AN EFFICIENT MODELLING APPROACH FOR PREDICTION OF POROSITY SEVERITY IN COMPOSITE STRUCTURES

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ABSTRACT

Porosity, as a manufacturing process-induced defect, highly affects the mechanical properties of cured composites. Multiple phenomena affect the formation of porosity during the cure process. Porosity sources include entrapped air, volatiles and off-gassing as well as bag and tool leaks. Porosity sinks are the mechanisms that contribute to reducing porosity, including gas transport, void shrinkage and collapse as well as resin flow into void space. Despite the significant progress in porosity research, the fundamentals of porosity in composites are not yet fully understood. The highly coupled multi-physics and multi-scale nature of porosity make it a complicated problem to predict. Experimental evidence shows that resin pressure history throughout the cure cycle plays an important role in the porosity of the cured part. Maintaining high resin pressure results in void shrinkage and collapse keeps volatiles in solution thus preventing off-gassing and bubble formation. This study summarizes the latest development of an efficient FE modeling framework to simulate the gas and resin transport mechanisms that are among the major phenomena contributing to porosity.

1. INTRODUCTION

1.1 Overview

Porosity is a process-induced defect that degrades mechanical properties of composite parts [1]–[3]. During the curing process, various sources contribute to the formation of porosity including entrapped air, volatiles & off-gassing, as well as bag & tool leaks (Figure 1).

The three key characteristics of porosity in a cured composite part are (1) location, (2) intensity, and (3) morphology. From a modeling standpoint, prediction of porosity is a complex problem due to the highly coupled multi-physics nature of the problem and the multi-scale nature of the cure process. Although porosity is a common issue encountered in all composites manufacturing methods, the scope of this study is limited to manufacturing using prepregs and curing under autoclave pressure.

There are three main locations within a laminate that voids are typically found: 1) between plies due to entrapped air during lay-up, 2) within partially infiltrated fiber tows, and 3) within the resin. Both resin and fiber tow voids have their roots in the prepreg manufacturing process, whereas entrapped air between plies occurs during deposition. The debulk step, which typically accompanies the lay-up is intended to remove most of the gas trapped between plies. Application of autoclave pressure during the cure process provides additional consolidation by further removal of the entrapped gas and shrinking and collapsing the voids. Several factors impact the void content in a cured part; including intrinsic prepreg characteristics, the lay-up method, the debulk procedure, laminate geometry, applied pressure, cure cycle, moisture and volatiles, laps and gaps, and the use of caul sheets [2].

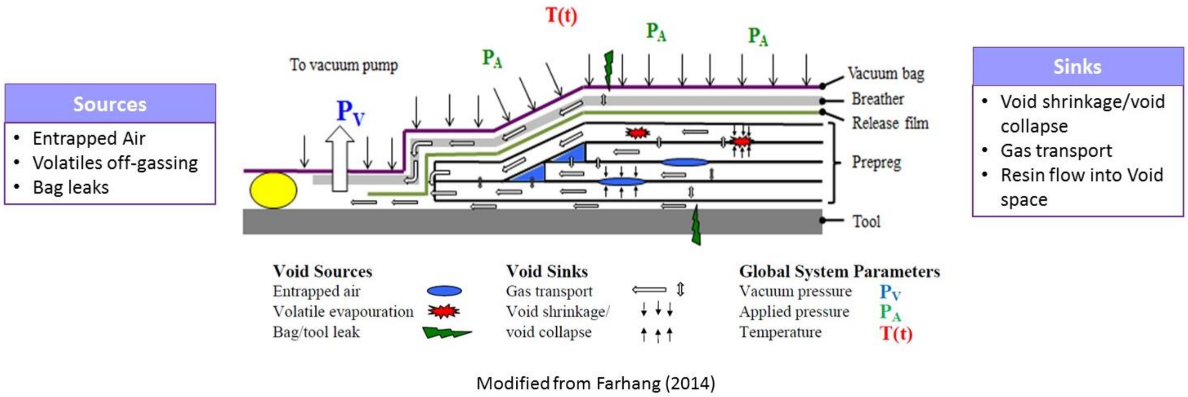


Figure 1. Schematic for possible sources and sinks in composite manufacturing, modified from [4].

