CHALLENGES OF AEROSPACE STRUCTURAL PART GEOMETRIES FOR HIGH-RATE COMPRESSION MOLDING

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ABSTRACT

Thermoset matrices continuous carbon fiber composites show opportunities for high-rate production of aerospace small structural parts when processed in compression molding. Previous studies have presented the material development and automated process development for press forming of carbon fiber composites. Takt times under 30 minutes were demonstrated for primary and secondary structures. This was achieved by building a flat blank, which was then formed into final shape and cured without pre-forming step.

A set of generic parts and associated steel tooling were generated. They include a range of geometries which present challenges for sub-30 minutes forming of a flat blank. The parts manufactured achieved aerospace structural performance. The paper presents how some of the main challenges were overcome, through both process and material development. The parts were designed by Boeing; pressed in Solvay's research and innovation facilities in Heanor, UK; and analyzed at Solvay research center in Anaheim, CA and at Boeing Saint Louis, MO USA.

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1. INTRODUCTION

In order to support the growth of new forms of high rate aerospace products [1], such as single aisle aircraft, drones, and flying taxis, a joint effort has been carried out by Solvay and Boeing in developing novel material and compression molding process [2].

The compression molding process developed has enabled takt times down to 20 minutes, thanks to both material chemistry, advanced automation, and the ability for a 2D blank to be formed isothermally into its final shape without pre-forming [3].

The constraint of forming parts in one step is particularly challenging when considering aerospace primary and secondary structures, presenting complex geometries, among which include vertical edges, thickness variations, beads, deep draws, double curvatures, etc.

The geometrical challenges have been investigated and solved through the design and manufacture of 4 geometries, one after the other and with increasing levels of complexity. The main prepreg materials considered are based on CYCOM® 5320-1 and CYCOM® EP2750 resin systems combined with woven T650 3k 8HS fibers. Other resin systems have also been considered but quickly discarded due to not meeting performance or manufacturability targets. The following Table 1 presents the main differences between CYCOM® 5320-1 and CYCOM® EP2750. The parts were designed at Boeing, the tools were made at C-Con GmbH, parts were manufactured at Solvay's Applications Centre in Heanor, UK, and tested at Solvay Anaheim, CA and Boeing St. Louis, MO USA.

Table 1. Comparison between CYCOM® 5320-1 and CYCOM® EP2750 pre-pregs [3]

	CYCOM® 5320-1	**CYCOM® EP2750**
Fibre	T650	T650
Weave	8 Harness satin	8 Harness satin
Resin content	36% wt.	40% wt.
Toughening	Medium	Medium
Impregnation	Medium to low	High
Bulk	High	Low
Tack	High	Tailored

The design of the three geometries studied is based on the anticipated challenges of molding at high-rate for aerospace applications as well as the complexity of an actual primary structure part. Features Include:

- Deep draw sections
- Thicknesses variations from 3.8 mm to 8.9 mm (0.15 inches to 0.3 inches)
- Double curvatures
- Vertical flanges

In chronological order, the geometries developed were:

<u>Beaded panel:</u>

- Beads of various geometry parameters
- Joggles
- Pad-up local thickness variations

- An edge going from 70° to 90° draft angle

Rib part:

- Centered pad-up thickness variation
- 4-sides vertical flanges
- Trimmed holes in the thickest area

C-Channel part:

- A deep draw U-section
- Vertical flanges
- Outer radius different from inner radius, resulting in a change of section shape
- Change in thickness along with the change in section shape

The compression molding process included both double diaphragm forming (DDF) and spring-frame in the first parts, then focuses exclusively on spring-frame. Both DDF and spring-frame use the principle of holding a flat blank and carrying it through an infrared (IR) preheat stage before shuttling it on top of the mold. The steel mold then closes following the press automated program, before applying full pressure to the prepreg for the rest of the on-tool time. Figure 1 below shows the overall process.

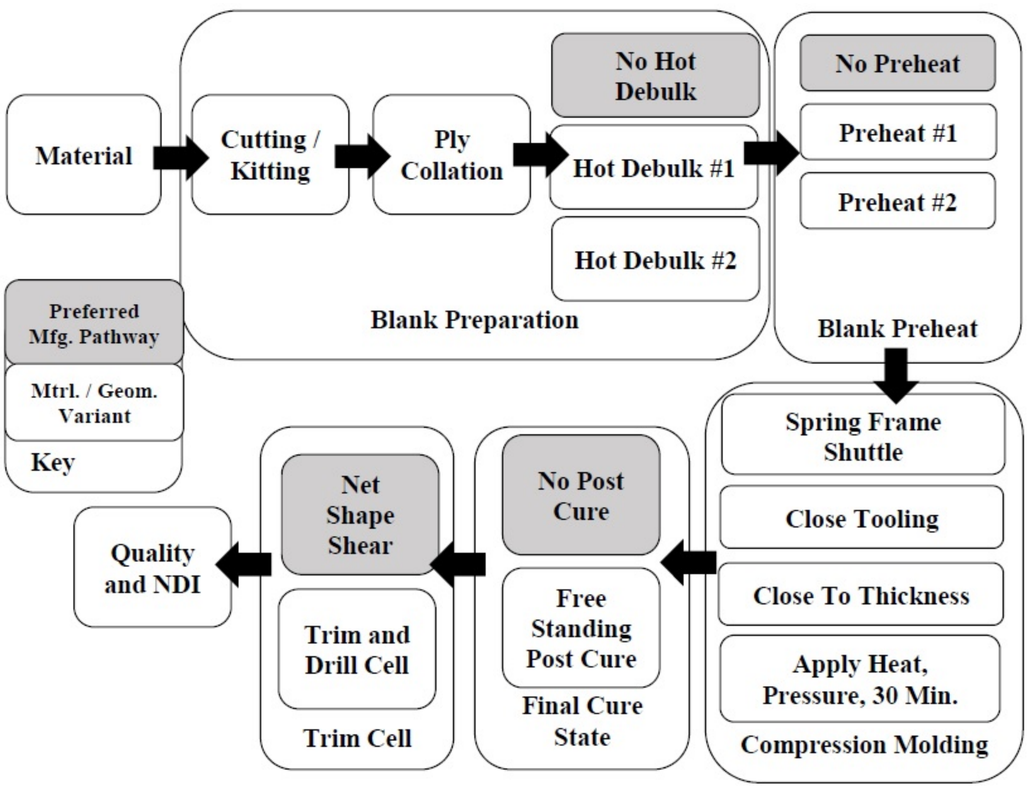

Figure 1. Flowchart of the automated process considered [4]

The main quality outcomes assessed are:
- Void content, using Non-destructive Test NDT (C-scan) analysis and photomicroscopy
- Resin content, using acid digestion method
- Cured ply thickness
- Degree of cure through the measurement of Tg on Differential Scanning Calorimetry (DSC) and Thermo-Mechanical Analysis (TMA)
- Mechanical performance, mainly through Short Beam Shear (SBS) test

2. EXPERIMENTATION AND RESULTS

2.1 TS-RAPM-009 Beaded Panel

Figure 2 illustrates the TS-RAPM-009 beaded panel. It is a 600 mm long flat part with various geometries parallel beads. The panel thickness builds up from 3 mm to 6 mm in one corner (pad-up). Another corner presents a joggle at constant thickness. The opposite edge presents a vertical flange with a draft angle varying linearly from 0° to 20°.

