A SIMPLE ANALYSIS TOOL TO SIMULATE THE CO-CURE OF HONEYCOMB CORE COMPOSITE SANDWICH STRUCTURES

Navid Niknafs Kermani, Pavel Simacek, Suresh G. Advani

Department of Mechanical Engineering, Center for Composite Materials, University of Delaware, Newark, Delaware 19716, United States

ABSTRACT

Honeycomb sandwich structures are fabricated using a co-cure process by bonding partially cured thermoset prepreg sheets with an adhesive layer to either side of the honeycomb core structure under a selected pressure and temperature cycle. High defect levels during the co-cure are common as the process development cycle is strongly dependent on many material and process parameters such as prepreg facesheet consolidation, adhesive bond-line fillet formation, porosity level within the prepreg and the adhesive, and core pressure evolution. In this work, a simple analysis tool is presented which can simulate these phenomena during the co-cure manufacturing of honeycomb sandwich composites. Inputs include material properties of the prepreg, adhesive and the honeycomb core and the specified pressure and temperature cycle. The tool conducts the analysis to provide the output, which includes the degree of prepreg facesheet consolidation, the porosity level at the adhesive bond-line, fillet shape of the adhesive along the core walls and the development of the core pressure. The tool should provide a better understanding of the relationships between the materials, process, and the final bond-line quality, which will result in improvement of the manufacturing process.

1. INTRODUCTION

Honeycomb sandwich structures are fabricated by placing partially cured thermoset prepreg facesheets on either side of a honeycomb core enclosed by a vacuum bag in an autoclave and co-cured, in a single step, under a prescribed pressure and temperature ramp (Figure 1A). Usually an adhesive layer is included to bond facesheets and the core. During the co-cure process of honeycomb sandwich structures, four main phenomena occur simultaneously; (i) prepreg consolidation, (ii) adhesive bond-line fillet formation, (iii) porosity evolution within the adhesive and the prepreg, and (iv) its interaction with the core pressure dynamics (Figure 1C-F). Modeling of the co-cure process of sandwich structures is complicated as these phenomena are coupled. Figure 1 shows a schematic of a sandwich structure and three different adhesive bond-line qualities and adhesive fillet shapes after co-curing of a honeycomb core sandwich structure. To understand the influence of material and process parameters, it is important to model the process physics and phenomena that occurs during the manufacturing cycle.

SAMPE Conference Proceedings. Charlotte, NC, May 20-23, 2019. Society for the Advancement of Material and Process Engineering – North America.

