

LOW-COST HIGH-RATE AEROSPACE STRUCTURAL PARTS: APPLICATION STUDY

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ABSTRACT

Increasing the manufacturing rate for aerospace structural parts through compression molding presents a range of challenges around the accelerated cure reaction, the complexity of some geometrical features, tool design and fiber draping. Those challenges have been characterized and addressed in previous studies, where the feasibility of a 30 minutes takt time was demonstrated. This was achieved through the co-development of prepreg material and processing technologies. The experience and lessons learnt from previous developments are applied in this paper to a case study. This case study is based on the manufacture of a representative commercial aircraft structural part presenting extreme geometrical features. Achieving sub-30 minutes takt time with high quality and repeatable output was made possible through novel tool design methods, as well as enhanced process cycle elements.

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1. INTRODUCTION

The current acceleration of manufacturing rate needs in civil and military aircrafts have challenged traditional composite fabrication processes. This applies to drones, urban air mobility (UAM) vehicles, and passenger aircraft. Specifically, there is a need for defining novel ways of manufacturing small complex-shaped lightweight parts. The Defense Advanced Research Projects Agency (DARPA) explored various angles of attack to this challenge in the Tailorable Feedstock and Forming program (TFF) [1]. This program included some Boeing and Solvay, who partnered through the RApid High-Performance Manufacturing project (RAPM) [2,3]. Their proposition to solve the technical challenges of enabling higher rates is to bridge automotive and aerospace technologies, and apply highly automated compression molding process to continuous fiber thermoset (TS) prepreps [4,5]. The approach taken has been to develop every aspect of the TS press-forming process, along with the formulation of a novel prepreg system, specifically designed for high rates: CYCOM[®] EP2750 [6,7,8]. The joint effort between Boeing and Solvay was directed towards forming simulation [9], advanced non-destructive inspection (NDI) methods [10],

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comparative novel manufacturing cells trade studies [11], and the manufacture of increasingly challenging geometries [12,13].

Based on lessons learned throughout its duration, the RAPM program culminated with the application of acquired knowledge and methods to a case study. This case study is the high rate manufacture of a representative commercial/transport aircraft structural part presenting extreme geometrical features. Predictive forming simulation and tooling design improvement in comparison in the early stages of the program, both work in complement to the experimental manufacturing trials and process adjustments. In continuity to the previous studies, both CYCOM[®] EP2750 and CYCOM[®] 5320-1 prepregs were used, and their differences analyzed. CYCOM[®] 5320-1 is an out-of-autoclave system, well-established in the aerospace industry. Its high performance and manufacturing versatility have made it widely qualified across the market. Similar in performance, CYCOM[®] EP2750 presents attributes which make it particularly forgiving and repeatable in press-forming, while at the same time able to be processed in autoclave. A brief comparison between the two materials in some of those attributes appears in the Table 1 below.

Table 1. Comparison between CYCOM[®] 5320-1 and CYCOM[®] EP2750 pre-pregs [7]

	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

2. EXPERIMENTATION AND RESULTS

2.1 TS-RAPM-007 challenge part geometry

The challenge part presents a combination of the challenging features of the path finding parts. Its tool design and its manufacturing happened chronologically after the 4 other geometries. The manufacturing of the parts was investigated in the order shown in Figure 1 below:

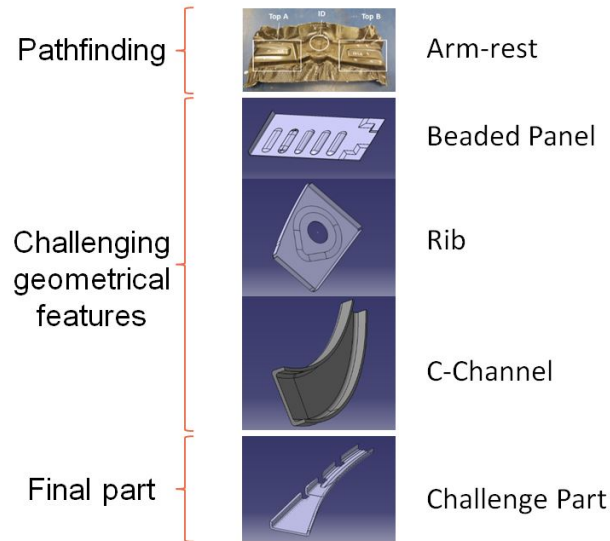


Figure 1: Part geometries investigated, in their chronological order

The parts investigated present increasingly challenging geometrical features, as well as an evolving scope for material and process selection. In the early stages of the project, both double diaphragm forming (DDF) and spring frame were considered, as well as a wide range of resin formulations and reinforcement architectures. The narrowing down of material and process, as well as the increased geometrical challenges through the project are summarized in Figure 2 below:

	Arm-rest	Beaded Panel	Rib	C-Channel	Challenge Part
Material	<ul style="list-style-type: none"> - 5320-1, 2750, 970, MTR 760 - 3K 8HS, 6K 5HS, PW, UD, Wet FW 	<ul style="list-style-type: none"> - 5320-1, 2750 - 3K 8HS, PW 	<ul style="list-style-type: none"> - 5320-1, 2750 - 3K 8HS 	<ul style="list-style-type: none"> - 5320-1, 2750 - 3K 8HS 	<ul style="list-style-type: none"> - 5320-1, 2750 - 3K 8HS
Process	<ul style="list-style-type: none"> - Manual loading 	<ul style="list-style-type: none"> - DDF - Springframe 	<ul style="list-style-type: none"> - Springframe 	<ul style="list-style-type: none"> - Springframe 	<ul style="list-style-type: none"> - Springframe
Challenges	<ul style="list-style-type: none"> - Draping challenge - Constant thickness 2mm (0.08") 	<ul style="list-style-type: none"> - Beads - Thickness 3mm to 6mm (0.12" to 0.24") 	<ul style="list-style-type: none"> - Centered padups - Vertical edges - Thickness 3mm to 5mm (0.12" to 0.20") 	<ul style="list-style-type: none"> - Deep draw - Vertical edges - Double curvature - Thickness 6mm to 9mm (0.24" to 0.36") 	<ul style="list-style-type: none"> - Deeper draw - Vertical edges - Double curvature - Thickness 4mm to 13mm (0.15" to 0.50")

Figure 2: Parts' scope and challenges

In anticipation of the challenge to manufacture vertical edges that would be encountered on the rib part, the C-channel and the challenge part, Figure 3, we worked on a beaded panel. That panel presented an edge with varying angle enabling the assessment of the quality threshold - indeed the draft angle is close to vertical - and of the quantification of spring-back angle when demolding.

