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# Experimental validation of co-cure process of honeycomb sandwich structures simulation: adhesive fillet shape and bond-line porosity

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#### ABSTRACT

Predictive models describing the co-cure process of honeycomb sandwich structures can increase manufacturing efficiency of aerospace structures by offering rapid, low-cost screening of viable combinations of material and process parameters. Honeycomb sandwich structures are co-cured to bond partially-cured thermoset prepreg facesheets with an adhesive layer to the core structure, during which multiple physical phenomena occur simultaneously. A physics-based predictive tool is developed to simulate this process by integration of submodels for the adhesive bond-line fillet shape, facesheet consolidation process, and the porosity development within the bond-line, which, due to the coupling effects, is highly dependent on the former two phenomena. In this work, the experimental validation of both the individual sub-models and an integrated model for bond-line porosity is conducted. Despite the stochastic behavior of the co-cure process, the models successfully capture trends in adhesive fillet shape and the bond-line porosity, demonstrating their utility as tools for process screening to maximize the quality of co-cured parts.

#### **KEYWORDS**

Honeycomb sandwich structures; fillet shape; porosity development; co-cure; consolidation

#### **GRAPHICAL ABSTRACT**



#### 1. Introduction

Fabrication of honeycomb sandwich structures requires bonding carbon fiber-reinforced polymer

facesheets, characterized by high stiffness and strength, to both sides of a low-density core. Fibers within the skins carry loads, while the core structure primarily increases the bending moment of inertia

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of the assembly by distancing the facesheets from the neutral axis and resisting shear loads. The inclusion of the core increases the stiffness of the overall structure with minimal additional weight, resulting in widespread use of sandwich composites in aerospace structures [1]. In general, producing honeycomb sandwich structures requires two steps: (1) curing of the prepreg facesheets and (2) bonding of the facesheets to honeycomb core inserts. During co-cure, these steps are combined, with uncured prepreg facesheets placed on both sides of the core inserts to be cured and bonded to the core in an autoclave under a prescribed cure cycle specifying the process parameters such as applied pressure, vacuum pressure and temperature as a function of time [2]. The co-cure process is preferred, as it reduces processing time and resources. Additionally, the use of drapeable, partially-cured prepreg, rather than rigid cured facesheets, facilitates the production of complex-shaped parts. However, during the cocure process, adhesive fillet formation and facesheet consolidation occur simultaneously and under limited compaction pressure (due to the risk of core crush). Consequently, the process is susceptible to defects such as poor bonding, poor consolidation across the facesheet, and porosity within the bondline (the region between the facesheets and the core) [3]. Therefore, a predictive model that simulates the co-cure process as a function of process parameters is potentially useful in reducing or eliminating such defects.

The processes of fillet formation, facesheet consolidation, and porosity development in composites processing are well-understood separately. For example, predictive models for fillet size exist for both an adhesive film [4] and a self-adhesive prepreg [5]. However, both models assume only a single resin (either by the use of a pre-cured facesheet or self-adhesive prepreg) and void-free fillets. Niknafs Kermani et al. [6] proposed a model for the adhesive fillet shape of the honeycomb sandwich structures depending on material contact angles, surface tension, density, and the size of the honeycomb cell. Also, facesheet compaction has been modeled for laminate composites (e.g. [7-11]), although the model geometry is not directly transferrable to the co-cure configuration. Finally, Simacek et al. [12] presented a model applicable to the co-cure process to simulate spatial and transient development of reinforcement deformation (fiber volume fraction), resin pressure, and the volume of bleeding resin. Likewise, existing models for diffusion-based void growth (e.g. [13-16]) assume boundary conditions relevant to laminates. The above models have been demonstrated to be viable under the relevant circumstances (e.g. monolithic laminates for void growth models, secondary bonding of sandwich panels for fillet shape models) but were not developed with assumptions and boundary conditions appropriate for application to the cocure process.