Objectives:

- Narrowing down material and process selection:
  - Plain weave (PW) is compared to 8-harness (8HS) for both CYCOM® 5320-1 and CYCOM® EP2750 systems
  - DDF and spring-frame blank carrying methods are compared

- Building correlation with process simulation models developed in house [5]

- Determining spring-in (reduction of enclosed angle after cure) for the lay-up considered

- Assessing compatibility of aerospace quality criteria with:
  - Bead geometries
  - Changes of thickness

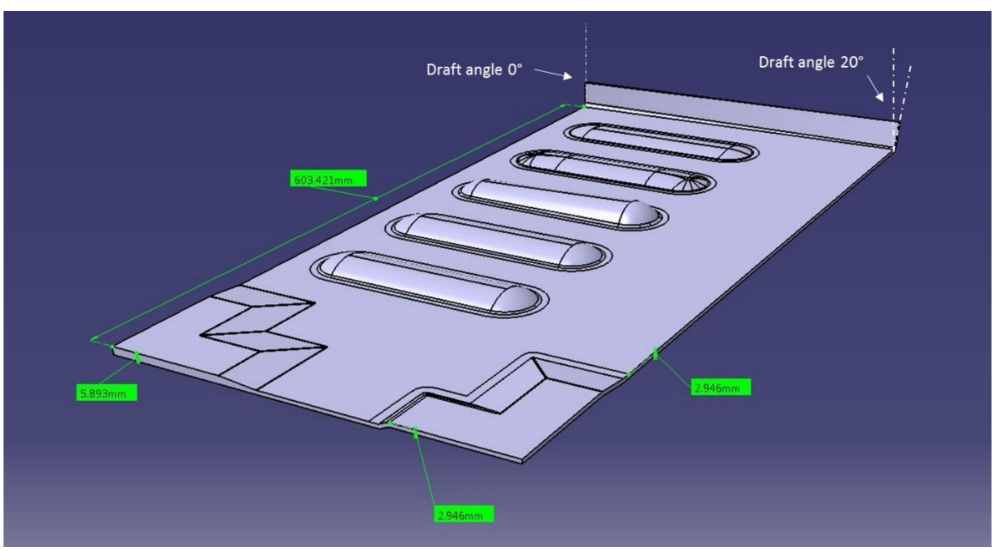

Figure 2. TS-RAPM-009 Beaded panel geometry.

The beaded panel study was carried out in Solvay's applications facility in the UK. The press equipment is capable of automatically shuttling the flat blanks into infrared preheating, then into the mold tool (Figure 3).

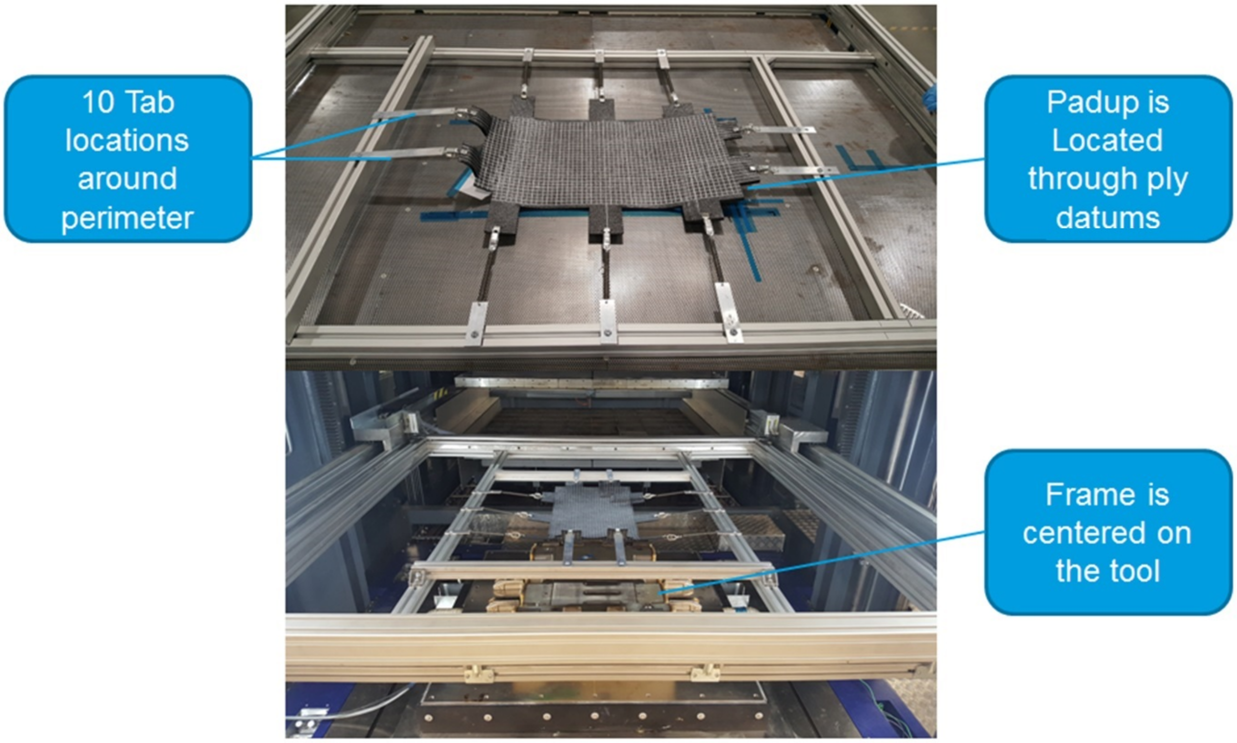

Figure 3. Beaded panel spring-frame configuration

The final part can be visualized on Figure 4. The dwell time has an impact on resin overflow: the image on the right presents a part with greater overflow than on the left, due to using 8 minutes dwell rather than 10 minutes.

Figure 4. TS-RAPM-009 beaded panel parts after spring-frame molding. Both parts are made using CYCOM® EP2750. On the left, a dwell time of 10 minutes was used. On the right, a dwell time of 8 minutes was used

A higher flow of resin has a positive effect on fiber wetting and pressure build-up in the tool cavity. The two above parts are compared on the below C-scan, which shows that the 8 minutes dwell time led to a lower void content. This is particularly true in the pad-up area. The sensitivity of this area to void content is due to its proximity to the edge of the tool cavity. There, two factors combine in providing a negative effect on porosity content:

1- The tool cavity does not present a shear edge or a reduction in section on the surrounding of the part. Therefore the pressure in the cavity decreases in the vicinity of the part edge, especially in thicker regions, where this section is actually bigger.
2- The beaded panel presents a relatively small, off-center pad-up area. This makes the pad-up plies subject to potential slippage through the process, due to spring tension, resin flow, and absence of back pressure from the outer edge of the part.

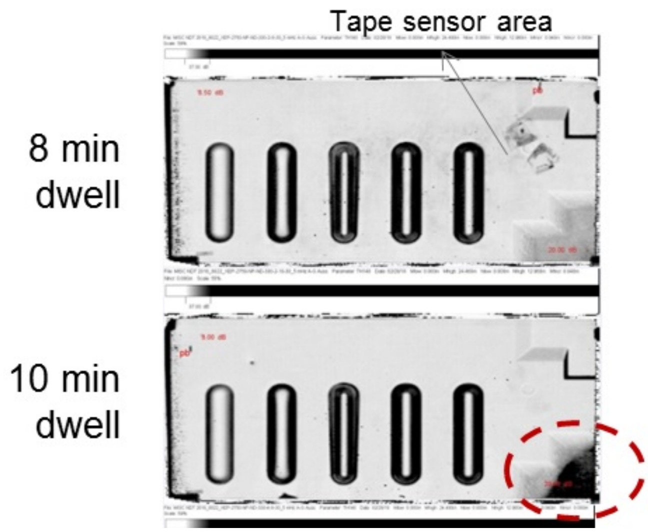

Figure 5. C-scan analysis of TS-RAPM-009 beaded panels shown in Figure 4, presenting respectively 8 minutes dwell time and 10 minutes dwell time

The pad-up zone for the above two parts is observed in photo-microscopy, visible in Figure 6. Although 8 minute dwell does not remove all porosity from the part, there is significant improvement compared to the 10 minute dwell time part. The void content goes from 5.5% to 0.4% on the padup area.

