CURE PROCESS DEFECTS IN COMPOSITE STRUCTURES WITH SHARP RADII

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ABSTRACT

The National Aeronautics and Space Administration (NASA) Advanced Composites Project (ACP) is intended to develop and transition technology which will lead to a reduction in the certification timeline for new composite aircraft structures. Within the ACP a particular task focuses on the defects that form, such as fiber waviness and porosity, during the curing stage of composite manufacturing. Various partners associated with this ACP task sought to study the effect of various processing conditions and techniques, prepreg materials and geometries to identify critical variables that lead to cure defects. For this study, United Technologies Research Center (UTRC) has chosen to cure composite laminates onto a mold with a staircase geometry with one convex corner and one concave corner where both corners have a small radius of curvature. Further this study varied the thickness of the laminates, autoclave pressure, corner radius, and end conditions. The experimental lay-ups were implemented on the staircase geometry tool instrumented with pressure sensors to collect data during the cure and correlate resin pressure to porosity. To explore the occurrence of fiber waviness the sheared geometry of fabric layers is inspected in and around the tight radius corner features. The results of these experiments will be used to evaluate the performance of a physics-based cure defect model that is being developed in parallel with this effort. The development, validation and verification of such a model would allow composite process design without long term and high cost trial and error and ultimately lower certification time and cost of new composites parts.

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1. INTRODUCTION

In composite fabrication that utilizes prepreg materials certain defects such as the formation of porosity and development of fiber waviness are common during the curing process. Such defects have, in general, negative effects on the structural properties on the final composite parts. In order to better understand the development of such defects the National Aeronautics and Space Administration's (NASA) Advanced Composites Project (ACP) seeks to perform various experiments and identify defect trends and also develop a validated and verified computational model for predicting the occurrence of such defects. Along with other partners in the ACP the United Technologies Research Center (UTRC) chose a common industrial material system and performed various experiments to first identify trends in defect occurrence and further provide validation data for a preliminary cure defect process model being developed by a NASA research partner. The major processing variables that are considered in the experimentation for identifying defects are radius of curvature, laminate thickness, cure pressure, and end conditions.

2. EXPERIMENTATION

2.1 Flat Panel and Staircase Molds

For the purpose of experimentation, a staircase style mold was chosen in order to include tight radii features into the geometry but also to keep the geometry simple enough to model without introducing additional sources of defects. Figure 1 shows a schematic of the representative

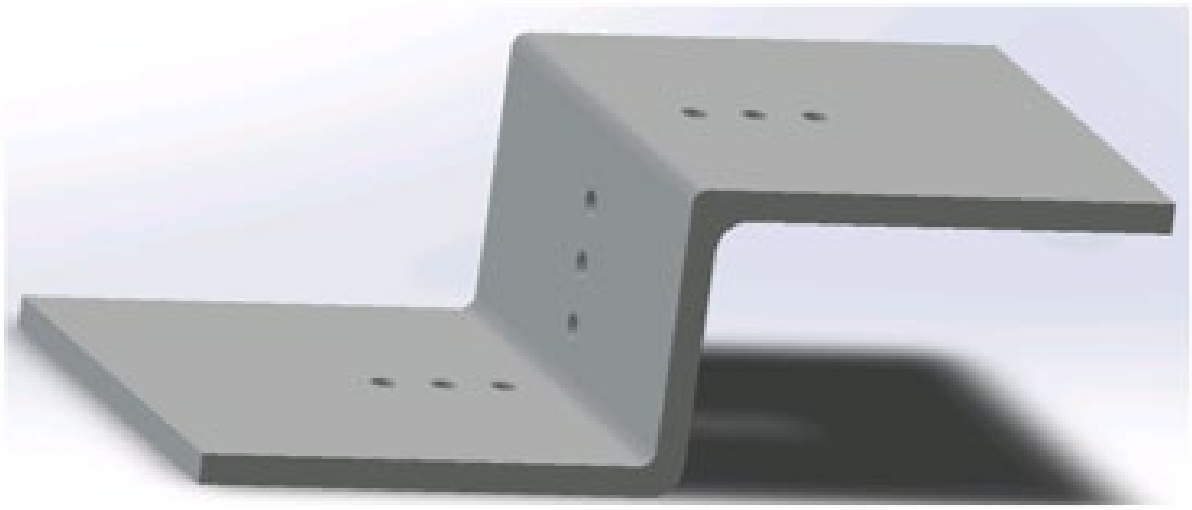


Figure 1: Staircase tooling schematic.

staircase mold. All flat panel experiments that are conducted are done so on the top surface of the same mold shown in Figure 1. The mold includes several holes for resin pressure sensors that will be discussed later in the characterization methods section. The staircase specimen geometry was chosen such that the flat section, concave corner, or the convex corner can be used along to study a variety of geometries. Further the staircase mold was designed to be reversible for studying two different radii sizes of 6.35 mm (0.25 in) or 12.5 mm (0.5 in), i.e. the concave and convex corners along one surface of the mold share one radius of curvature and the opposite surface the two corners share the other radius of curvature.