The bond-line porosity is a critical property of sandwich structures, as it affects facesheet adhesion. Consequently, the effects of various material and processing parameters on porosity in the bond-line have been reported [17-23]. These studies identify resin viscosity, solvent content, cure temperature, and adhesive film thickness as influential factors. Studies have also identified applied pressure as a key parameter affecting bond-line development, with Nagarajan et al. demonstrating that vacuum level has an inconsistent influence on fillet quality during vacuum bag-only co-cure [22]. Alteneder et al. used an in-bag pressurization technique to impose super-ambient gas pressure in the honeycomb core cells, reporting reduced bond-line porosity as a result [24]. Moreover, to investigate timedependent void behavior in the bond-line, an in situ visualization method was employed, identifying core pressure and differences in the prepreg resin and adhesive viscosity profiles as key factors determining development of porosity in the bond-line [3, 25].

The combination of models proposed by Niknafs Kermani et al. [6, 23], for the porosity development within the bond-line and adhesive fillet shape, and Simacek [12] for the facesheet consolidation process, into a simple analysis tool [6, 26] provides a comprehensive simulation tool for the co-cure process of honeycomb sandwich structures that accounts for interactions between material and physical phenomena. However, while the proposed models capture the correct physics [6, 26], they have not been experimentally validated.

This work outlines the validation of the integrated co-cure simulation, accounting for both adhesive and prepreg behavior, as well as geometric considerations, with the desired output being the bond-line porosity. To date, there is no simulation model that integrates the entire physics of the cocure process of honeycomb sandwich structures to predict bond-line porosity. The sensitivity of the model to process parameters and the number of prepreg plies in the facesheet are studied. Key submodels are presented and compared with experimental data. The integrated model for porosity is then described and the simulated porosity in three cases of co-cure cycles is compared to experimental results. The porosity model captures important process phenomena, including the timing at which void growth begins, as well as the escape of voids from the bond-line under vacuum. Model predictions also capture trends in porosity in response to changing



Figure 1. Geometry used in the model for fillet formation. a) Fillet geometry as modeled. b) Fillet dimensions and contact angles. c) Parametrization of applied force.

core pressure and facesheet thickness, which can guide manufacturing decisions to reduce porosity in the bond-line.

#### 2. Materials

The materials selected for this study - prepreg, adhesive, and core - are typical of those used for aerospace structures. The prepreg consisted of a plain-weave carbon fiber fabric impregnated with a modified epoxy resin (Hexcel HexPly AGP193PW/ 8552S, where the 'S' denotes a solvated tower manufacturing process). Previously, residual solvent was identified in the prepreg using Fourier-transform infrared spectroscopy [27], and the solvent was identified as a source of porosity in the adhesive bond-line [25]. Thermal properties, including cure kinetics and viscosity, have been characterized and modeled for the neat resin (e.g. [28,29]). Models used were adapted from those developed by Hubert et al. [29] based on a supplied 8552-1 resin film that behaves similarly to the prepreg resin.

The adhesive used was a modified, flow-controlled epoxy supported by a non-woven glass mat (Henkel Loctite EA 9658 NWG). Thermal properties for the adhesive were characterized and reported previously [30]. The honeycomb core consisted of phenolic-dipped Nomex (The Gill Corporation HD132) with 3.2 mm (1/8 in) hexagonal cells, 12.7 mm (1/2 in) thickness, and a density of 48 kg/m<sup>3</sup>.

#### 3. Adhesive fillet formation

### 3.1. Model development

The model used for the adhesive fillet shape is a steady-state model based on the Young-Laplace equation, which accounts for surface tension, gravitational force, and the cell geometry [6]. The steadystate condition is assumed due to the relatively short characteristic time of fillet formation compared to the characteristic time of the overall co-cure cycle (hours). As the actual shape of the hexagonal honeycomb cell would be difficult to model numerically, the fillet shape for two simplified cases (linear and radial wall) were investigated (Figure 1a).

The schematic of the fillet geometry is shown in Figure 1a. The curve is determined by hydrostatic and surface forces, the volume of the fluid (adhesive resin), and contact angles  $\alpha$  and  $\beta$ . As the adhesive does not de-wet the prepreg surface, the angle  $\alpha$  between the adhesive and the facesheet is 0° and the width *W* has a maximum value of half the cell size but ultimately depends on the total volume of adhesive. The developed equations to predict the fillet shape in linear and radial cases and the corresponding boundary conditions are as follows [6]:

$$\gamma W^2 \frac{\ddot{y} - \dot{y}^2 \ddot{y} + \dot{y} \ddot{y}^2}{\left(1 - \dot{y}^2\right)^{3/2}} = \dot{y} \quad \text{(linear)} \tag{1}$$