Experimental evidence has shown that resin pressure plays a key role in formation of porosity [5]. Higher resin pressure helps push entrapped gas out of the system and shrinks and collapses remaining isolated voids. In areas that experience lower resin pressure, there is a possibility of vaporization and off-gassing of moisture and volatiles leading to an increase in the void content. Therefore, one of the major thrusts of the modeling activity in this study is to provide a tool that accurately predicts local resin pressure during the different stages of processing as this is a key parameter that controls porosity formation.

1.2 Process Stages

Porosity can form throughout almost the entire process cycle. To simplify the discussion, we will divide the process cycle into a few distinct stages. The following stages are meant to represent a general autoclave process; however, some stages may not be present in every process.

<u>Stage 0 – Deposition</u>

In this stage plies are deposited onto the surface of the tool in one of several different ways: hand layup, AFP, etc., as shown in Figure 2. At this stage the plies are at low temperature, the resin viscosity is high, and the material adheres to itself due to the tack of the resin. During deposition, while the resin viscosity is still high, the primary source of porosity is entrapped air between the plies. The void volume fraction is relatively high (up to 15-30% volume fraction) as there often are significant pockets of air present which needs to be removed before the resin is cured to achieve low porosity parts.

<u>Stage 1 - Debulk</u>

Once plies have been deposited there is often a debulk stage which is defined as Stage 1 in Figure 2. In this stage, vacuum is applied to the part to encourage the removal of entrapped air from the layup and consolidate the plies. Debulk is typically performed at room temperature or at a slightly elevated temperature. As air is slowly removed from the part through the application of vacuum, there is considerable reduction in the thickness (debulk) of the laminate. The debulk stage varies in length but most entrapped air is typically evacuated within the first hour. However, the time required for debulk may be much longer for larger and/or thicker parts. A consideration in this stage is that while the amount of air is reduced, all air may not be removed if there are no continuous evacuation paths to the vacuum system.