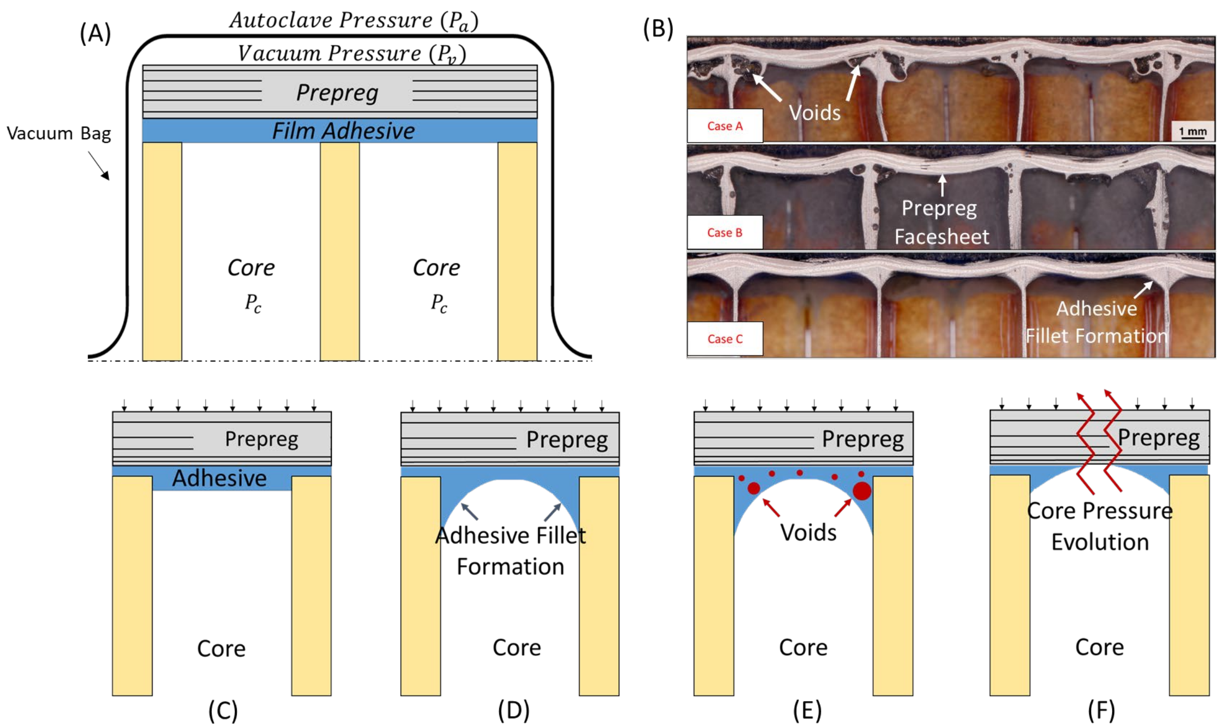

Figure 1. (A) Schematic of a honeycomb sandwich composite (B) Micrographs of co-cured samples exhibiting a wide range of bond-line qualities [1], Case A: voids within the adhesive bond-line, Case B: voids within the prepreg facesheet and adhesive bond-line and Case C: void free facesheet and bond-line. (C)-(F) Schematics of identified phenomena during the co-cure of sandwich structures : (C) prepreg facesheet consolidation, (D) adhesive bond-line fillet formation, (E) porosity within the adhesive bond-line and (F) core pressure evolution.

Prepreg consolidation during autoclave processing is better understood for monolithic laminates as compared to the consolidation during the co-cure process. In the co-cure process of prepreg with honeycomb cores, the applied pressure is lower than the consolidation pressure for monolithic laminates, as it should not exceed the yield pressure of the core. Additionally, due to the geometry of the core, higher pressures can cause the prepreg fibers to deform between the core walls. To model prepreg consolidation in such systems, the effect of consolidation on fiber volume fraction and the permeability of the prepreg is considered. In addition, it has been reported that voids present in the prepreg migrate into the adhesive bond-line during the co-cure process and degrade the quality of the adhesive bond-line [1,2]. Thus, mass transfer between the core, adhesive, and prepreg needs to be addressed as well.

The quality of the adhesive bond-line is one of the critical factors in the co-cure process, as having a low quality bond will cause the structure to fall apart, and this quality is dependent on two factors. First, it is the shape of the fillets between the core and face sheets. Second, it is the adhesive internal structure within these fillets, described usually by its porosity. The latter undergoes significant changes during the co-cure process due to void formation, growth, and transport within the prepreg and the adhesive as a result of the out-gassing process. The presence of porosity (voids) in fiber reinforced polymer composites is known to degrade mechanical properties of composites [2,3,4]. It has been shown that voids within the prepreg sheets can be reduced by employing very high-pressure cycles in autoclaves [5] but during manufacturing of sandwich structures, the autoclave pressure is bounded by the yield pressure of the core. Compared to prepreg sheets being consolidated in a monolithic structure, the void evolution during the co-cure process with thermoset prepregs as in honeycomb sandwich structures, is more complex to model due to (i) the heterogeneity introduced by the presence of different materials, (ii) low consolidation pressure to ensure the core does not collapse and (iii) pressure dynamics within the honeycomb core. Moreover, all these phenomena during the co-cure process are highly coupled which makes it challenging to develop a process model. A unique feature due to the presence of the core is that the void formation and growth can be affected by not only the bag and autoclave pressure but also the core pressure.

In this research, a simple analysis tool, consisting of multiple sub-models, is provided to simulate the co-cure process of honeycomb sandwich structures in an autoclave. The required inputs are the prepreg, adhesive and core material properties, and specified temperature and pressure profiles during the co-cure process. The outputs will be the degree of consolidation of the prepreg facesheets, time history of the core pressure and the porosity level and the fillet shape of the adhesive bond-line. This tool should prove useful to better understand the co-cure process of sandwich structures.