2.2 Materials, Layup, and Processing Parameters

The commercially available Hexcel AS4/8552 (193 gsm, 38wt% resin) plain weave prepreg fabric was used exclusively during the experimentation. Hand layup was used to lay onto the mold described earlier in Section 2.1 and the layup was designed to be symmetric and balanced, specifically [[0/902, ±452]2]S. To process the layup a baseline cure cycle is established with a single temperature dwell of 176 °C (350 °F) with an autoclave cure pressure of 310 kPa (45 psi), and full vacuum pressure at the beginning of the cycle but moves to half as shown in Figure 2.

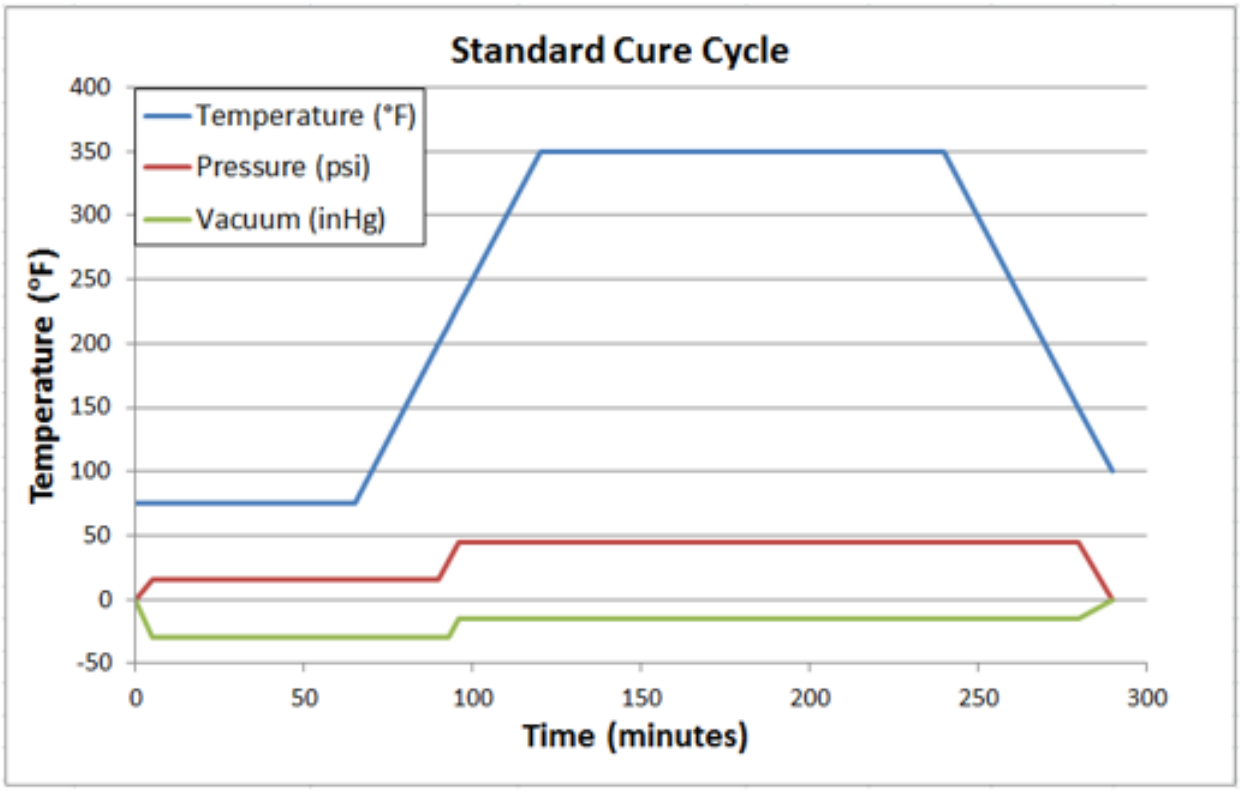


Figure 2: Baseline cure cycle to be used during the cure process model evaluation with rapid prototype tooling experiments.