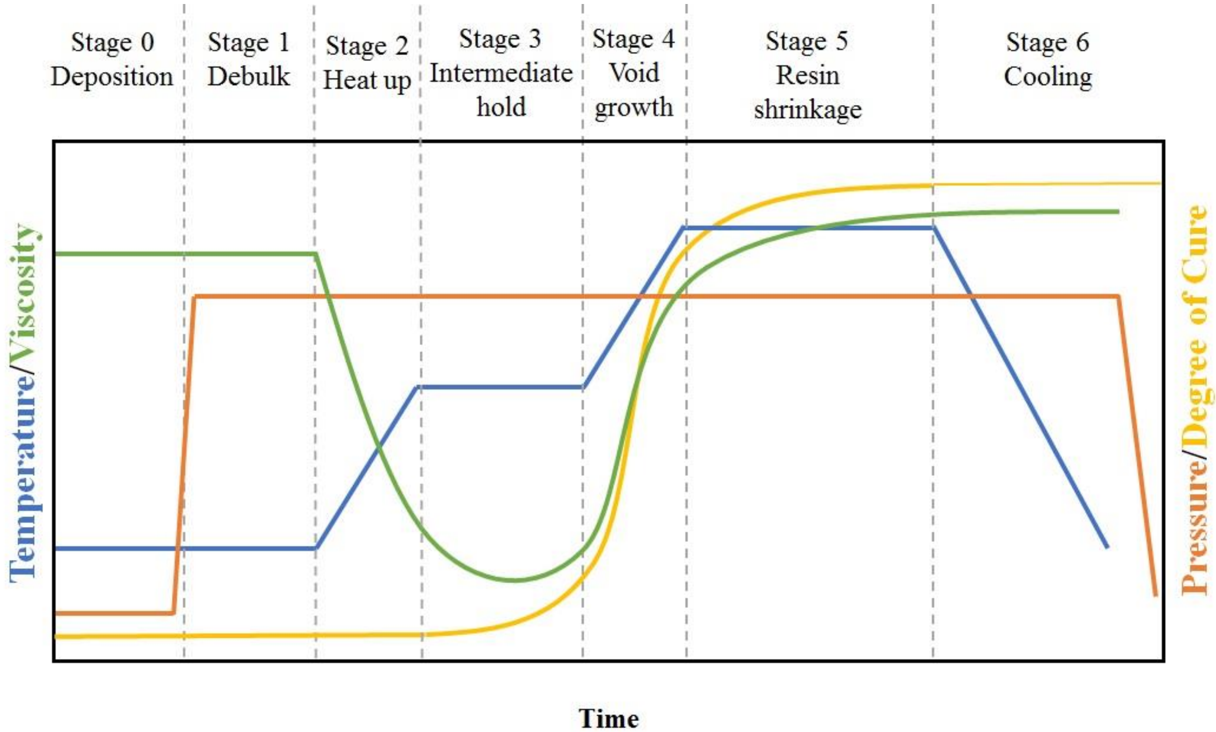


Figure 2. Schematic of the stages in an autoclave process cycle

Stage 2- Heat-up

After debulk, the part is typically placed in an autoclave to cure under pressure and elevated temperatures. Stage 2 is the first step which takes place in an autoclave. Increase of temperature in this stage leads to a decrease in resin viscosity. This stage is considered a transitory stage as the resin properties are changing drastically. The reduction in viscosity will cause any gas evacuation pathways to collapse.

Stage 3 – Intermediate hold

In some cases, there is an intermediate hold in the temperature cycle, which has been defined as Stage 3. This is an optional step designed to prolong the time the resin is at low viscosity to help evacuate air, remove moisture and volatiles, and to consolidate the plies. From this point, the behavior of isolated gas pockets is very dependent on the resin as they move with the resin and their growth or shrinkage depends on resin pressure surrounding them.

Stage 4 – Void growth

Further increase in temperature at this stage leads to increase in vapor pressure of the moisture and volatiles in the resin. If vapor pressure of the volatiles exceeds the resin pressure, volatiles will come out of solution and form new bubbles. Even if the vapor pressure of the volatiles does not exceed the resin pressure, an increase in temperature will promote diffusion of volatiles from the resin to existing gas bubbles that may grow during this phase. During this stage, as a result of the increase in temperature, the internal pressure of pre-existing isolated bubbles also increases leading to their growth. Resin shrinkage due to crosslinking can also lead to reduction of resin pressure causing further void growth.

Stage 5 – Resin shrinkage

Entering Stage 5, the temperature is at the final hold. The degree of cure and the resin viscosity have increased significantly and the cure rate slows down as most of the resin has already crosslinked and chemical shrinkage has occurred. It is at this stage and Stage 6 (cooling) that any voids remaining become locked in the material and ultimately become the final porosity in the cured part.

Stage 6 – Cooling

At this stage the resin has fully cured and the part temperature is cooled down to ambient conditions. At this point any voids in the resin have become locked into the part as final porosity. Any volatiles that have remained in solution no longer influence the porosity. Bulk porosity is a combination of resin voids and trapped gas in the inter-layer.

2. MODEL DEVELOPMENT

2.1 Simulation Framework

As discussed earlier, in the pre-gelation regime, three phases are present: fibers, resin, and gas, which all contribute to the system response and formation of defects. Therefore a 3-phase simulation framework is ultimately needed to capture the physical phenomena involved. Niaki and co-workers have developed a 3-phase approach to capture the behavior of the system including transport mechanisms of each phase and load sharing among the phases. They have extended Biot’s poro-elastic framework to three phases. This approach allows for independent tracking of resin and gas pressures and their transport mechanisms. Due to limitations of commercial finite element software which currently allows for only single phase Darcy flow, implementation of a 3-Phase model in such solvers is not yet achievable.

In absence of a full 3-phase model, simplifications can be made to capture some of the key phenomena including debulk, and compressibility within a 2-phase model. Even the simplified 2-phase model provides valuable information about resin pressure history and pressure distribution within the part.

2.2 Bubble Severity Index

As discussed earlier, resin pressure history has a critical role in porosity formation. The experimental work of Wells [6] showed that Kardo's equation determining the onset of diffusion driven bubble growth can be used to effectively predict bubble formation onset due to moisture vaporization. The critical resin pressure leading to bubble growth is expressed as:

$$P_{R,Critical} = 4962 \exp\left(-\frac{4892}{T}\right)(RH_0) \quad (1)$$

where T is the temperature in K, RH_0 is the relative humidity in percent and the resulting critical pressure is in atm.

The Bubble Severity Index (BSI) defined below, provides a normalized metric to compare resin pressure and the critical threshold pressure:

$$BSI = \frac{P_R}{P_{R,Critical}} - 1 \quad (2)$$

3. CASE STUDY

Experimental work of Roy [5] showed that caul sheet stiffness in configured structures can be a defining factor affecting resin pressure history and distribution. Roy showed that using a stiff caul plate (thick caul) on a laminate with ply drop off leads to reduction in resin pore pressure resulting in higher porosity levels.