2. THEORY

During co-curing of composite sandwich structures in the autoclave, the inputs, defined and controlled by manufacturers, are the pressure and temperature of the autoclave, the pressure in the vacuum bag and the material properties of the prepreg, adhesive and the core. The desired sandwich structure must be fully cured and have uniform properties, with a strong bond-line and minimal porosity and consequently, the desired strength.

To simulate the behavior of materials (prepreg, adhesive, and core) during the co-cure process, four coupled phenomena need to be modeled simultaneously: (i) prepreg facesheet consolidation, (ii) adhesive fillet formation, (iii) porosity evolution within the adhesive bond-line, and (iv) core pressure development. Figure 2 schematically shows how these four models are coupled. The coupling is the result of pathways between the core and the vacuum bag through the adhesive and prepreg facesheets, which controls the core pressure but in turn, is influenced by the core pressure and through thickness gas permeability of the prepreg facesheets. The adhesive fillet formation or the porosity within the adhesive bond-line may create pathways for the isolated gas inside the core to flow through the prepreg and be evacuated by the vacuum. This phenomenon connects the adhesive fillet formation, adhesive bond-line porosity, and core pressure via through thickness gas permeability of the prepreg facesheets to the prepreg consolidation modeling.

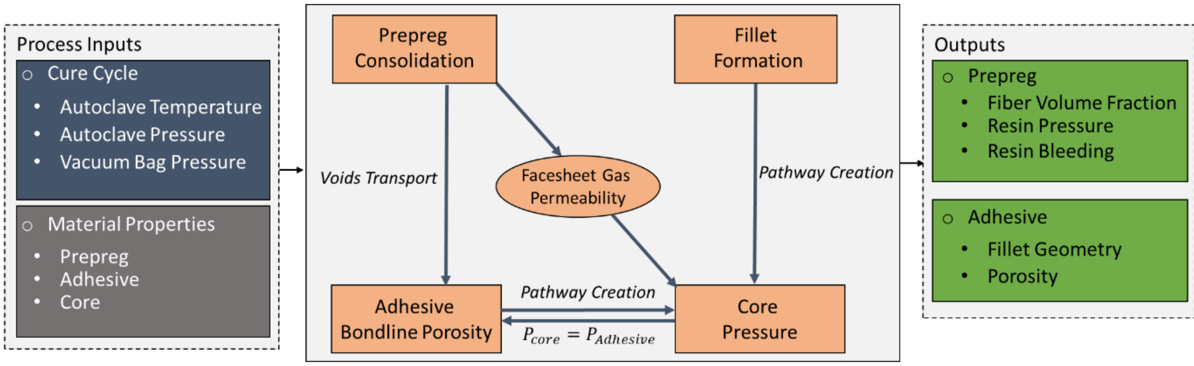

Figure 2. Flowchart showing the inputs, coupling of different sub-models and the outputs of the analysis tool.

2.1 Prepreg Consolidation

Prepreg facesheet consolidation has been modeled previously for monolithic laminates (e.g. [6]). However, during the co-cure process of honeycomb core composite sandwich structures, these models are not directly applicable due to the specifics of co-cure like the non-uniform load distribution and curved shape of facesheets (dimpling effect). To model the prepreg facesheet consolidation over the honeycomb, a single scale porous media flow with compaction in the thickness direction is considered. The unit contains prepreg facesheets, adhesive layer and a core cell (Figure 3). Prepreg is represented as the curved domain supported by core walls. The applied compaction stress on the fibers on the core side is equal to zero while at the bag side is equal to the difference between the autoclave and the bag pressures (P_a-P_v). The resin pressure equals the vacuum pressure (P_v) on the bag side while on the core side, it is equal to the core pressure (P_c) and varies within the prepreg sheet in equilibrium with the reinforcement stress. The resin pressure variation within a porous reinforcement obviously results in resin flow relative to the fiber bed. This facilitates filling of the voids, but can also lead to resin flowing (bleeding) into the adhesive layer towards the core.