$$\gamma W^{2} \left( \frac{\ddot{y} - \dot{y}^{2} \ddot{y} + \dot{y} \ddot{y}^{2}}{\left(1 - \dot{y}^{2}\right)^{3/2}} + \frac{\ddot{y} (W - r) - \dot{y} \sqrt{1 - \dot{y}^{2}}}{\left(W - r\right)^{2}} \right)$$
(2)  
=  $\dot{y}$  (Radial)

$$x(0) = W$$
  

$$y(0) = 0$$
  

$$x(L) = 0$$
 (B.C.) (3)  

$$\dot{y}(0) = \sin(\alpha)$$
  

$$\dot{y}(L) = \cos(\beta)$$

Here,  $\gamma = \frac{\sigma}{\rho g W^2}$ , which is the reciprocal of the Bond number. The coordinates are parametrized by arc (s) from 0 to unknown length *L*. Dots denote the derivative with respect to the arc [6]. It is shown that by solving Eqs. (1) and (2) for the same  $\gamma$  and boundary conditions, the predicted fillet shape in linear and radial cases are similar [6]. Therefore, it can be concluded that the fillet shape for the hexagonal wall configuration, which is between the two extents of the linear and radial cases as well.



Figure 2. a) Cross-section of adhesive fillet model validation sample. b) Sample of fillet height measurement.

According to the boundary conditions for the model and definition of  $\gamma$ , the simulated fillet shape is dependent on several material parameters:

- 1. The surface tension  $\sigma$ , which determines the curvature of the fillet, was measured to be  $\sim 40 \text{ mJ/m}^2$ . The model is not sensitive to small changes in  $\sigma$ , as even a change in value by 25% results in only a small shift in the modeled fillet shape.
- 2. The contact angle between the adhesive and the core cell wall  $\beta$  was 34.7°, as measured from micrographs of cross-sections. This property strongly impacts the fillet height *H*.
- 3. The width of the fillet W varied from fillet to fillet and from sample to sample, so 1 mm was selected as an upper bound on all measured data. It was shown to provide a reasonable fit. Note that the selected value for W is less than the cell half-width.

#### 3.2. Experimental methods

Fillet formation tests consisted of bonding honeycomb core ( $76 \text{ mm} \times 76 \text{ mm} \times 13 \text{ mm}$ ) to aluminum facesheets ( $102 \text{ mm} \times 102 \text{ mm}$ ) using a layer of film adhesive ( $76 \text{ mm} \times 76 \text{ mm}$ ). As the purpose of these tests was to generate validation data for the independent fillet formation model, testing conditions were chosen to most accurately satisfy key assumptions of the model: (1) the facesheet is rigid, (2) the bond-line contains a constant volume of resin, (3) fillet shape is a function of applied pressure, (4) the bond-line is void-free, and (5) fillet formation occurs counter to the influence of gravity. Aluminum facesheets were selected to satisfy the first two requirements, as prepreg would be flexible and potentially transfer resin to the bond-line.

Because the model is dependent on applied pressure (in this case, the gas pressure within the core cells), that pressure must be known. To achieve this, samples had only a single facesheet, leaving the second side of the core exposed. For all tests, the core cavity was vented to atmospheric pressure ( $\sim 100 \text{ kPa}$ ), which produced bond-lines with minimal porosity. The aluminum facesheets were placed on the tool side of the layup (i.e. underneath the core), so that fillet formation occurred upward.

After cure, sections (38 mm in length) were cut from samples, polished (Buehler MetaServe), and imaged (Keyence VHX-5000). Two samples were assessed, with  $\sim$ 20 fillets measured for each sample. Fillet cross-sections were analyzed using image processing software (Adobe Photoshop CC) to obtain fillet height as a function of distance from the cell wall. Fillet height was measured from the surface of the adhesive to the adhesive/facesheet interface. At the point at which the contact angle between the adhesive and the facesheet goes to  $0^{\circ}$ , the measured height was defined as the adhesive thickness and subtracted from measured heights (this volume of adhesive is not accounted for in the model). Height was measured at eight points in addition to the adhesive thickness, so that nine total points ranging



Figure 3. Model predictions compared to experimental data for fillet formation model.