The first variable that will be studied in the experiments is the autoclave cure pressure, where in the baseline cure cycle the autoclave pressure is set to 310 kPa (45 psi). In various experiments the cure pressure is reduced to 103 kPa (15 psi) and others the cure process is increased to 585 kPa (85 psi). The next variable studied was the radius of the concave and convex corners which is varied between 6.35 mm (0.25 in) or 12.5 mm (0.5 in). Another critical variable will be the end conditions which is used on either side of the laminate. In some experiments the ends will be free where the edges of the laminate will be allowed to move only constrained by the vacuum bag with no edge damming which allows the plies to slide relative to each other and against the tool during processing. The fixed edge condition was accomplished by using silicone edge sheet material along the ends of the laminate on the staircase mold. This silicone edge dam is placed under the vacuum bag material which holds the silicone in place through the cure process which then further prevents the plies from sliding against each other at the ends of the mold. The last variable that is

considered is the portion of staircase mold which the laminate is laid up on. In most cases the full the staircase mold is used such the finished laminate in the shape of a 'Z', but in other cases the laminate is only laid up on a single corner such that the finished laminate is in the shape of an 'L'. The purpose of the 'L' shaped corner experiments are to eliminate the potential interaction, ply sliding and tension, that could occur within the plies between the two corners.

2.3 Characterization Methods

To evaluate the composites for cure defects such as fiber waviness and porosity UTRC will take cross sections of the specimens and mainly rely on optical microscopy for evaluation. Focus will be on the propagation of wrinkles and porosity in the specimen in tight radii regions as a function of process conditions. Specimen edges will also be a focus of inspection to observe the existence of fiber waviness and porosity. To assist in the visual inspection of shear deformation and fiber waviness thin copper wires will be inserted into the layup across the width of the laminate in specific experiments designed to induce such defects.

Additionally, UTC will be measuring and recording processing parameters during the layup and autoclaving of the experimental panels. These parameters will include the local resin pressure using pressure sensors embedded in the mold surface. The resin pressure inserts, shown in Figure 3, are screwed into the threaded holes in the staircase mold previously discussed in Section 2.1

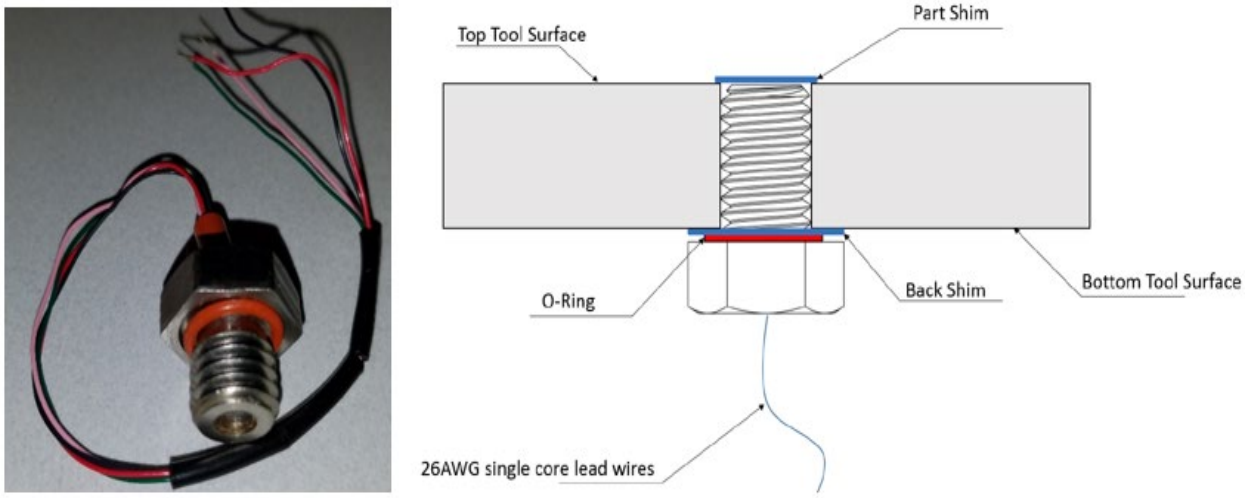


Figure 3: (Left) A resin pressure insert provided by Convergent Manufacturing Technologies US (CMT-US); (Right) Schematic of resin pressure insert installed into a mold surface [1].

and shown in Figure 1. The pressure sensor portion is exposed to the laminate during autoclave cure such that the resin pressure at that location can be recorded in-situ. Lastly, local and autoclave temperature and laminate thickness at each stage in the lay-up processing including after debulk are recorded. Local resin pressure will only be measured in experiments that are designed specifically for inducing porosity. No specific experiments are planned to investigate matrix off-gassing since the chosen resin is very common in industry and already well characterized.

3. RESULTS

3.1 Cure Pressure Study

A key and common parameter in the development of porosity in composites is low resin pressure. Such a pressure condition leads to inadequate pressure to maintain compaction and keep any potential gases in saturation. Since the driving pressure for developing resin pressure is mainly the autoclave pressure which acts upon the vacuum bag material, it follows that inadequate resin pressure will occur more often with lower applied autoclave pressure. In the following pressure result graphs the resin pressure will be shown along the length of staircase mold by examining the numbered sensors over processing time.