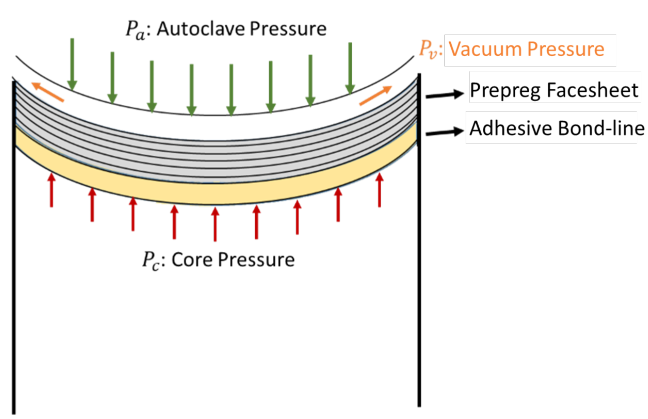

Figure 3. Schematic of a honeycomb cell depicting autoclave, vacuum and core pressures.

The resin bleeds out of the prepreg either into the breather or into the core, increasing the fiber volume fraction of the reinforcement within the prepreg. As resin bleeds out of the prepreg, any existing voids within the prepreg will enter the adjoining adhesive layer, which is reported as one of the major sources of porosity within the adhesive bond-line [1,7].

In addition, compaction of the prepreg facesheets affects the through thickness gas permeability of the prepreg [7]. As the fiber volume fraction increases, the gas permeability of the prepreg decreases, which is the key to model the gas flow through the prepreg, which influences the core pressure.

2.2 Adhesive Fillet Formation

In the co-cure process, when the viscosity of the adhesive decreases, adhesive starts to wet the surface of the core cells. It forms a fillet shape as a result of the interaction between the surface tension force and the contact angle between the adhesive and the core walls, gravitational force, and the viscous forces of the adhesive (Figure 4). The contact angle between the adhesive and the core walls can be calculated in quasi-steady state, which provides the depth of the formed adhesive fillet. The fillet shape of the adhesive governs the areas of the core and the facesheet covered by it, which determines the strength of the bond. Also, the shape of the adhesive bond-line that covers the surface of the adjoining prepreg determines if the gas trapped in the core will flow through the pores of the facesheets toward the vacuum bag (due to the pressure gradient between the gas volume in the core and the bag pressure). Even if the adhesive wets the entire surface of the prepreg, voids within the adhesive bond-line may penetrate across the adhesive and create a pathway between the core and the prepreg, which allows the evacuation of gas volume from the core into the bag (if the necessary pressure gradient between the core and bag is satisfied). Thus, the coupling between the minimum thickness of the adhesive layer and the size of the voids within the adhesive needs to be considered to model the evolution of the core pressure.

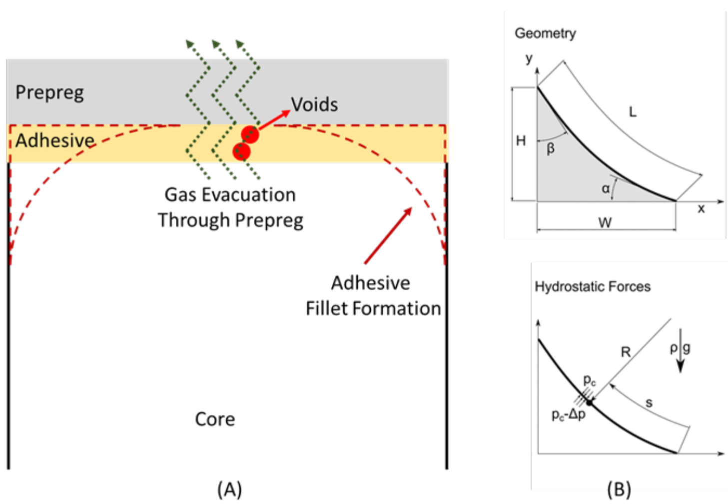

Figure 4. (A) Evacuation of gas inside the core through the prepreg due to the created pathway controlled by the through thickness gas permeability. (B) Fillet shape, dimensions, pertinent parameters and acting forces.