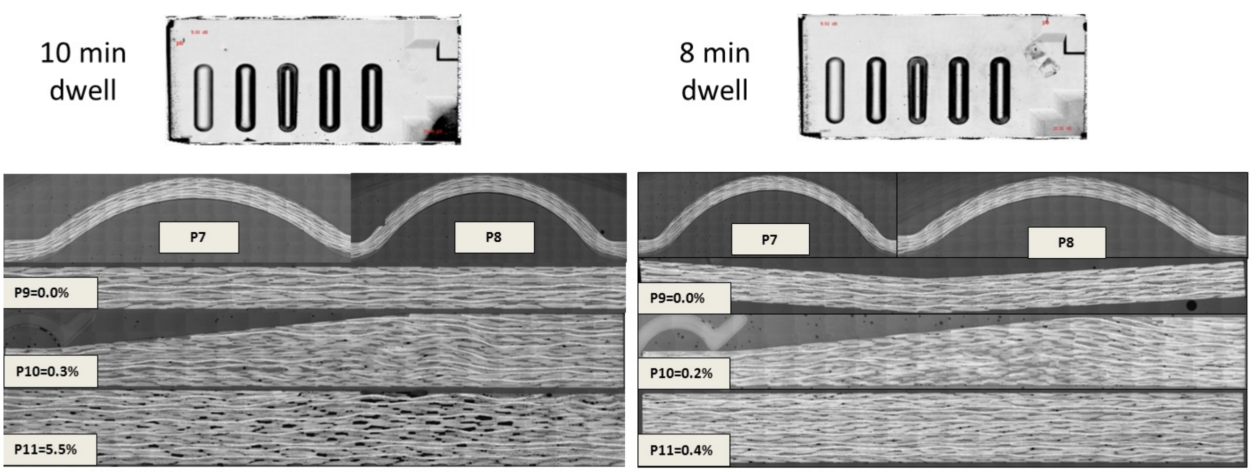

Figure 6. Photo-microscopy comparison of the beaded panel parts shown in Figure 4 and Figure 5. The section observed are extracted from the thin, tapered, thick, and beaded areas of the panels.

Unlike autoclave processing, compression molding takes advantage of forced resin flow for increasing part quality due to higher pressures applied. The process repeatability and manufacturing window are smaller for a material which is close to the final part's fiber volume fraction (Vf). Figure 7 shows that parts made with CYCOM® 5320-1 end up on the lower resin content limit due to the application of the necessary resin flow during the process to achieve sufficient part quality.

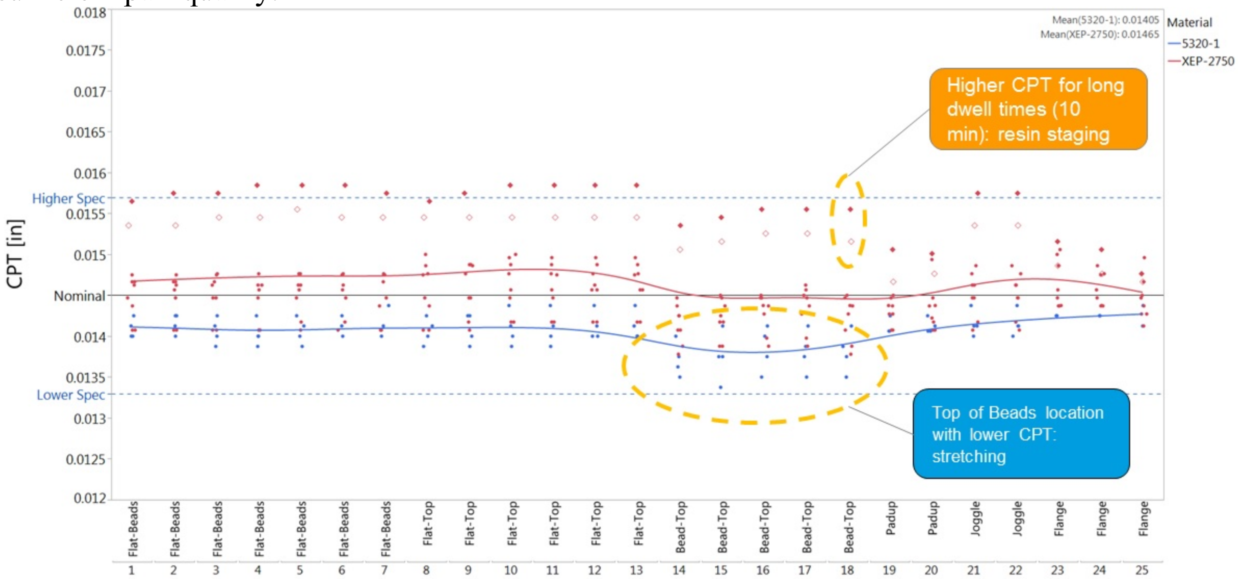

Figure 7. Cured Ply Thickness (CPT) of TS-RAPM-009 panels at 25 locations

Another key observation from Figure 7 is the reduction in CPT for the top of the beads, which can be verified by microscopy, see Figure 6. The fibers are locally put in tension and will create a Vf gradient from the bead's outer radius to the bead's inner radius. This local tension also propagates into fiber disturbance on the flat zone of the panel. This has been captured and integrated by the process simulation model developed for compression molding at Solvay [5], see Figure 8.