In this case study, a composite laminate featuring a ply drop-off is subjected to compaction through caul plates with different thicknesses (2, 4 and 8mm). As shown in Figure 3, due to symmetry, only half of the geometry is simulated. Consolidation simulation is performed using COMPRO implemented in ANSYS. The material system used in this simulation is MTM45-1/CF0526A prepreg system. Material properties (resin viscosity and fiber- bed compaction response) reported in [5] were employed in this case study.

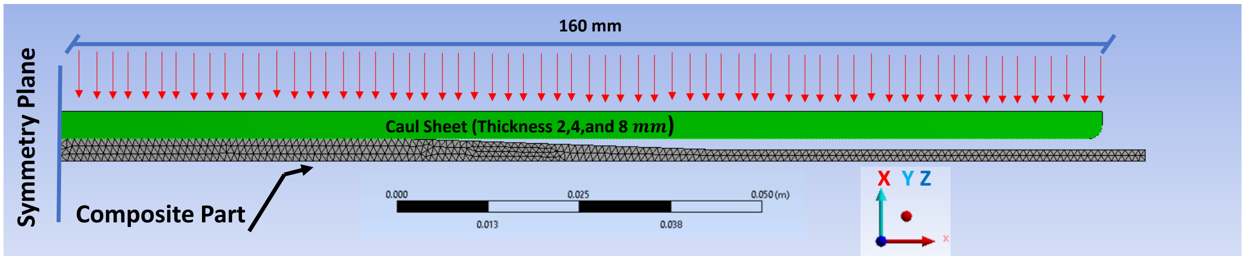


Figure 3. Schematic of Composite Part and Caul model

Figure 4 shows the applied temperature and pressure as well as calculated resin viscosity throughout the cure cycle.

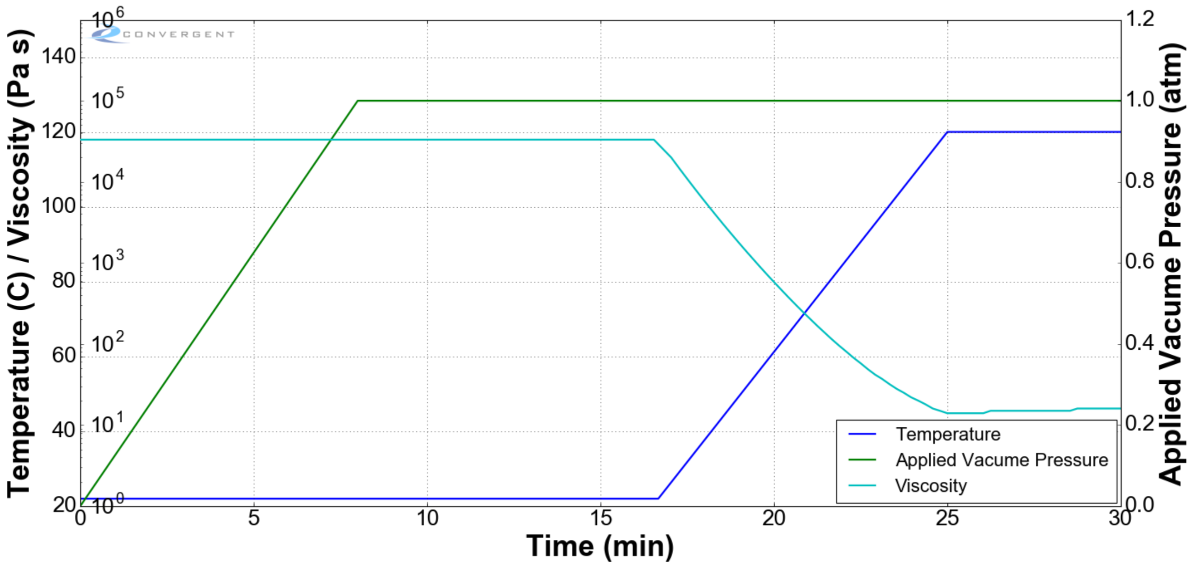


Figure 4. Temperature and Pressure histories as well as calculated resin viscosity.