2.3 Void Dynamics and Adhesive Bond-line Porosity

With the purpose of simulating the adhesive bond-line porosity during the co-cure process, void evolution in the adhesive needs to be described. To model the behavior of bubbles in viscous liquids (resin), a unit cell containing a bubble surrounded by the liquid shell with a limited amount of dissolved gas (volatiles) is assumed (Figure 5). During the cure cycle, as the applied pressure and temperature varies, there will be two phenomena influencing the bubble growth or collapse. The major driving force for bubble evolution is the applied pressure by the liquid, which is assumed to be equal to the pressure inside the honeycomb core due to the thin thickness of the adhesive. It is known from experiments that by increasing the pressure in an autoclave during the curing process, the level of porosity is reduced as the bubbles collapse due to the high surrounding liquid pressure [5]. The other influential factor that induces bubble growth is the diffusion of volatiles from the resin into the bubbles, which depends on the volatile concentration in the liquid close to the bubble boundary. If the dissolved gas from the resin shell diffuses into the bubble, the bubble will grow and if the gas diffuses back into the resin from the bubble, the bubble will shrink.

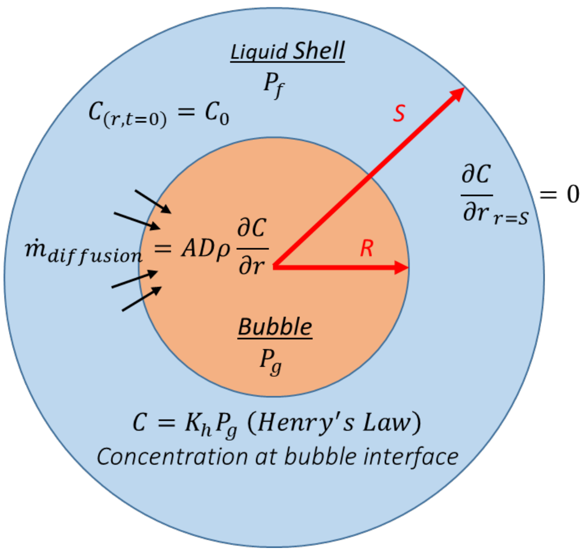

Figure 5. Schematic of a bubble (radius R) surrounded by an adhesive film (radius S) with C_0 as the initial concentration of volatiles and C_w as the concentration of volatiles next to the bubble interface. P_g is the gas pressure inside the bubble and P_f is the pressure of the surrounding liquid. The unit cell is bounded and there is no diffusion at $r = S$.[8]

The diffusion induced growth of voids is modeled in the liquid containing a limited amount of volatiles by solving the mass diffusion transport of volatiles within the resin and at the bubble boundaries [9].

After modeling the evolution of a single void, the porosity of bond-line adhesive can be simulated with respect to the input temperature ramps and applied pressure. As the adhesive pressure is assumed to be equal to the pressure inside the honeycomb core, the core pressure development directly influences the adhesive bond-line porosity and needs to be investigated.

2.4 Core Pressure Evolution

In this tool, to analyze the pressure of gas volume inside the core, there are two different models according to the assembly of the sandwich structures (sealed or open core). For the open-core case, the gas volume in the core is connected to the vacuum bag. Thus, the core pressure equals the pressure under the vacuum bag $P_c=P_v$ (Figure 1). For the sealed-core case, the pressure of the gas volume inside the core may be calculated by using the equation of state (ideal gas law) and mass balance between the panel's core and bag in which the mass of the volatiles released from the adhesive, prepreg or even core walls into the core has to be accounted for. This phenomenon may result in significant pressure build-up in the core.

In order to model the gas flow through the prepreg facesheet by Darcy's law, one has to estimate the gas permeability of the prepreg facesheets, which is related to the consolidation state (as provided by the consolidation model) and resin viscosity within the prepreg. Also, as in this analysis, the core pressure is assumed to be equal to the pressure within the adhesive bond-line, due to the very thin thickness of the adhesive (of the order of 100 microns to a millimeter), it is equal to the pressure imposed on the voids suspended within the adhesive. If voids grow due to the decrease in core pressure, they may burst and puncture the adhesive layer, creating pathways between the core and the prepreg assisting the gas flow toward the vacuum bag, which will also significantly impact the core pressure as well.