Figure 4. Coupling between physical phenomena that affect porosity development in the adhesive bond-line.

from the cell wall (highest point along the fillet) to the end of the fillet (0 height, by definition) for each fillet. A sample cross-section along with height measurement method are shown in Figure 2.

Because experimental data were not easily measured at specific and regular points along the fillet, data were interpolated quadratically using the three closest points before comparison to model predictions (Figure 3). Results showed predicted height to be slightly higher (0.82%) than experimental values when using the measured contact angle  $\beta = 34.7^{\circ}$ . Error was greater in Panel B than A, likely caused by variability inherent in the process (e.g. variation in substrate smoothness, non-uniform temperature, etc.) Model predictions, however, still fell within the error range.

#### 4. Bond-line porosity development

The bond-line region considered for the purpose of modeling and validation is created during the bonding of the prepreg facesheets and the honeycomb core. Generally, the bond-line can be formed by an adhesive film layer or by the prepreg resin (through the use of a self-adhesive prepreg). In the former

procedure, which is focus of this work, resin squeezed out from the facesheet may also be present in the bond-line region, along with the adhesive. The presence of the squeezed-out resin from the facesheet has been observed previously [31]. Previous studies have demonstrated the possibility depending on processing conditions - of voids in the bond-line growing and escaping into the core cell [3, 25]. Experimental observations and the proposed stochastic models [6, 23], which relate void growth and the escape process, highlight the importance of capturing the escape process in the overall porosity development. Void escape is determined primarily by the bond-line shape, as well as the porosity level within the bond-line. A flow chart illustrates the interactions of different physics during the co-cure process (Figure 4) [23].

As shown in Figure 4, multiple factors affect porosity development within the bond-line:

- 1. Facesheet consolidation can affect the bond-line porosity through mass transfer of either resin (and therefore solvent mass) or existing voids.
- 2. Fillet formation determines the shape of the adhesive volume within which bond-line



Figure 5. Schematic of the co-cure fixture used in void growth model validation experiments. The glass viewport enables direct visualization of the adhesive bond-line during cure [3].

porosity exists, thus directly affecting the void content as well as the growth, transport, and escape of voids within the adhesive.

3. Gas pressure within the core cells is the pressure applied to the bond-line and therefore influences void growth via the adhesive resin pressure. Due to the relatively thin bond-line, the resin pressure is assumed to equal the core gas pressure. Therefore, voids within the bond-line are assumed to be exposed to the core pressure.

In this work, only the equilibrated-core process is considered, in which a direct connection between the core cells and the vacuum bag enables equilibration of the two volumes of gases. This simplifies modeling by eliminating the need for a core pressure model (typically a function of several parameters including temperature, time, facesheet permeability, etc.) and replacing it with an explicitly controlled core pressure processing parameter.

The mechanisms of void growth can be categorized as void size evolution due to (1) gas expansion based on ideal gas law behavior, and (2) diffusion-induced growth [13]. In the latter case – which has a greater influence on void size than gas expansion – dissolved volatiles in the liquid phase surrounding the voids diffuse into the gas bubble under appropriate pressure and temperature conditions. A stability map is proposed to identify pressures and temperatures at which the diffusion-induced growth occurs.

#### 4.1. Experimental methods

Experiments related to void growth consisted of two parts. First, *in situ* observations of void growth in the bond-line were used to compare with the

stability maps and estimate the volatile concentration. Second, bond-line porosity values were measured from sample cross-sections and compared to model predictions. In both cases, samples were prepared using a custom testing fixture that simulated autoclave conditions while allowing direct visualization of the bond-line during cure (schematic presented in Figure 5) [3]. The fixture featured a recessed pocket with a glass window, into which the core insert can be placed, with the adhesive and prepreg facesheet placed on top. A digital microscope (Dino-Lite Edge) was used to record time-lapse videos of the bond-line during cure. Separate pressure sensors were integrated to measure and record autoclave, vacuum bag, and core gas pressure. These gas volumes could be controlled independently, and the core cavity could also be sealed to allow the core pressure to evolve during cure.