The first case shown in Figure 4 is the baseline cure cycle case where the autoclave pressure is set to 310 kPa (45 psi). In Figure 4 the autoclave pressure, vacuum, and resin pressure readings along the mold are shown. In the baseline case it is seen that there is very little variance in resin pressure before autoclave pressure is applied. Note that the temperature ramp is initiated at about the 60

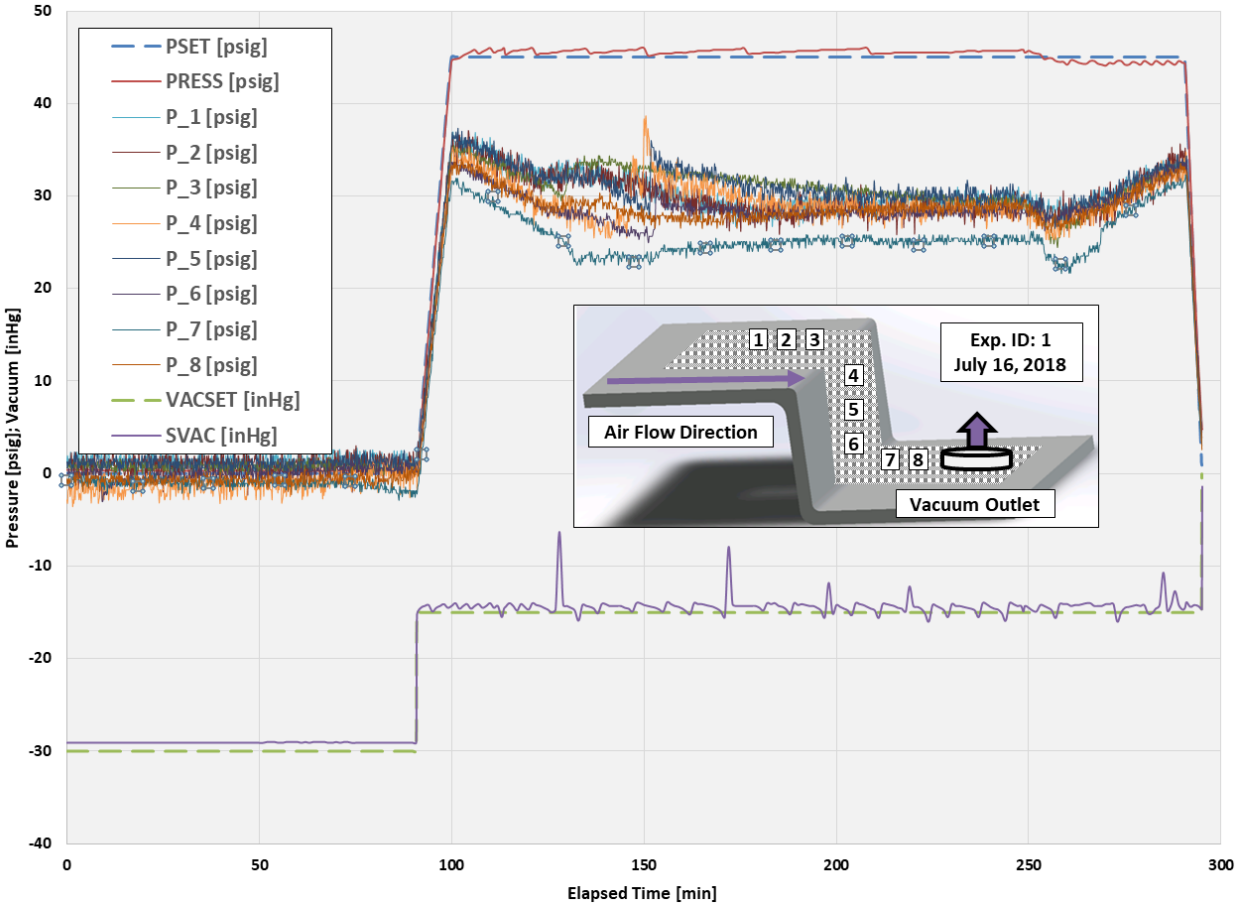


Figure 4: Baseline cure process with free ends.

minute mark. As the resin starts to warm and soften there is a noticeable but small decrease in resin pressure mostly near the concave corner at sensors 6 and 7. As autoclave pressure increases the

chart shows that resin pressure tracks similarly lagging behind the applied pressure. The difference between resin pressure sensor readings and the autoclave pressure is understood to be the pressure that is supported by the fibers. The most interesting result in Figure 4 is the lower pressure developed in the concave corner around sensors 6 and 7 as well as the sharp increase in pressure close to the convex corner, particular sensor 4, which corresponds with gelation and cure.