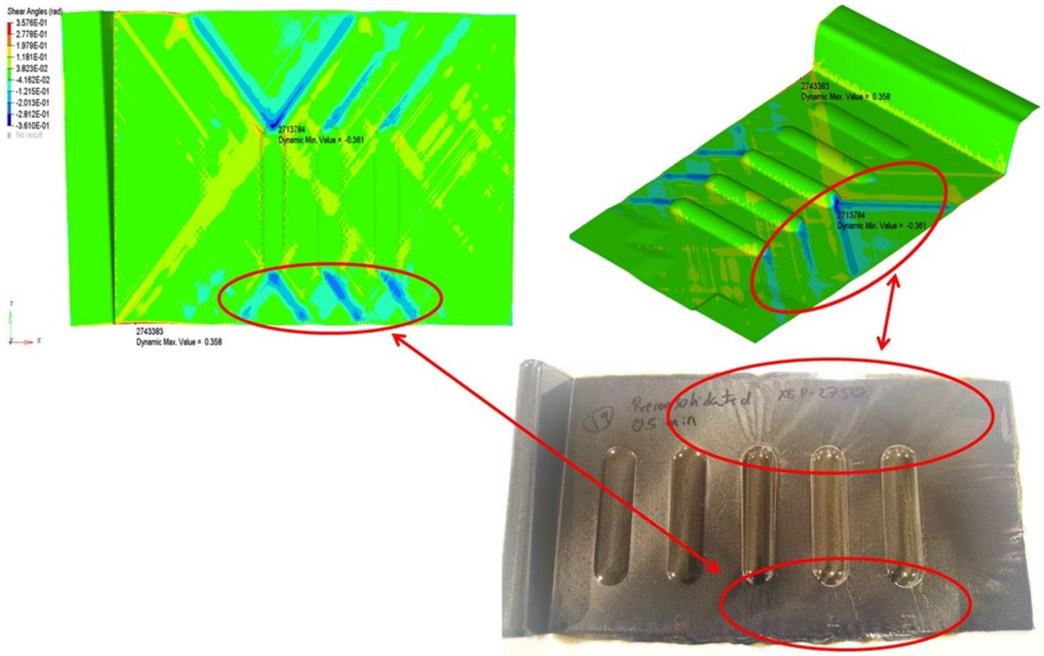

Figure 8. Visual correlation between process simulation and manufactured panel

2.2 TS-RAPM-002 Rib Part

Figure 9 illustrates the TS-RAPM-002 rib configuration. The thickness builds up in the center of the part, from 3.3 mm to 5.2 mm. The longer edge of the part is 540 mm long and the depth of the draw is 42 mm on the final trimmed part. The 4 walls are vertical. The spring-in compensation angle determined during the beaded panel studies has been applied to the tool geometry

Objectives:

- Integration of Transformer Film (patent pending) for increasing hydrostatic pressure for low resin content CYCOM® 5320-1 prepreg

- Assessment of surrounding vertical edge quality and finish

- Development of automated blank preparation in order to mitigate the hand layup uncertainty brought by positioning accurately a set of pad-ups which have no common edge with the rest of the part.

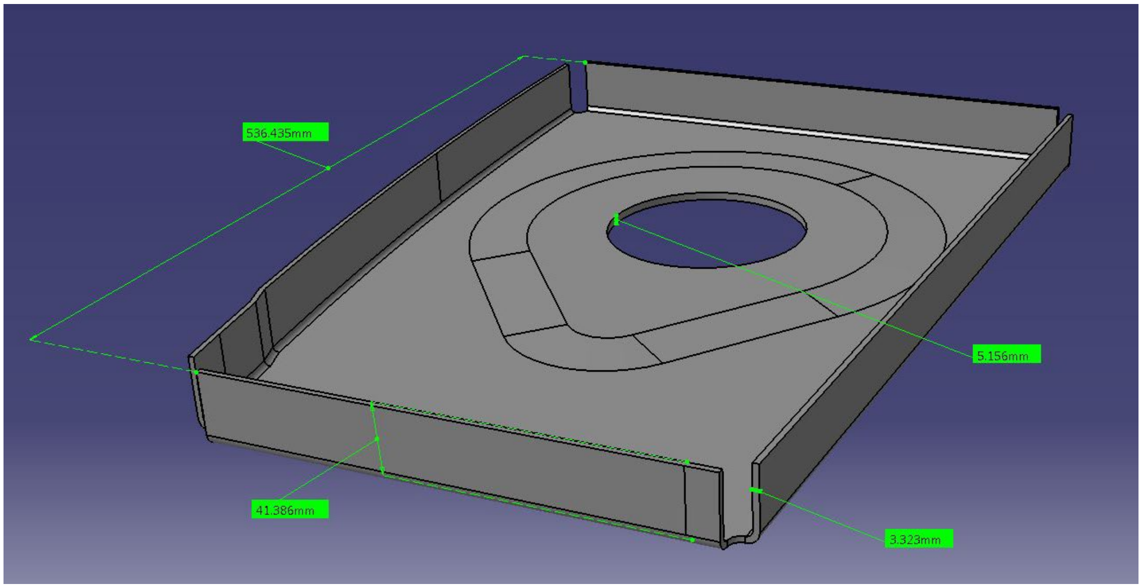

Figure 9. TS-RAPM-002 rib part geometry.

Observations made on the beaded panels led to higher tension capability and spring location modularity on the spring-frame. Figure 10 highlights loading and release of the parts for both spring-frame and Double Diaphragm Forming (DDF) method. Due to the deep draw of the TS-RAPM-002 rib, material excess is required in order to attach the spring clamps, whereas material excess can be more limited when using DDF. This effect is further increased here by tool design which does not allow necessary room for the spring clamps to be in close vicinity with the tool cavity.

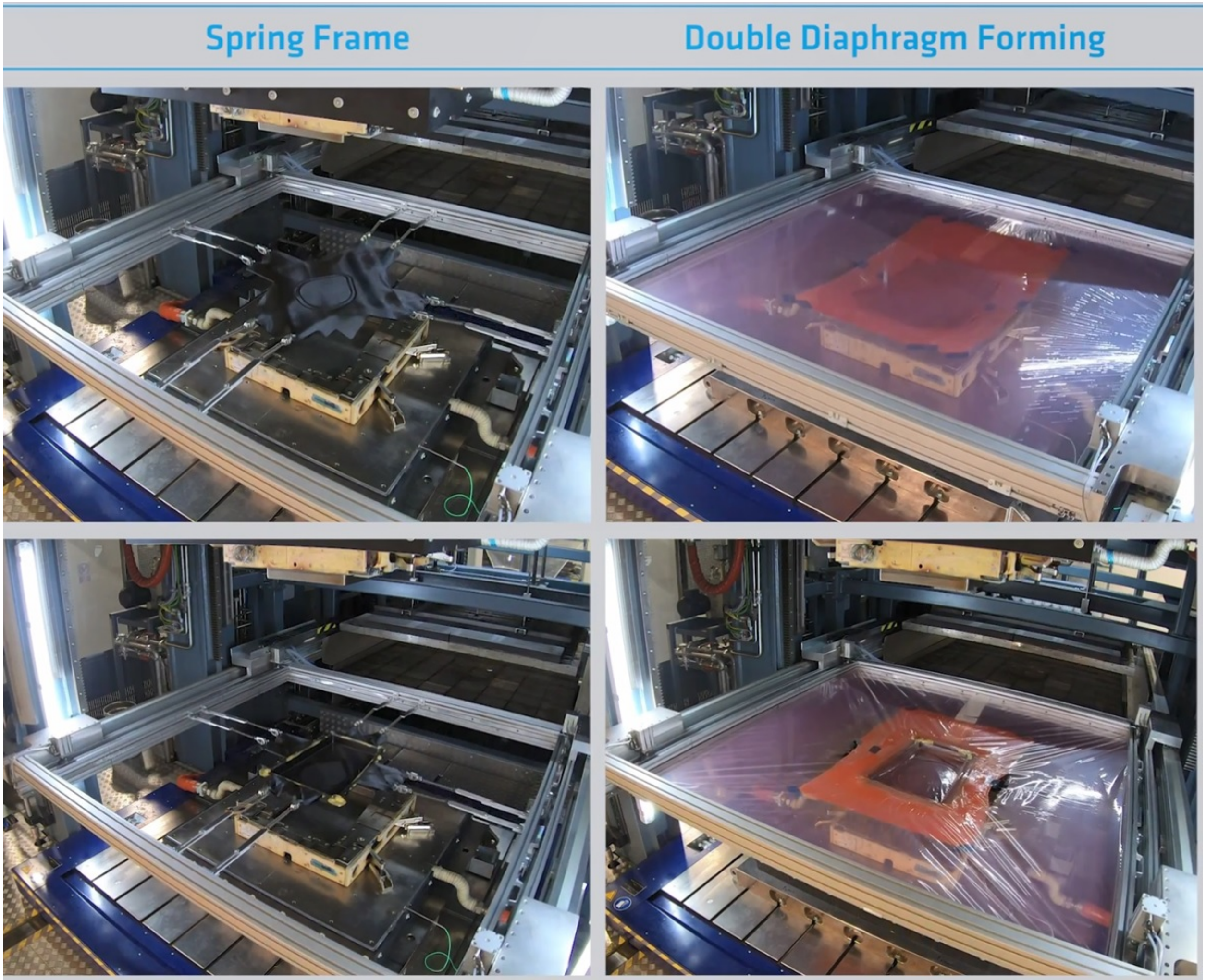

Figure 10. On top: blank shuttling from preheat to tool before closing. On bottom: part release