Three tests with varying processing parameters were considered (Table 1), with each test conducted once. The same temperature cycle was used for all cases and consisted of a 60 min dwell at 110 °C and a 120 min dwell at 177 °C, with a 2 °C/min heating rate. Samples A and B were fabricated, respectively, with the vacuum bag and core pocket vented to ambient pressure ( $\sim 100$  kPa) with vacuum applied (< 5 kPa). For both tests, an autoclave pressure of 377.1 kPa was applied. All pressures were imposed prior to the start of the temperature cycle and held constant throughout the cure. Both cure cycles are shown in Figure 6.

Table 1. Conditions for Samples A, B, and C.

Sample	Plies in Facesheet	Vacuum Bag/Core Pressure (kPa)
A	4	101.3
В	4	< 5
С	8	< 5



Figure 6. Cure cycles I and II used for fabrication of validation samples for void growth model. a) Cure cycle I for Sample A had the vacuum bag and core vented to ambient pressure. b) Cure cycle II for Samples B and C had vacuum applied to the bag and core.



**Figure 7.** In situ images of the bond-line during cure. Images a-e are from Sample A and f-j from Sample B. Times, which correspond to cure cycles in Figure 6, are a) 0 min, b) 30 min, c) 60 min, d) 112 min, e) 150 min (cured state), f) 0 min, g) 2 min, h) 30 min, i) 120 min, j) 150 min (cured state).

Layup for Samples A and B were identical and consisted of a facesheet  $(102 \text{ mm} \times 127 \text{ mm})$  with 4 plies of prepreg  $([0^{\circ}/90^{\circ}]_{2s})$ , a layer of adhesive film  $(102 \text{ mm} \times 127 \text{ mm})$ , and a honeycomb core insert (Nomex, 76 mm  $\times$  76 mm). A third sample, C, was fabricated under the same vacuum pressure conditions as Sample B, but with a thicker facesheet (8 plies,  $[0^{\circ}/90^{\circ}]_{4s}$ ). Otherwise, the layup was identical to that of Samples A and B. Following cure, samples were sectioned and polished to measure porosity in the bond-line.

To measure porosity, samples were sectioned (50 mm in length), polished (Buehler MetaServe), and imaged (Keyence VHX-5000). Two sections for each sample were analyzed, each containing  $\sim 20$  fillets. Individual fillets and their contained voids were traced using image processing software (Adobe Photoshop CC) to quantify porosity, taken as the ratio of void area to total area.

#### 4.2. In situ void growth results

Selected frames from time-lapse videos for Samples A and B are shown in Figure 7, with times corresponding to cure cycles in Figure 6. The adhesive film can be seen in both tests in the initial states (A and F). During the first temperature ramp, adhesive temperature increases, and the viscosity drops, and resin flows to form the fillet. For Sample A, as the cure cycle progresses into the second temperature ramp (D, at 112 min), voids were observed to grow and inflate the fillets. These voids remained trapped in the adhesive after gelation (E).

On the other hand, when vacuum was applied to Sample B, void growth started early in the cure cycle ( $\sim 2 \min$ ), as temperature increased and both adhesive and prepreg resin viscosity decreased (G). These voids grew and escaped by bursting at the surface, which continued through the initial stage of



**Figure 8.** Stability maps of each cure cycle used. Cure Cycle I: Ambient pressure within the core. Cure Cycle II: Vacuum pressure applied to the core. The time and temperature for the initial void growth are 112 min/124°C and 2 min/24°C respectively.

cure (H). After some time ( $\sim$  70 min through the cure cycle), the number of voids growing and escaping reduced, indicating the mass of dissolved volatiles had escaped through the adhesive bond-line (I). No further void growth was observed for the remainder of the cure cycle, and the final state did not display any inflation of the fillets due to entrapped porosity (J).

The utility of a void stability map in the co-cure of sandwich structures was discussed previously [32]. Moisture was treated as the main volatile in the materials (to simplify modeling), and a stability map was created to predict stable and unstable pressure and temperature conditions for a given volatile concentration. Stability maps for cure cycles used for both Samples A and B are shown in Figure 8. The corresponding cure cycles were mapped for each sample. Volatile concentrations were estimated based on the temperature and pressure at which void growth was observed to be triggered from the *in situ* time-lapse videos.