Thus, in the modeling of the co-cure process of honeycomb core sandwich structures, each phenomenon affects the others, creating a coupled system of sub-models, which need to be solved simultaneously. In the current approach, this is accomplished by explicit modeling. From the current well-described state, all sub-models develop independently for a short amount of time. Then, their results are used to update the state of the entire system. The results are presented in the next section.

3. RESULTS AND DISCUSSION

The user interface of this tool is designed to let users simulate the co-cure process of sandwich composite structures. The user selects materials and consolidation cycle and explores the predictions for such systems. There is also an option to examine some intermediate results – the behavior of certain subsystems (materials) – during the process and to adjust it.

Thus, the interface provides three separate tabs designed for inputs (material and process selection), components (materials) behavior and adjustments, and finally for the simulation outputs. In the input pane, the user selects the material from the list of characterized materials and enters some additional information, like the number of plies of the prepreg, adhesive thickness and the core size. The temperature and pressure profiles inside the autoclave and the vacuum bag during the cure cycle can be imported as a table, which can be modified as needed. Accordingly, the selected pressures and temperature profiles are shown in graphs to have better visualization of the designed cure cycle (Figure 6).

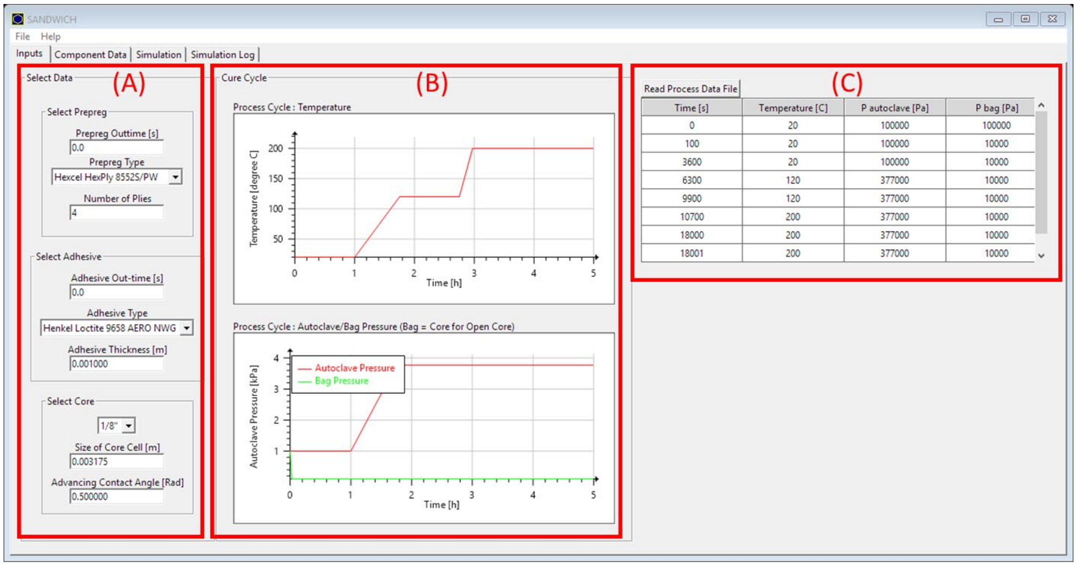

Figure 6. The user interface of the analysis tool: (A) inputs about the prepreg, adhesive and core properties, (B) graphs showing the cure cycle and (C) table of the temperature and pressure profiles inside the autoclave and the vacuum bag.

The Component Data tab (Figure 7), contains the automatic execution of the material models. This allows an easy inspection to identify the regions where the viscosity is too high for the process to have no effect. The plotted values include the degree of cure, viscosity and volatile generation. Additionally, for the prepreg, the reinforcement elastic behavior is shown. The material model coefficients of the prepreg and the adhesive are presented in an editable table that allows the user to either modify the material model or even introduce different materials described by the same equation sets. These can be saved and reloaded as needed.