With regards to the TS-RAPM-009 beaded panel, Figure 7, the same observations can be made regarding the cured ply thickness (CPT) of CYCOM® 5320-1 TS-RAPM-002 rib, which is on average lower than the one of CYCOM® EP2750, Figure 11. The CPT is higher on the flat parts than on the vertical edges, regardless of the material used. The hypothesis is that this is due to flow restriction induced by the geometry of the part. The resin is kept within the central flat area of the part, as the vertical flanges act as a resin seal. This is helping compaction and part finish in the central flat area. However, the vertical flanges suffer from strong shear during tool closing, bringing surface roughness (but no porosity, see Figure 13). This is mitigated by the use of a lower bulk material, such as CYCOM® EP2750. Pre-consolidation of CYCOM® 5320-1 is a viable way to reduce bulk factor.

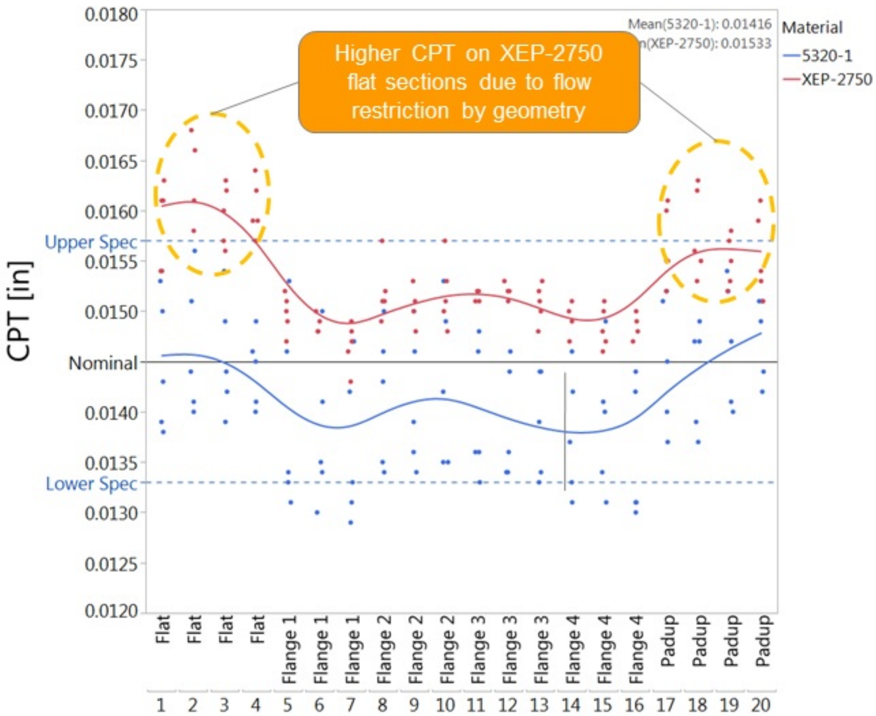

Figure 11. rib part CPT by location

In order to increase resin content from nominal quantity for CYCOM® 5320-1, a Transformer Film (patent pending) was applied ahead of the compression process. As a result, the average CPT of a low porosity CYCOM® 5320-1 part has been brought up to nominal (Figure 12). This has the effect of being able to move away from pre-consolidation, which is a time consuming extra step to the industrial automated manufacturing scenario. In summary, the use of Transformer Film allows the manufacturing of high-quality part with net resin content.

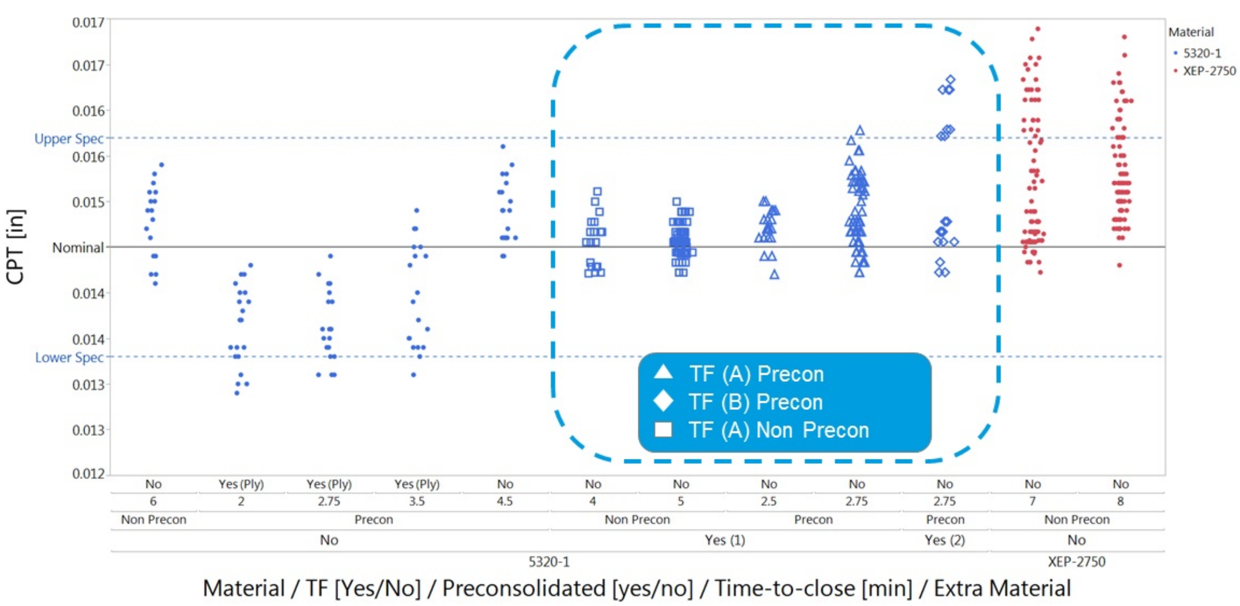

Figure 12. CPT increase from CYCOM® 5320-1 (blue dots), to CYCOM® 5320-1 with "TF" liquid shims (blue polygons), to CYCOM® EP2750 (red dots)

Figure 13 provides photo-micrographs of cross sections demonstrating the quality of the TS-RAPM-002 part discussed.