The stability maps enabled bond-line porosity to be predicted qualitatively without further computation. Previous work showed that the diffusioninduced bubble growth is more extensive if the cure cycle advances further in the unstable region [23]. Figure 8 illustrates that, in the cure cycle used for Sample A, the voids within the prepreg resin remained within the stable region for most of the cycle, and only experienced critical growth conditions for a relatively short period of time (at 124 min) before the adhesive gelled (gelation time of the adhesive was at 130 min). Therefore, the voids within the prepreg resin which are growing at this stage may become trapped under the gelled adhesive until prepreg resin gelation at 143 min. This potentially leads to the higher level of porosity within the bond-line. Conversely, in the cure cycle used for

Sample B, both the prepreg resin and the adhesive enters the unstable growth condition in the early stage (at 2 min) of the cure cycle due to the reduced pressure, providing sufficient time for void growth and escape which may result in low final porosity. This qualitative comparison of cure cycles with the stability maps indicates that the final porosity of Sample A will be greater than Sample B. This hypothesis is validated by the experimental results in the following section.

#### 4.3. Porosity simulation

The bond-line porosity simulation is achieved by integration of multiple sub-models; (i) the bubble growth model, (ii) the stochastic model for the bubble escape process, (iii) the model for the adhesive fillet shape, and (iv) the prediction of the prepreg resin volume, and the corresponding bubbles, bleeding into the bond-line. The simulation for bubble growth requires assumptions about the initial size of voids and initial porosity in both the prepreg resin and adhesive, as well as the initial volatile concentration of each material. The parameters used are summarized in Table 2. One percent porosity represents the minimal void content of the aerospace grade materials typically used in the co-cure process of honeycomb sandwich structures. The initial radius of voids in the adhesive is assumed to be 10  $\mu$ m, selected based on prior studies [16]. The initial radius of voids entering the bond-line from the prepreg resin is assumed to be  $5 \mu m$ , with the

Table II Talanceels asea in the tota growth mode	Table 2.	Parameters	used i	n the	void	growth	mode
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	Initial Void Radius	Initial Porosity	Effective Relative Humidity
Adhesive	$R_{0,AD} = 1*10^{-5}m$	$\phi_{0,AD} = 1\%$	$RHO_{AD} = 20\%$
Prepreg	$R_{0, PR} = 0.5 * 10^{-5} m$	$\phi_{0,\textit{PR}}=1\%$	$RHO_{PR} = 45\%$



Figure 9. a) Simulated fillet shape and b) simulated volume of prepreg resin squeezed out of the facesheet for each sample.

smaller size relative to the adhesive voids reflecting the size of pinholes in the prepreg fabric that voids must pass through to reach the bond-line.

Simulation results for fillet shape and volume of prepreg resin that bled from the facesheet for the three samples are shown in Figure 9. The predicted fillet shape was similar across all samples, as the same temperature cycle was used, and parameters affecting fillet shape (surface tension, contact angle, and density) vary with temperature, but not pressure. The volume of prepreg resin that bled from the facesheet varied due to differences in pressure gradients across the facesheet as well as the total volume of resin. The initiation of resin bleed was dependent primarily on resin viscosity and the pressure profile within the facesheet; therefore, resin bleed was slightly delayed in Sample C due to the thicker facesheet that yields a different pressure distribution than in Samples A and B. As autoclave pressure was the same for each sample, the compaction pressure (defined as  $P_{auto} - P_{core}$ ) varied depending on the applied bag pressure. Because the equilibrated-core configuration was used, the core pressure  $(P_{core})$  was equal to the bag pressure  $(P_{bag})$ . In Sample A, the bag and core were vented to ambient pressure, and thus compaction pressure was reduced compared to Samples B and C with vacuum pressure in the bag and core. Sample A, therefore, had the least volume of resin that bled from the facesheet. Sample C had double the number of prepreg plies and therefore double the initial volume of prepreg resin compared to Sample B, and thus had the largest volume of resin that bled from the facesheet. These results affect bond-line porosity through porosity transport from the facesheet to the bond-line.