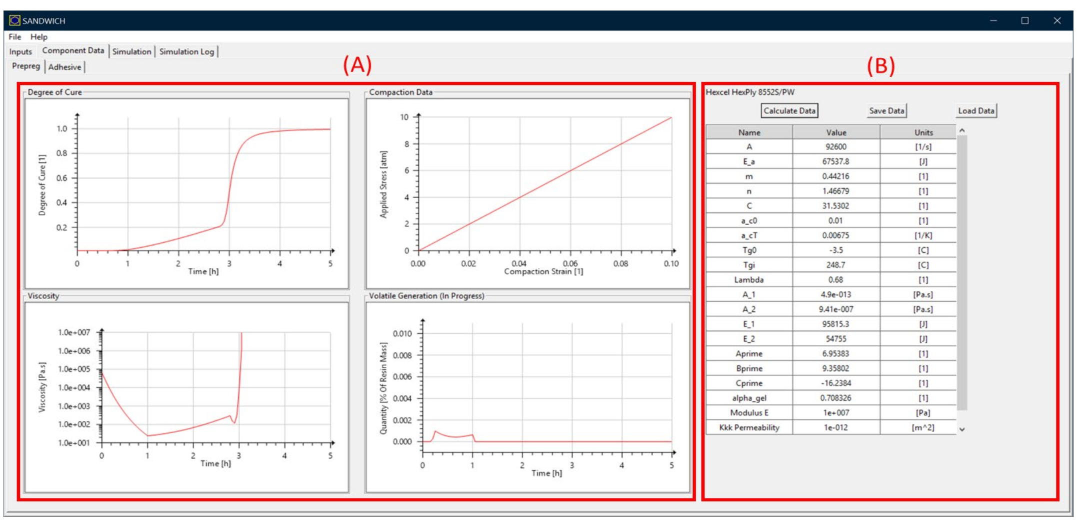

Figure 7. The component tab (A) graphs showing viscosity, degree of cure, compaction data and volatile release during the co-cure cycle and (B) the material properties table.

Finally, after defining the material properties of the prepreg, adhesive, and the core and importing the co-cure cycle pressures (autoclave and vacuum bag) and temperature in the Input pane and checking materials behavior, the coupled simulation can be executed in the Simulation pane. One can choose the simulation model type (open core or sealed core) and the time step for advancing the simulation. The outputs are displayed in the Simulation tab in different graphs (Figure 8). There are options for the user to run the entire cure cycle at once or to simulate the process within specific time steps.

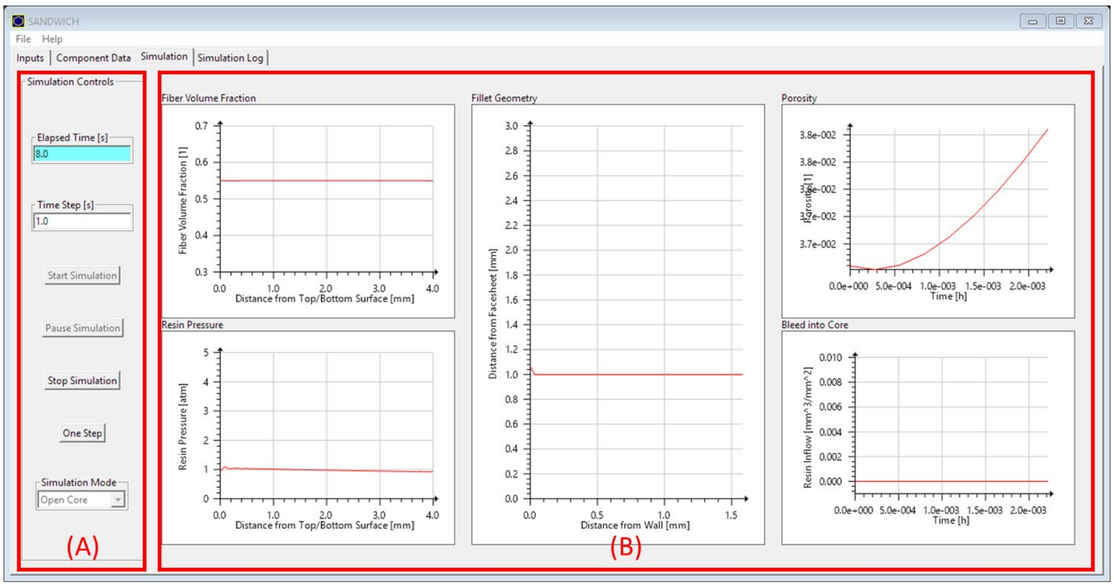

Figure 8. Simulation tab shows the outputs of the co-cure process of sandwich structures simulation: (A) simulation mode options (open or sealed core) and the simulation time step inputs, (B) outputs of the simulations for each sub-model; fiber volume fraction and resin pressure and resin bleeding from the prepreg consolidation sub-model, fillet geometry from the adhesive fillet formation sub-model and adhesive bond-line porosity.