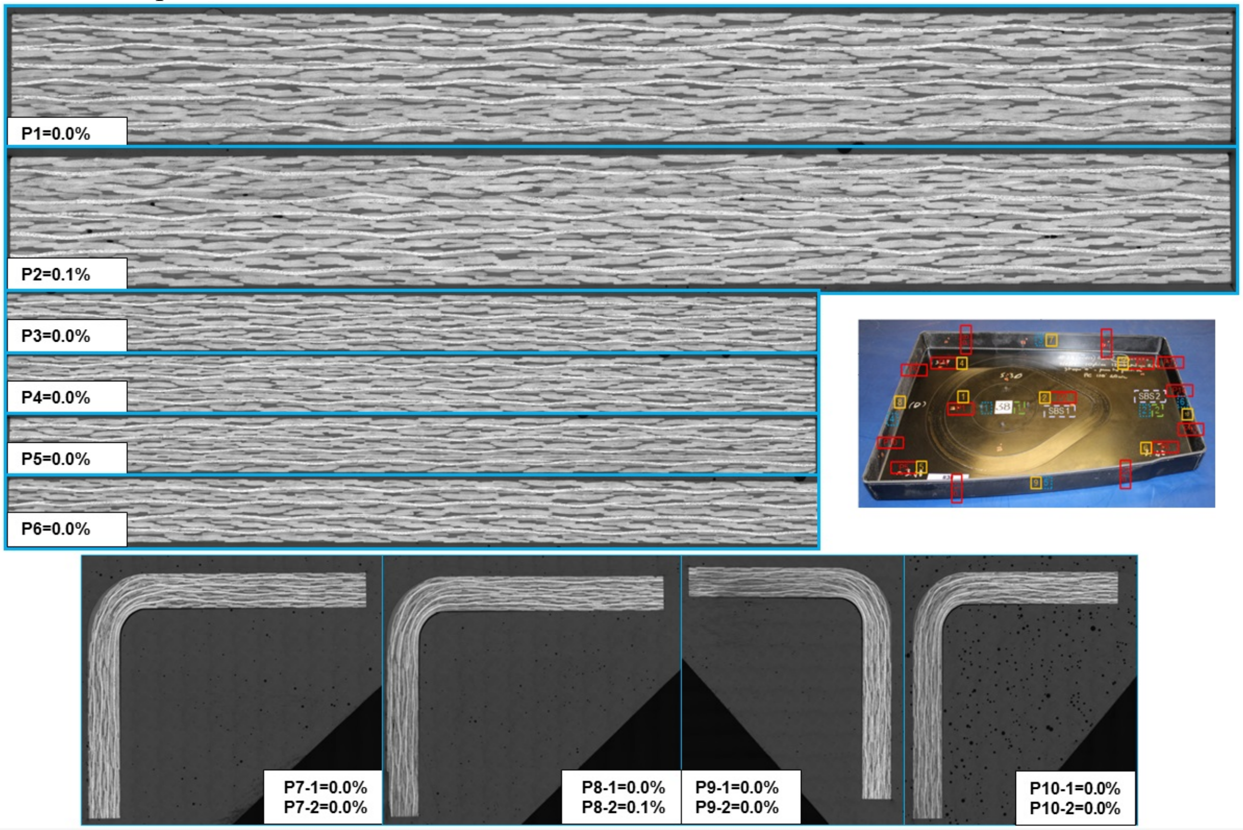

Figure 13. TS-RAPM-002 rib part photo-microscopy. The section are taken from the red areas on the rib part photograph.

2.3 TS-RAPM-003 C-Channel Part

Figure 14 illustrates the TS-RAPM-003 Curved Channel. The part is 640 mm long and presents a U-section 40 mm deep on the final trimmed piece. The inner radius of the section is greater than the outer radius. The thickness transitions from 6.6 mm in the narrow section of the part to 8.8 mm in the thick section of the part.

<u>Objectives:</u>

- Observation of the effects of a higher thicknesses on part quality and manufacturability

- Observation of the effects of an asymmetrical change in section on part quality and manufacturability

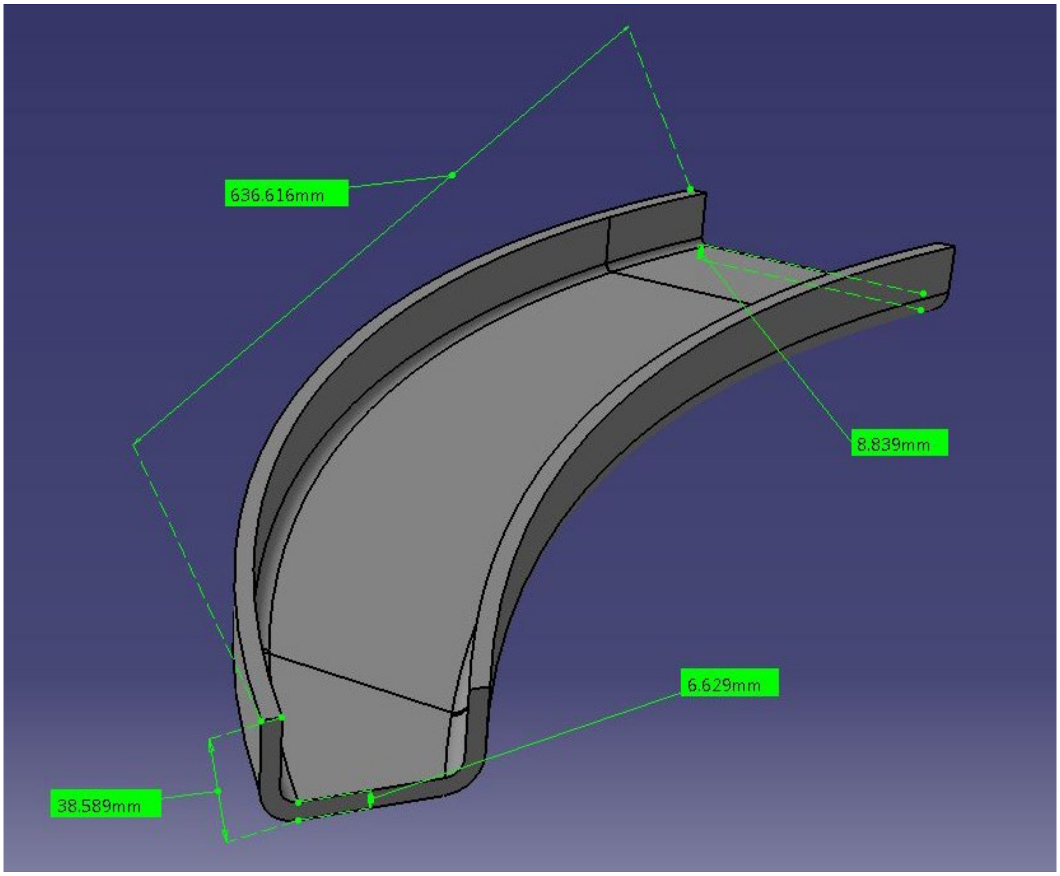

Figure 14. TS-RAPM-003 C-Channel part geometry.

Due to its thickness, the C-channel part is substantially heavier than the previous part configurations discussed. Therefore, the spring-frame has more attachment points than with previous shapes, as shown on Figure 15. The study of the beaded panel presented in the section above led to predicting wrinkle propagation through the part when the 2D blank is formed into multiple curvatures – this, however, is very dependent on fabric and viscosity profile of the part during forming. In the case of the C-channel geometry, the U-section evolves along the part in thickness, and the outer curvature differs from the inner curvature. This translates into potential fiber distortion through the part, which is visible on C-scans for the initial manufacturing trials (Figure 16).