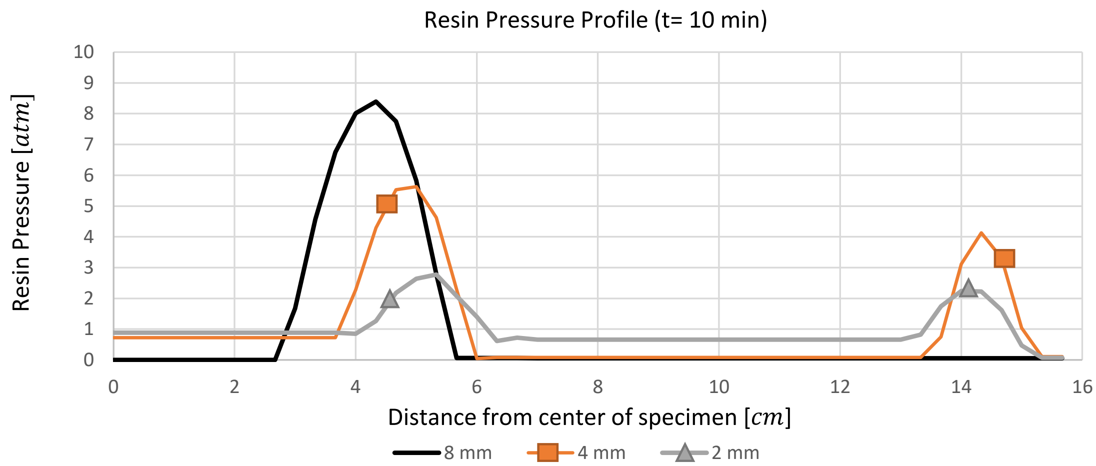
Figure 5 shows the resin pressure profiles of the specimen with different caul sizes at two different times during the compaction cycle. The pressure profile at t=10min is just after pressure is applied. In the model with 8mm caul, there is a large pressure concentration at the start of the ply drop off region. The pressure concentration decreases as the caul thickness decreases (see Figure 6).

Figure 5b shows the resin pressure distribution in the same specimen at t=30min, after the temperature reaches 120°C and resin pressure equilibrium is about to be achieved. At this point, the resin pressure in the specimen with 8mm caul is significantly lower than the resin pressure in the other two models. This is due to the lack of conformance between the stiff caul and the laminate surface leading to a large gap and consequently movement of resin into the gap region and drop in resin pressure. In the case of the 8mm caul plate, the fiber bed is carrying a bigger share of the applied pressure.

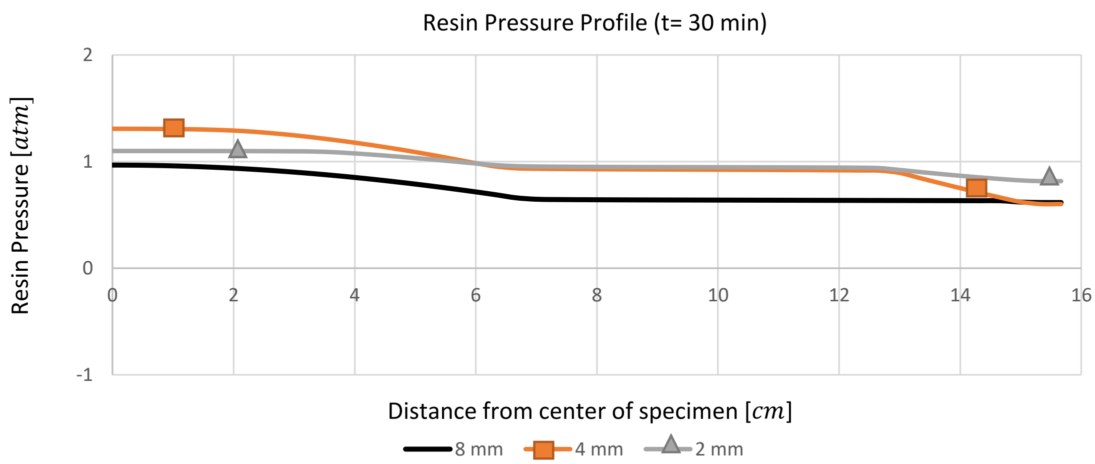
Figure 7 shows the bubble severity index in specimens with 2mm and 8mm cauls, respectively. The BSI parameter is calculated using a 40% relative humidity assumption. In this figure, blue color represents positive BSI (Resin Pressure>Critical value) and red color represents negative BSI (Resin Pressure <Critical value).