This tool allows users to change the co-cure cycle for a defined assembly of prepreg, adhesive and core structure to find the appropriate cycle to obtain the desired outputs. Hence, application of this tool prior to manufacturing sandwich structures will reduce the trial and error approaches to define the proper co-cure cycle to manufacture composites with the desired cured properties.

4. CONCLUSIONS

A simple tool is developed to model the co-cure manufacturing process of honeycomb sandwich structures. The inputs are the material properties of the core, prepreg facesheet and the adhesive, and the applied pressure and temperature cycle for the autoclave and the vacuum bag. Four coupled phenomena, prepreg consolidation, adhesive bond-line fillet formation, bond-line porosity, and core pressure evolution, influencing the process and the quality of the manufactured part are simultaneously modeled. The tool is designed to be flexible so as to simulate different prepreg, core, and adhesive materials for the manufacture of sandwich composites with different pressure and temperature ramps.

5. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the funding support from NASA Langley Research Center through NRA NNL16AA13C and the collaboration of the M. C. Gill Composites Center at the University of Southern California.

6. REFERENCES

[1] Anders, M., Zebrine, D., Centea, T. and Nutt, S.R., 2019. "Process diagnostics for co-cure of sandwich structures using in situ visualization." *Composites Part A: Applied Science and Manufacturing*, 116, pp.24-35. https://doi.org/10.1016/j.compositesa.2018.09.029.

[2] Bowles, K. J., & Frimpong, S., 1992 "Void effects on the interlaminar shear strength of unidirectional graphite-fiber-reinforced composites." *Journal of Composite Materials* vol. 26, no. 10 pp. 1487–1509 https://doi.org/10.1177/002199839202601006.

[3] Kizito, J., Balasubramaniam, R., Nahra, H., Agui, J. and Troung, D., 2009. "Vapor-gas bubble evolution and growth in extremely viscous fluids under vacuum." In *47th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition* (p. 1147). https://doi.org/10.2514/6.2009-1147.

[4] Pearce, P. J., D. R. Arnott, A. Camilleri, M. R. Kindermann, G. I. Mathys, and A. R. Wilson. "Cause and effect of void formation during vacuum bag curing of epoxy film adhesives." *Journal of adhesion science and technology* 12, no. 6 (1998): 567-584. https://doi.org/10.1163/156856198X00795.

[5] Boey, F. Y. C., and S. W. Lye. "Void reduction in autoclave processing of thermoset composites: Part 1: High pressure effects on void reduction." *Composites* 23, no. 4 (1992): 261-265.

[6] Hubert, P. and Poursartip, A. "Review of flow and compaction modelling relevant to thermoset matrix laminate processing." *Journal of Reinforced Plastics and Composites 17*, 4 (1998), 286–318. https://doi.org/10.1177/073168449801700402.

[7] Centea, T., Simacek, P., Anders, M., Niknafs Kermani, N., Zebrine, D., Advani, S.G., and Nutt. S. "Understanding and modeling the co-cure of honeycomb core sandwich structures" *Proceedings of the SAMPE 2019 Conference*, Society for the Advancement of Material and Process Engineering (2019).

[8] Arefmanesh, A., and S. G. Advani. "Diffusion-induced growth of a gas bubble in a viscoelastic fluid." *RheologicaActa* 30,no.3(1991):274-283 https://doi.org/10.1007/BF00366641.

[9] Niknafs Kermani, N., Simacek, P., Erdal, M., and Advani, S.G. "A numerical model to simulate void dynamics during processing of honeycomb core sandwich structures with prepreg face-sheets." *Proceedings of the 33rd Technical Conference of the American Society for Composites*, American Society for Composites (2018).