The next important case is shown in Figure 5 where the autoclave pressure is reduced as compared to the baseline case, specifically 103 kPa (15 psi). In comparison to the baseline case the difference between the resin pressure and the autoclave pressure is significantly reduced indicating that the pressure being taken by the fibers is less. Overall the variance between sensors along the mold are

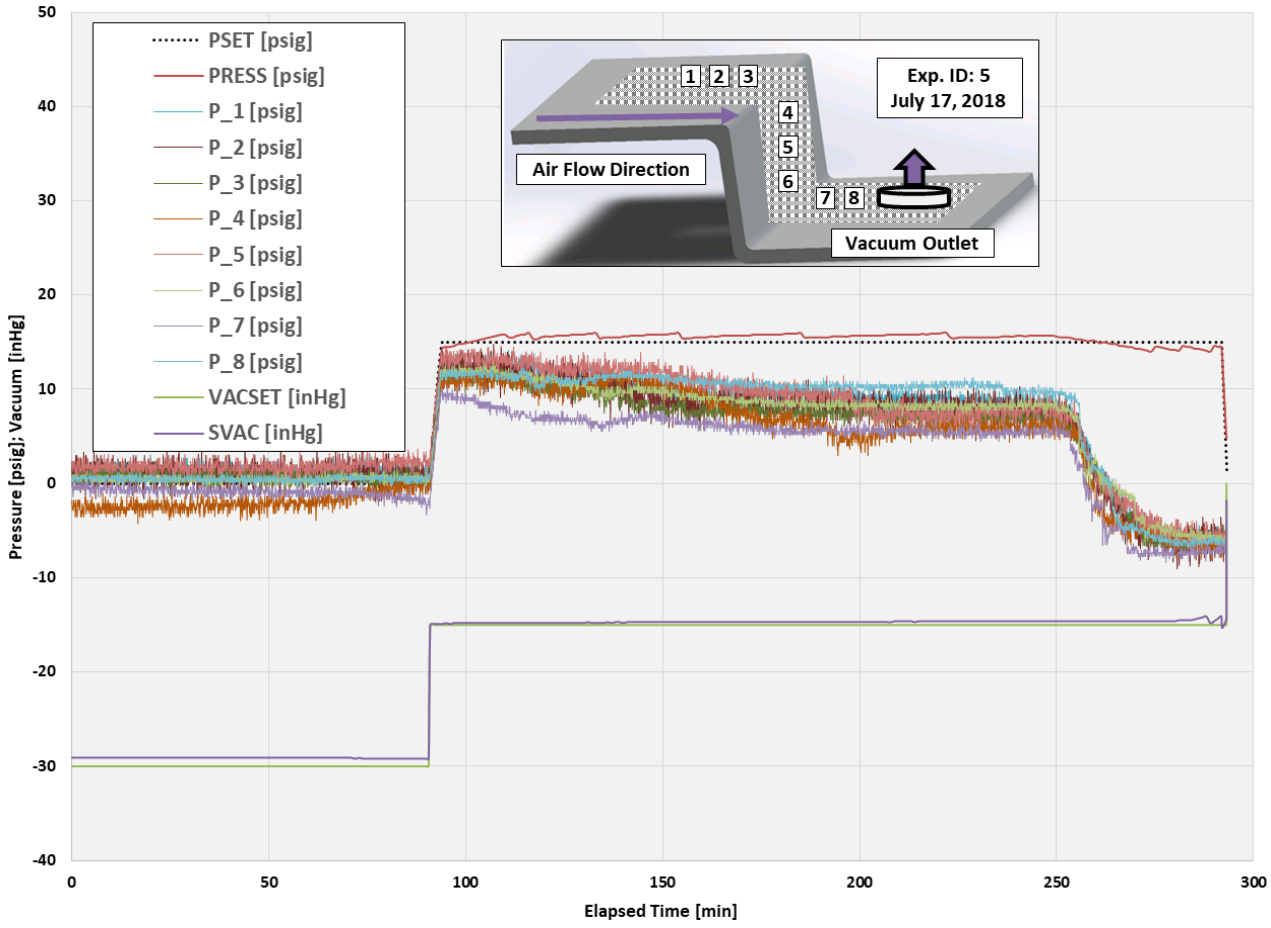


Figure 5: Resin cure pressure chart with lower than baseline autoclave pressure.

more uniform than in the baseline case where autoclave pressure is higher with exception of sensor 7 near the concave corner which shows a noticeably lower pressure than the others.

