scale honeycomb sandwich panels with minimal sensor interference, and leaks were prevented along the wiring. The honeycomb panels were configured with impermeable boundary conditions at the panel edges to reproduce curing of large scale honeycomb structures in a laboratory environment. The embedded pressure sensors offer researchers a technique to measure the honeycomb core pressure for oven or autoclave co-curing when evaluating different material and process variables. The measured pressure response was compared to process models developed using characterization techniques where only the bag-side honeycomb skin...
was considered. The honeycomb core pressure evolution during processing agreed with the process model predictions. In the cases of moisture–absorbed by the honeycomb cores, variable vacuum and external pressures, the measured pressure response was captured by the process models. These results reinforce that material characterization and process modelling can be used to predict holistic phenomenon if intelligent assumptions are used. Neglecting the tool-side skin during characterization and modelling was an accurate assumption for large parts because gas flow is predominantly in the out-of-plane direction.

In the case of traditional autoclave processing, the external bag pressure can be much higher than an atmospheric pressure oven. As a result, the consolidation pressure applied to the honeycomb skin increases, reducing air permeability, causing the honeycomb core pressure to rise above the levels observed in VBO processing. However, the process models were accurate if the vacuum bag was vented to atmospheric pressure and the autoclave pressure was twice atmospheric pressure. In this case, the consolidation pressure is effectively the same as VBO processing. This inspires confidence in the models chosen to analyze the honeycomb pressure behaviour. The models accurately predict the honeycomb core pressure behaviour for any combination of vacuum and positive pressure that apply an equivalent consolidation pressure to the conditions used during material characterization.

**Acknowledgements**

This work received financial support from the Natural Sciences and Engineering Research Council of Canada (NSERC), the Consortium for Research and Innovation in Aerospace in Quebec (CRIAQ), Bell Helicopter Textron Canada, Bombardier Aerospace, and Delastek. We would like to thank Bell Helicopter Textron Canada and Bombardier Aerospace for providing the materials used in this study, and the National Research Council of Canada for providing access to their autoclave.

![Figure 1. Miniature surface mounted pressure sensor from Measurement Specialties.](image1)

![Figure 2. Cross-section schematic showing the sensor position and embedding technique.](image2)

![Figure 3. Embedding procedure: (a) honeycomb core with embedded pressure sensor in the centre, (b) adhesive film covering the core and sandwiching the wires, (c) tool-side skin with surfacing film and taped edges, and (d) bag-side skin with taped edges skin thermocouple and embedded sensor wires exiting the panel between sealant tape.](image3)
Figure 4. Cure cycle showing the measured skin temperature during oven cure and the viscosity profile of the adhesive film and epoxy resin.

Figure 5. Air permeability of the bag-side skin during processing. Key stages in the cure cycle are shown: A – the dry tows are saturated, B – the adhesive film gels and resin approaches minimum viscosity, and C – the resin gels. Each symbol represents a permeability measurement. A high and low bound was applied to the data.

Figure 6. Predicted and measured honeycomb core pressure during the vacuum hold prior to cure for the embedded sensor panels: (a) VBO trials and (b) autoclave trials.
Figure 7. Predicted and measured honeycomb core pressure during oven co-curing of honeycomb panels. The model captures the pressure behaviour with increasing moisture absorbed by the honeycomb core: (a) 1.59 wt. %, (b) 2.44 wt. %, and (c) 3.93 wt. %.
Table 1. Curing test matrix.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Cure type</th>
<th>Core moisture content, $MC_{Core}$ (wt. %)</th>
<th>Target consolidation pressure, $\Delta P_{Skin}$ (mbar)</th>
<th>Measured vacuum bag pressure (mbar)$^d$</th>
<th>Measured external bag pressure (mbar)$^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Oven$^a$</td>
<td>1.59</td>
<td>1000</td>
<td>118 ± 23</td>
<td>1024 ± 1</td>
</tr>
<tr>
<td>2</td>
<td>Oven$^b$</td>
<td>2.44</td>
<td>1000</td>
<td>16 ± 4</td>
<td>1021 ± 2</td>
</tr>
<tr>
<td>3</td>
<td>Oven$^c$</td>
<td>3.93</td>
<td>1000</td>
<td>118 ± 23</td>
<td>1024 ± 1</td>
</tr>
<tr>
<td>4,5</td>
<td>Autoclave$^c$</td>
<td>2.44</td>
<td>1000</td>
<td>1017 ± 1</td>
<td>2028 ± 140</td>
</tr>
<tr>
<td>6,7</td>
<td>Autoclave$^c$</td>
<td>2.44</td>
<td>2000</td>
<td>99 ± 4</td>
<td>2028 ± 140</td>
</tr>
</tbody>
</table>

$^a$Cured together on the same tool in the same oven run  
$^b$Cured on an identical tool, in the same oven, but a different oven run  
$^c$All panels cured in the same autoclave run on separate tools  
$^d$Average and standard deviation measured during cure
References