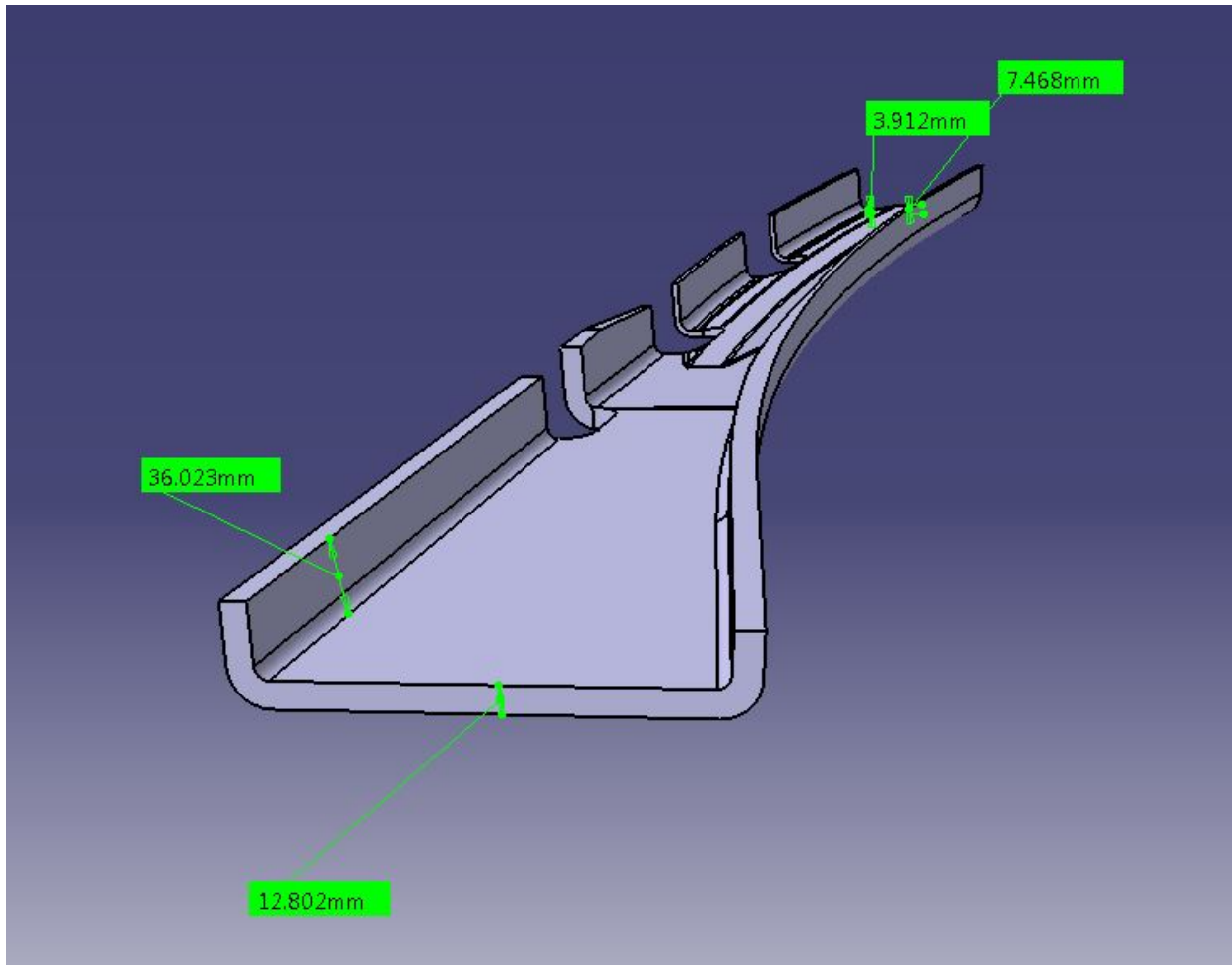


Figure 3: Challenge part thicknesses and depth of draw

2.2 Tooling design and manufacture

Compression mold tools were designed and manufactured one after the other through the project. First the path finding investigation was carried out using an existing automotive geometry (armrest) tool available at the toolmaker's facilities. The three following tools (beaded panel, rib, C-channel) were designed to enable spring frame and DDF processes including: pockets around the part cavity in order to get the spring clamps as close as possible to the cavity and increase material usage; guiding is made by machined cones which prevent the films in the DDF process from being punctured during tool closing (Figure 4).