Lastly in Figure 6 shows a similar chart when autoclave pressure is considerable higher than in the other cases, specifically 585 kPa (85 psi). The same trends are evident in this higher autoclave pressure case but simply exaggerated as compared to the lower pressure cases. The resin pressure everywhere along the mold is almost completely uniform until autoclave pressure is increased at

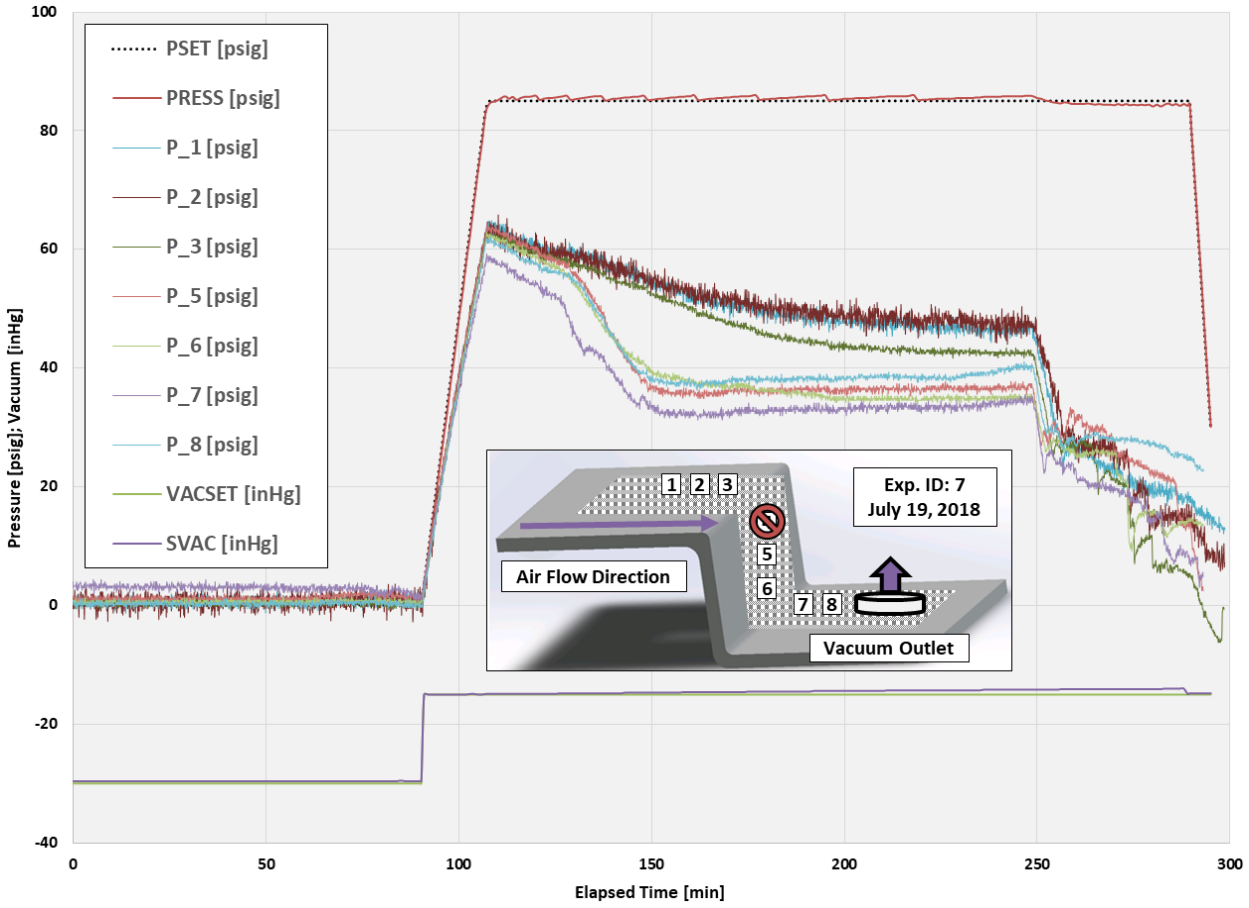


Figure 6: Resin cure pressure chart with higher than baseline autoclave pressure.

about 90 minutes into the run. Further in this case the difference between the autoclave pressure and the pressure readings from the sensors is considerable greater than in other cases. Evident in this high pressure case is the significantly lower resin pressure that is present in sensors near the concave corner where the lowest is again sensor 7. Also similarly low resin pressure is seen in locations 5, 6 and 8. In all cases the sensors in the upper flat region away from the vacuum outlet tend to have higher and more uniform pressure.

3.2 Ply Shearing

In order to study ply waviness thin copper wires are inserted into the laminate at key locations during layup such that those same locations can be examined after cure. In particular these copper wires are inserted at the radius area on apex of the radius as well as 25 mm (1 in) before and after the radius as shown schematically in Figure 7. The thin copper wires are placed in the laminate after the first ply is laid down, after the eighth ply and before the last ply. Each wire was placed across the entire width of the laminate with overhang such that it possible to overlap the three wires through the thickness of the laminate directly on top of each other.