In the model with an 8mm caul, a large region of the composite specimen, starting from the ply-drop off region, is showing a negative BSI indicating that there is a larger likelihood for formation of porosity in this specimen. In contrast, the model with the 2mm caul sheet exhibits positive BSI values everywhere indicating a lower likelihood of porosity formation in this specimen.

Model predictions agree with the trends reported in [5] where lower equilibrium resin pressure was measured in specimen with stiffer caul. The specimen with thicker caul showed higher porosity levels.



(a)



(b)

Figure 5. Resin pressure profiles of specimens with different caul thicknesses at (a) t=10m (just after application of pressure) and (b) at t=30min (when temperature is applied).

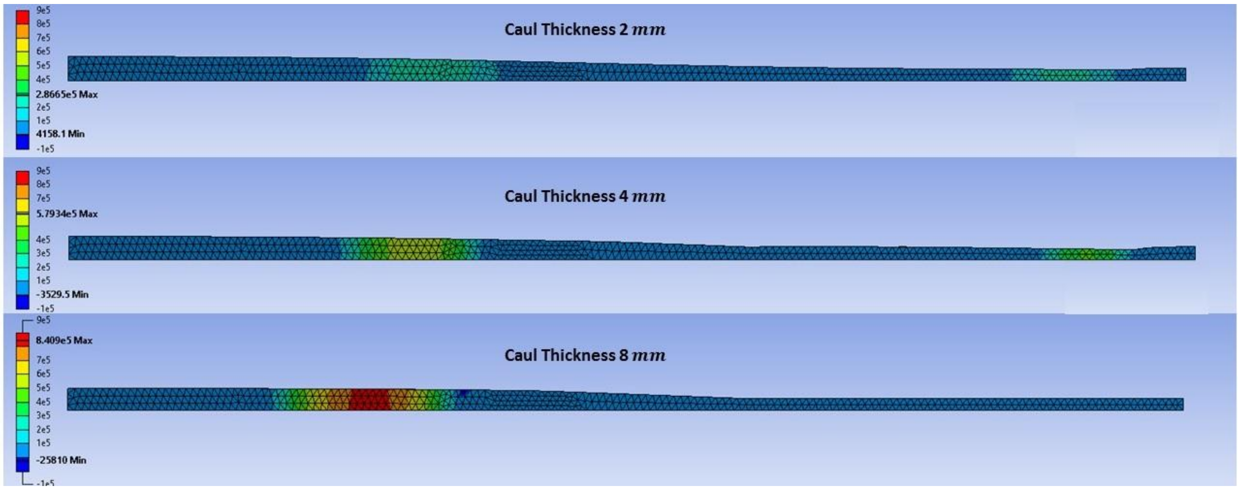


Figure 6. Resin pressure distribution right after application of pressure at t=10min.

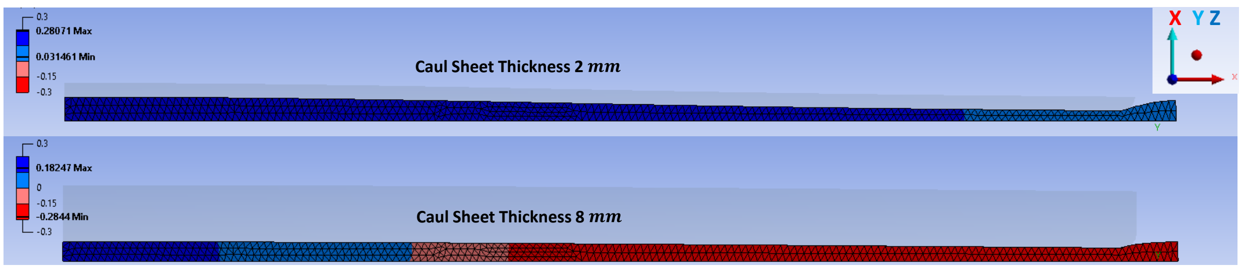


Figure 7. Bubble Severity Index in models with 2mm and 8mm caul sheets.

4. CONCLUSIONS

This study shows how compaction simulation can provide valuable information about resin pressure history and pressure distribution in parts with geometric features. A Bubble Severity Index (BSI) was defined as a measure to compare resin pressure to critical values corresponding to moisture driven bubble growth. The BSI parameter can be used to identify process conditions and zones with high risk of bubble formation.

5. ACKNOWLEDGMENTS

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