Figure 10 illustrates the development of bondline porosity during the cure cycle for the samples. As described previously, three porosity values in the

bond-line can be defined: (i) the porosity within the adhesive, (ii) the porosity within the prepreg resin that bled into the bond-line, and (iii) the effective porosity, which is the weighted average of the adhesive and prepreg resin porosity values in the bondline [6]. The influence of bled prepreg resin porosity on the effective porosity depends on the bled prepreg resin volume. Because the volume of adhesive in the bond-line is greater than the volume of prepreg resin transferred to this region, the adhesive porosity is dominant in the calculation of effective porosity. In Figure 10a, corresponding to Sample A, the porosity advances based on the ideal gas expansion until the last stage of the cure cycle. At 112 min, the cure cycle enters the unstable bubble growth region of the stability map and consequently, diffusion-induced growth is invoked within the bubbles in the bled prepreg resin. As the cure cycle proceeds, the bubbles within the adhesive experience the diffusion-induced growth at 126 min. However, because of the selection of the process parameters of the cure cycle, the bubbles do not grow large enough to escape the bond-line before the material gels, trapping them in the gelled adhesive.

Figures 10b and 10c demonstrate the porosity development within Samples B and C. These samples were fabricated using the same temperature cycle as Sample A but with vacuum pressure applied to the bag and the core. In the simulations, the vacuum pressure is 1 kPa. According to the stability map, the cure cycle enters the unstable growth region in the early stage of the process, while the temperature continues to rise according to the prescribed temperature ramp. Therefore, the diffusioninduced growth initiates early in the cure cycle, which accelerates the bubble growth within the adhesive. The bubbles grow and escape once they



**Figure 10.** Simulated time-dependent development of bond-line porosity for each sample. The porosity considered is the effective porosity, which is the weighted average of the porosity in the adhesive itself and bled prepreg resin. a) Sample A, 4-ply facesheet, ambient core pressure (cure cycle I), b) Sample B, 4-ply facesheet, vacuum core pressure (cure cycle II), and c) Sample C, 8-ply facesheet, vacuum core pressure (cure cycle II).

reach the bond-line surface. At 11 min, the consolidation process drives the prepreg resin and the corresponding bubbles from the facesheet into the bond-line, which we refer to as the bled prepreg resin. Therefore, at this time, porosity within the bled prepreg resin starts increasing as well due to diffusion-induced bubble growth. As the cure cycle proceeds and temperature increases, porosity of the bled prepreg resin decreases and attains a constant final porosity value because of two phenomena that occur simultaneously: (i) bubbles within the bled prepreg resin grow and escape at the bond-line and (ii) the prepreg resin bleeding stops as the consolidation process approaches the steady-state condition. The difference between Sample B and Sample C is the number of prepreg plies of the facesheet. As Sample C contains 8 layers of prepreg plies, it contains more prepreg resin and consequently, transfers more resin and voids compared to Sample

B (4 prepreg layers). The porosity reported by the model is specific to the bond-line region (for both the adhesive and bled prepreg resin), and the overall porosity (the effective bond-line porosity shown by red dashed line) is a weighted average of each material. While the percent porosity in the bled prepreg resin is the same for Samples B and C, the porosity remaining after the cure is primarily sourced from the prepreg resin and therefore the weighted average increases with increased volume of prepreg resin bleed. The findings show the sensitivity of the simulation model to the number of prepreg layers.

Cross-sections for each sample are shown in Figure 11, with measured and corresponding simulated porosity values summarized in Table 3 and Figure 12. At the center of the cell, fillet area included the region up to the location where the adhesive contact angle approached zero. In some instances, this boundary could not be clearly



Figure 11. Cross-sections for each sample fabricated. a) Sample A, 4-ply facesheet, ambient core pressure, b) Sample B, 4-ply facesheet, vacuum core pressure, and c) Sample C, 8-ply facesheet, vacuum core pressure.

 Table 3. Experimental and simulation results for bond-line porosity in each sample.

Sample	Experimental Data (%)	Simulation Result (%)
A	41.1± 18.2	29.4
В	6.5± 10.4	5.1
С	23.5± 17.01	6.7

determined (e.g. due to porosity in the center of the cell, as shown in Figure 11a), and these fillets were not included in the measurements. The layer of adhesive between the facesheet and  $0^{\circ}$  adhesive contact angle was not accounted for in the fillet formation sub-model, but is included in the porosity model and hence is counted as part of the fillet region during porosity measurements.

The model predicted greatest porosity levels in Sample A and the lowest in Sample B. Despite identical temperature and pressure cycles, the porosity of Sample C was predicted to be greater than that of Sample B, due to the greater volume of bled resin from the facesheet transporting more voids to the bond-line.