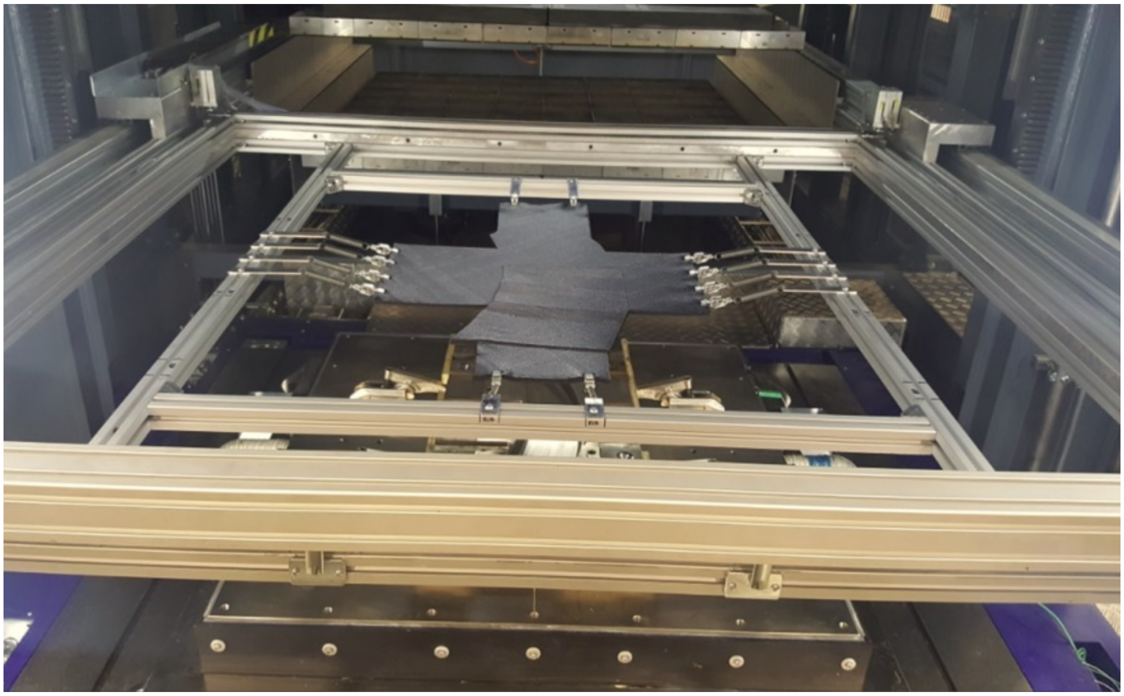

Figure 15. C-channel spring-frame configuration.

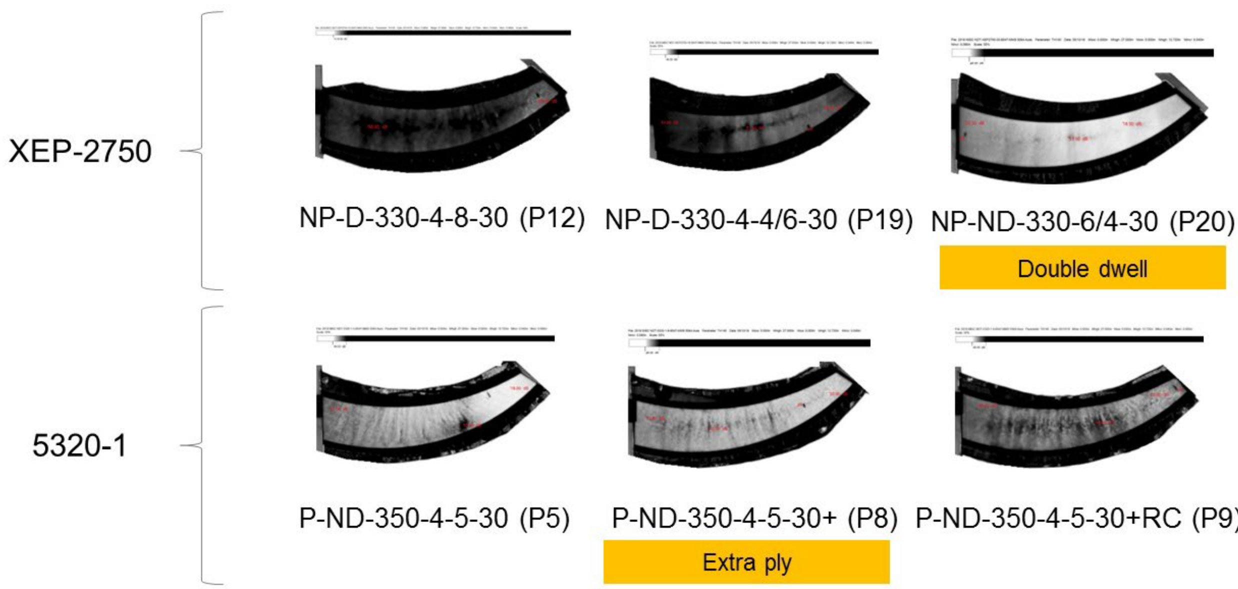

Figure 16. C-channel parts C-scan analysis. Initial manufacturing trials parts manufactured using CYCOM® EP2750 (top) and preconsolidated CYCOM® 5320-1 (bottom).

The C-scans shown on Figure 16 above highlight the presence of wrinkle propagating from the inner radius to the outer radius of the parts for parts using preconsolidated blanks. The grey scale indicates the wrinkles also carry porosity. For CYCOM® EP2750, the "double dwell" improved porosity and removed wrinkles from the parts. This consists of applying a certain amount of pressure during the dwell, in a sequence which follows the viscosity build-up of the material. For CYCOM® 5320-1, the addition of an extra ply reduced porosity and wrinkle magnitude but did not eliminate them at first. This is explained by the increased viscosity of the CYCOM® 5320-1 blanks advanced during the preconsolidation process – higher viscosity increases the potential of getting wrinkles on the parts.

In order to resolve the wrinkling and porosity of parts manufactured on the initial trials, the Transformer Film was used to increase the resin content on the material prior to manufacturing. This increases in resin content eliminates the need of preconsolidating and also guarantees a low porosity part but enabling the hydrostatic pressure on the mold cavity. Figure 17 shows the same part manufactured without preconsolidation and by addition of the Transformer Film. As shown in the C-Scans, wrinkles are significantly reduced and the parts show low porosity.

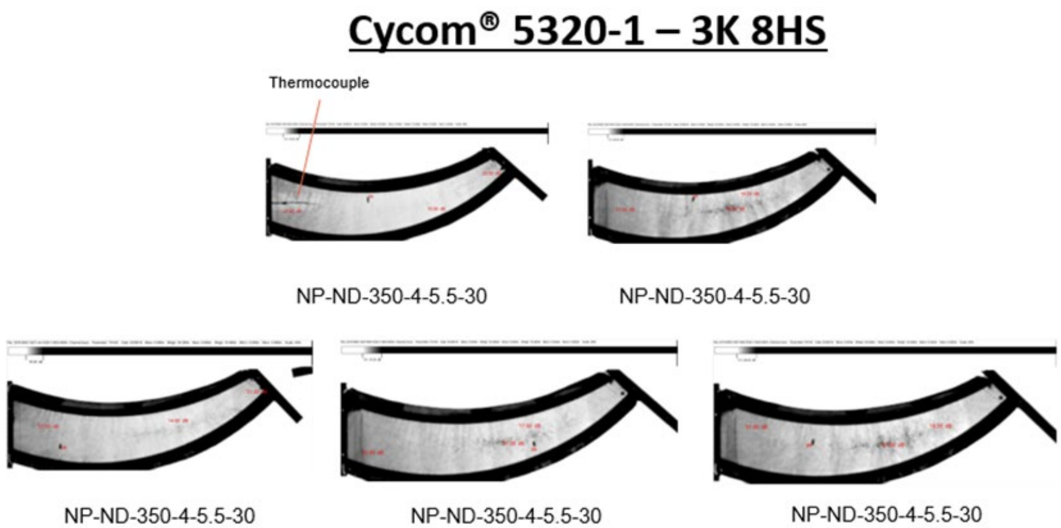

Figure 17. Manufacturing of C-Channel parts through compression molding using CYCOM® 5320-1 3K 8HS and Transformer Film. Repeated manufacturing of parts using same materials and processes show robustness of this high-rate manufacturing process

Figure 18 shows the effect of double dwell on part thickness. It is possible to retain more resin within the part while having satisfactory wetting of the fibers. Therefore the thickness is enabled to build up and reach nominal whilst keeping low porosity levels and low fiber distortion levels. The early pressure application of the double dwell leads some of the resin contained in the blank to flow from the thick to the thin area of the part. This results in thicknesses slightly beyond nominal on the thin side of the part (Figure 18) due to higher resin content. This also explains brighter C-scan reading in the thin area of the part (Figure 16).