The following images shown in Figure 8 and Figure 9 are examples of a convex and concave corner, respectively. In both cases the autoclave pressure and temperature cycle are the same as the baseline processing cycle shown in Figure 2. Also in both cases no edge damming were used

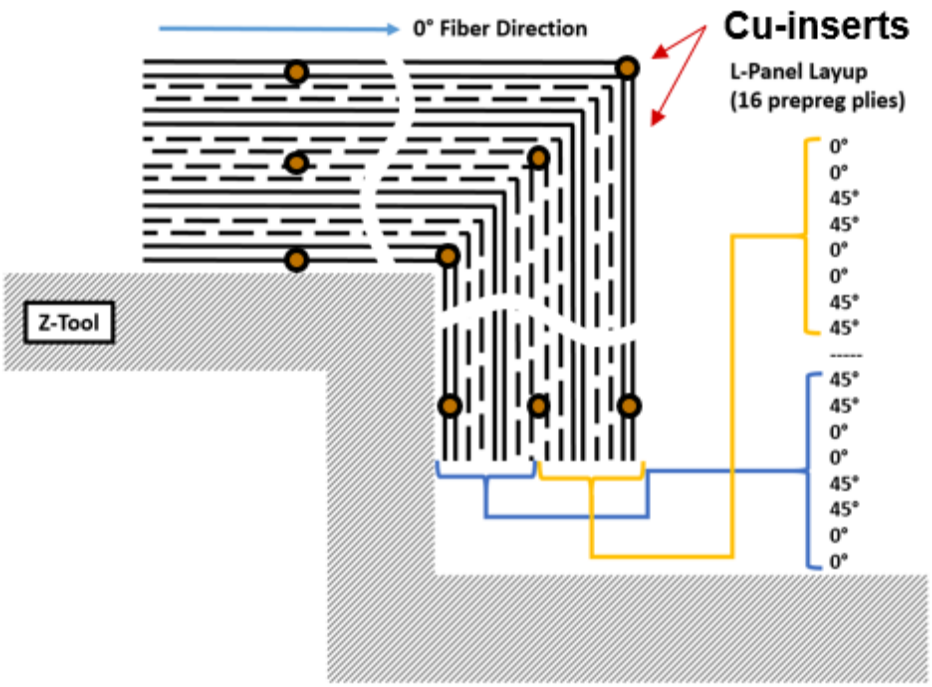


Figure 8: Schematic layup using thin copper wires.

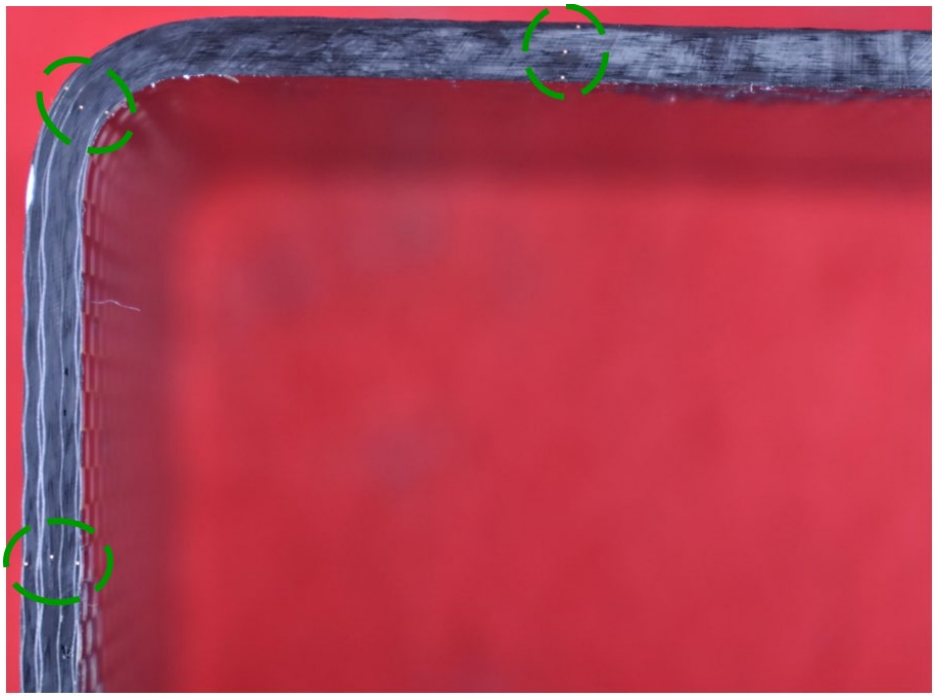


Figure 7: Panel fabricated with thin copper wire laid onto the convex corner of the staircase mold.