As demonstrated in Figure 12 and Table 3, the measured porosity shows large variations, an observation attributed to stochasticity in the co-cure process and multi-scale geometries inherent in sandwich panels, which lead to nonuniformities. For example, the distance between pinholes in the prepreg fabric compared to the diameter of honeycomb cells results in different numbers of pinholes within each core cell. This affects the volume of the bled resin and consequently, the number of voids migrating from the facesheet to the bond-line.

The measured porosity confirms that the model can predict the bond-line porosity of the honeycomb sandwich structures fabricated by the co-cure process in the autoclave. However, integration of multiple models, each with specific assumptions and simplifications, assumptions for material properties, and non-uniformities in fabrication, make accurate prediction of bond-line porosity nonviable. Although the presented model yielded underestimates of the porosity in the processed samples, trends were correctly predicted. The results correctly predicted the effects of process parameters and the number of facesheet plies on bond-line porosity.

#### 5. Summary and conclusions

In this work, physics-based models related to the adhesive bond-line and porosity development during co-cure of honeycomb sandwich structures were compared with experimental results. First, a validation experiment was conducted to evaluate the model to predict adhesive fillet shape. Model predictions agreed with experimental data, and the model was viable for integration into the porosity development simulations in which multiple sub-models were combined. The porosity model integrated diffusion-induced void growth with descriptions of void transfer from the facesheet to the bond-line and void escape from the adhesive fillets, phenomena which are not captured by existing models intended for porosity in monolithic composite structures [13, 16]. Stability maps of critical pressure and temperature conditions for unstable void growth were used to identify when porosity would form, and three cure cycles under different pressure and material conditions were simulated using the integrated porosity model. Comparison to experimental results indicated that the model could describe trends in porosity as a function of applied pressure and facesheet thickness despite the stochastic nature of the process.

Contrary to the common belief that decreased vacuum pressure increases the final porosity, results



Figure 12. Measured bond-line porosity and simulation results for each sample fabricated.

showed that due to gas escape during co-cure, applying vacuum resulted in the lower bond-line porosity. Thus, there are two plausible solutions to mitigate the bond-line porosity in the co-cure process of sandwich structures: (i) devising a cure cycle that avoids the unstable bubble growth region in the stability map, either by pressurizing the core (e.g. [3, 25]) or deploying a temperature cycle that achieves cure prior to the unstable growth region (e.g. [33]), or (ii) applying high vacuum early in the cure cycle, before the unstable bubble growth region. The latter strategy will cause intensive bubble growth and consequently, their escape from the bond-line to the core.

In the work described here, only the case of equilibrated-core co-cure was considered to reduce the complexity of simulations. In the sealed-core configuration, the core cavity is isolated from the vacuum bag *via* an adhesive layer and prepreg facesheet on both the bag and the tool sides, and core pressure changes during cure based on the temperature, pressure gradient, and facesheet permeability [34–36]. In future work, the simulation model presented for bond-line porosity could be coupled with a model predicting core pressure evolution to describe this sealed-core configuration. Sealing the core, however, also isolates individual core cells from each other, and introduces cell-to-cell variation, making modeling more complicated and challenging.

Despite the success of the model in capturing trends in porosity in response to parameter changes, quantitative predictions did not match experimental measurements. Experimentally, scatter in measurements was large due to stochasticity of the co-cure process, as well as uncontrolled variability in material parameters (such as locations of pinholes in the fabric relative to the core cells, which affect resin bleed). More precise material characterization and smaller-scale modeling (e.g. modeling on the scale

of fiber tows) could improve model accuracy. Combining the proposed model with a description of the stochastic behavior of the co-cure process yield more accurate predictions. could also Variability in model predictions also stemmed from the complexity of integration that compounds assumptions and simplifications of several sub-models. The complex physics and interactions involved in co-cure, coupled with the need for detailed characterization of multiple material parameters made precise quantitative predictions of the bond-line porosity impractical. However, the ability to predict trends based on changes in material and processing parameters provides a potentially valuable tool to guide material selection and cure cycle design for more efficient and robust production of honeycomb sandwich panels with void-free bond-lines [37].

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The authors have no competing interests to disclose.

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#### Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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