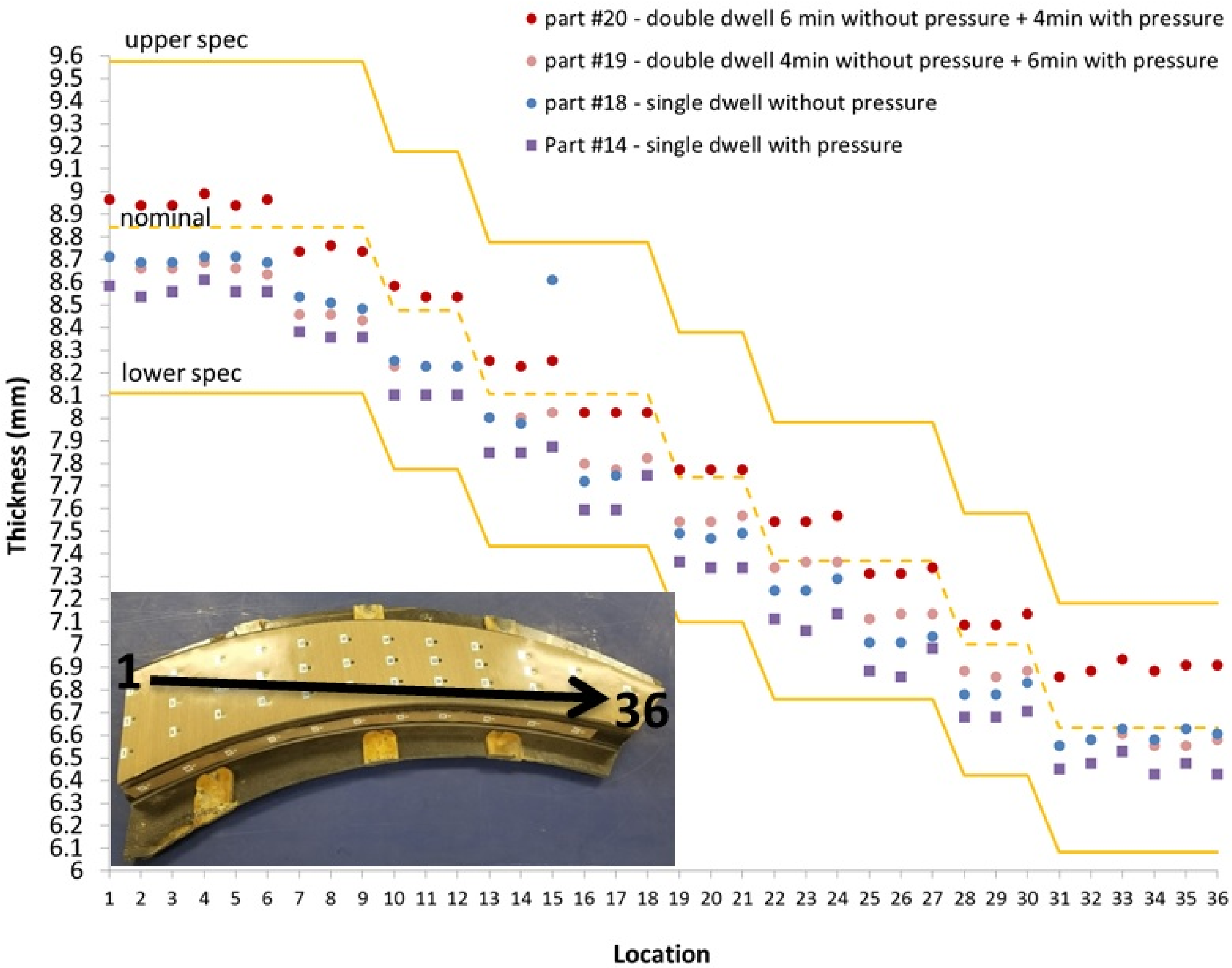

Figure 18. C-channel thickness measurement vs location. 36 samples have been extracted and measured on microscope. Those points go from the thicker area of the part to the thinner one.

3. CONCLUSIONS

The design and manufacture of a set of challenging part geometries has enabled generating knowledge towards the industrialization of high-rate manufacturing of aerospace structural parts by compression molding. Key pieces of learning are summarized by category.

<u>Material design and formulation:</u>

- Low bulk is beneficial for part quality, specifically to contain porosity levels and increase surface finish in vertical edges. This is achievable through high levels of impregnation during prepreg manufacture

- Higher resin content allows a wider manufacturing parameter window, as well as increased process repeatability

Tooling design:

- A reduction in section in the surrounding of the tool cavity will help pressure build up, particularly for parts with varying thicknesses

Equipment and machinery:

- Ideally, the pressing equipment should include:

  - IR preheat station
  - Automated carrier frame shuttling
  - Tight parallelism tolerances between platens
  - The ability to control and monitor position of platens to a tight tolerance
  - Ideally, the ability to press to low forces

Process cycle:

- “Double dwell” is beneficial for thick parts, but can induce CPT unevenness in parts of varying thicknesses

- A shorter dwell will increase fiber wetting but can lead to resin starvation, insufficient pressure build-up, or insufficient cured ply thicknesses

- Pre-consolidation allows reducing fiber disturbance in vertical walls, and contributes to reducing overall porosity levels

-Use of Transformer Film increases the process robustness by guaranteeing hydrostatic pressure in the mold cavity during consolidation

4. ACKNOWLEDGMENTS

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5. REFERENCES

1. J. Vandenbrande, "Tailorable Feedstock and Forming (TFF)," DARPA, [Online]. Available: https://www.darpa.mil/program/tailorable-feedstock-and-forming. [Accessed 04th December 2019].
2. G. L. Hahn and T. K. Tsotsis, "Rapid High-Performance Molding (RAPM) of Small Parts," in SAMPE 2019 Conference Proceedings, Charlotte, 2019.
3. A. Bras, A. J. Rodriguez, S. A. Rogers, A. Whysall, R. Russell, J. Brudenell, S. Lucas, T. Wybrow and S. Hill, "High-rate Manufacturing of Aerospace Structural Parts through Compression Moulding," in SAMPE Europe Conference Proceedings, Nantes, 2019.
4. T. J. Luchini, A. J. Rodriguez, S. A. Rogers, A. Bras, A. Whysall, R. Russell, S. Lucas and G. L. Hahn, "Spring Frame Press Fabrication of Aerospace Production Components," in SAMPE America conference, Charlotte, NC, 2019
5. F. Bressan, "Methodology for Press Forming Simulation of a Continuous Fiber-Reinforced Polymer Composite," in SAMPE America Conference Proceedings, Seattle, 2020.