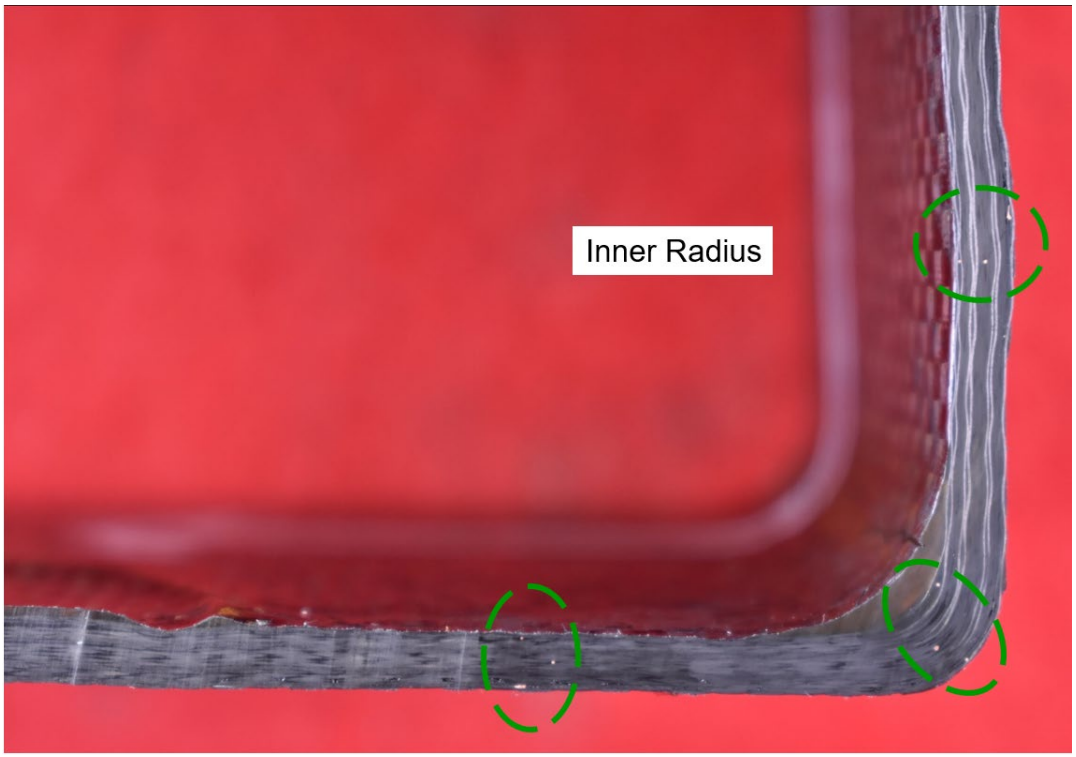


Figure 9: Panel fabricated with thin copper wire laid onto the concave corner of the staircase mold.

so the ends of the laminate were free to slip and move. Lastly, both laminates were laid up on the side of the staircase mold were the radius of curvature was 6.35 mm (0.25 in).

The results shown in Figure 8 indicate that shear flow is occurring during compaction and autoclave processing. In particular with the convex corner laminate thinning is present around the corner where the opposite is true in the concave corner shown in Figure 9 where a resin rich region is present and the laminate is thicker. Also evident in Figure 8 is the middle of the laminate shifting and in the case between the radius and the lower flat section they are shifting together which is causing a localized thicker region below the radius. It is expected that fixed end conditions would cause more ply wrinkling and waviness in this region because of the constriction at the end of the plies. In Figure 9 not only is the concave corner have a resin rich region but the laminate is not well compacted and thicker than the flat sections. This agrees well with resin pressure sensor data shown earlier that indicated that these concave corners experience less compaction pressure.

4. CONCLUSIONS

In support of the NASA Advanced Composite Project (ACP) cure defects project UTRC developed a mold with a staircase geometry and the capability to utilize embedded pressure sensors to improve the understanding of resin pressure development during autoclave cure of prepreg materials and how it is related to defects such as porosity and ply waviness that occur during cure. Currently a system for attaching the sensors and monitoring the resin pressure has been constructed and tested and the results correspond well with expected behavior. Results from the resin pressure sensor runs indicate that the position along the mold and in particular around tight corners plays a

significant role in the resin pressure that is developed during cure and as such the likelihood of potential cure defects. Further the resin pressure data comparison of increasing autoclave pressure showed that with increased autoclave pressure resulted in a larger portion of that pressure being supported by the fiber suggesting that even higher autoclave pressure would have a diminishing effect on preventing low resin pressure region. Data collected relating to the movement of plies during cure corresponds to thinner and thicker regions of the laminate and further that thicker section without adequate compaction correspond with low resin pressure regions near concave radius sections.

5. ACKNOWLEDGMENTS

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