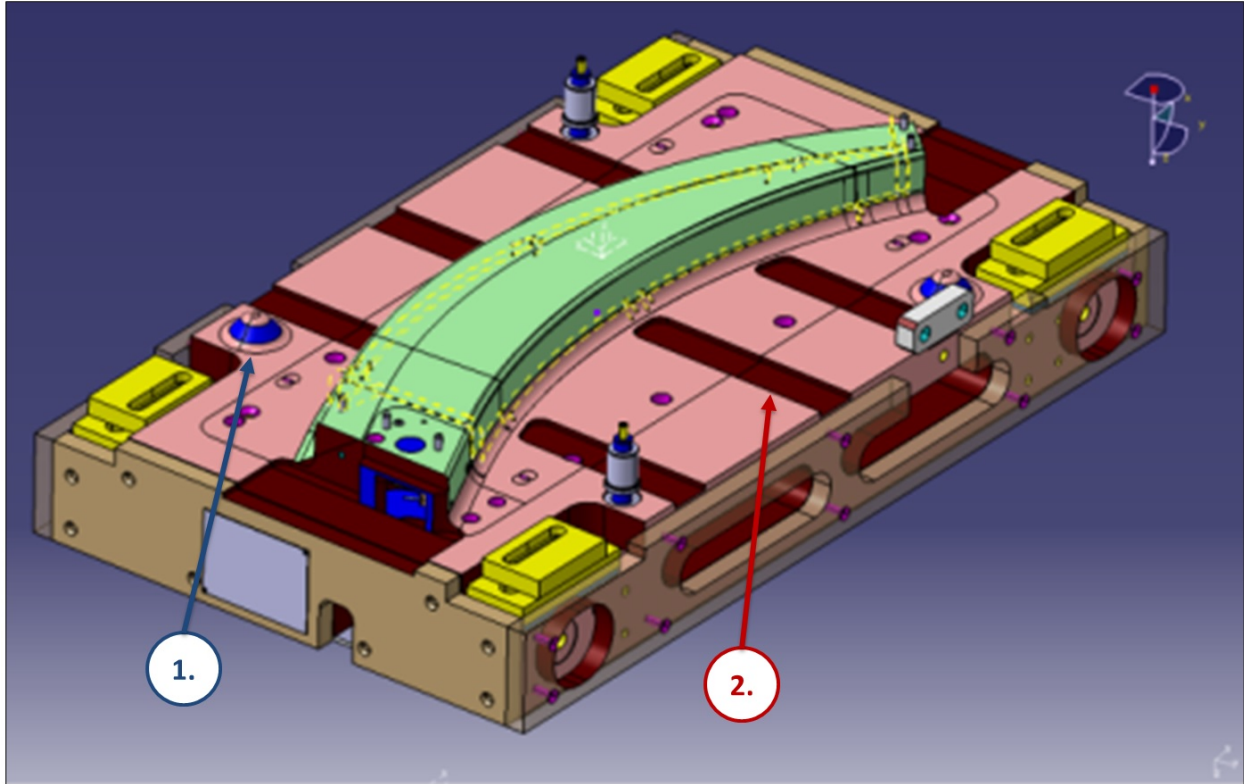


Figure 4: C-channel upper tool. The two guiding cones appear in blue (1.); 3 spring clamp pockets are machined on each long side of the cavity, and 1 pocket on each short side (2.)

A few design modifications were implemented from the first parts' tool design to the challenge part's tool design:

- The guiding was still performed via cones, but they were made adjustable in height, in order to limit the hyperstatism during tool closing, especially that the increased length of the part led to use 6 stops rather than 4 stops.
- The spring clamp pockets were substantially widened, in order to maximize the modularity for spring frame configurations, as well as optimizing the material efficiency by getting closer to net shape molding.
- Sealing mechanisms were put in place to guarantee hydrostatic pressure conditions within the tool cavity.
- Particular attention was given to resin bleed control, not only through sealing, but also through avoiding the creation of resin traps, which would be a health and safety concern when considering the increased thickness of the Challenge Part and potential exothermic reactions.
- The challenge part tool is self-heated with oil, which was required due to limited available heated platens size, but also guarantees higher temperature evenness through the tool

surface during press-forming. This was identified previously as one of the main factors for quality control of the press-formed part [7].

- A vacuum system was added too, in anticipation for potential air entrapment due to higher thicknesses and material quantity.

The tool design concept and evolution from initial geometries is illustrated on the Figure 5 below:

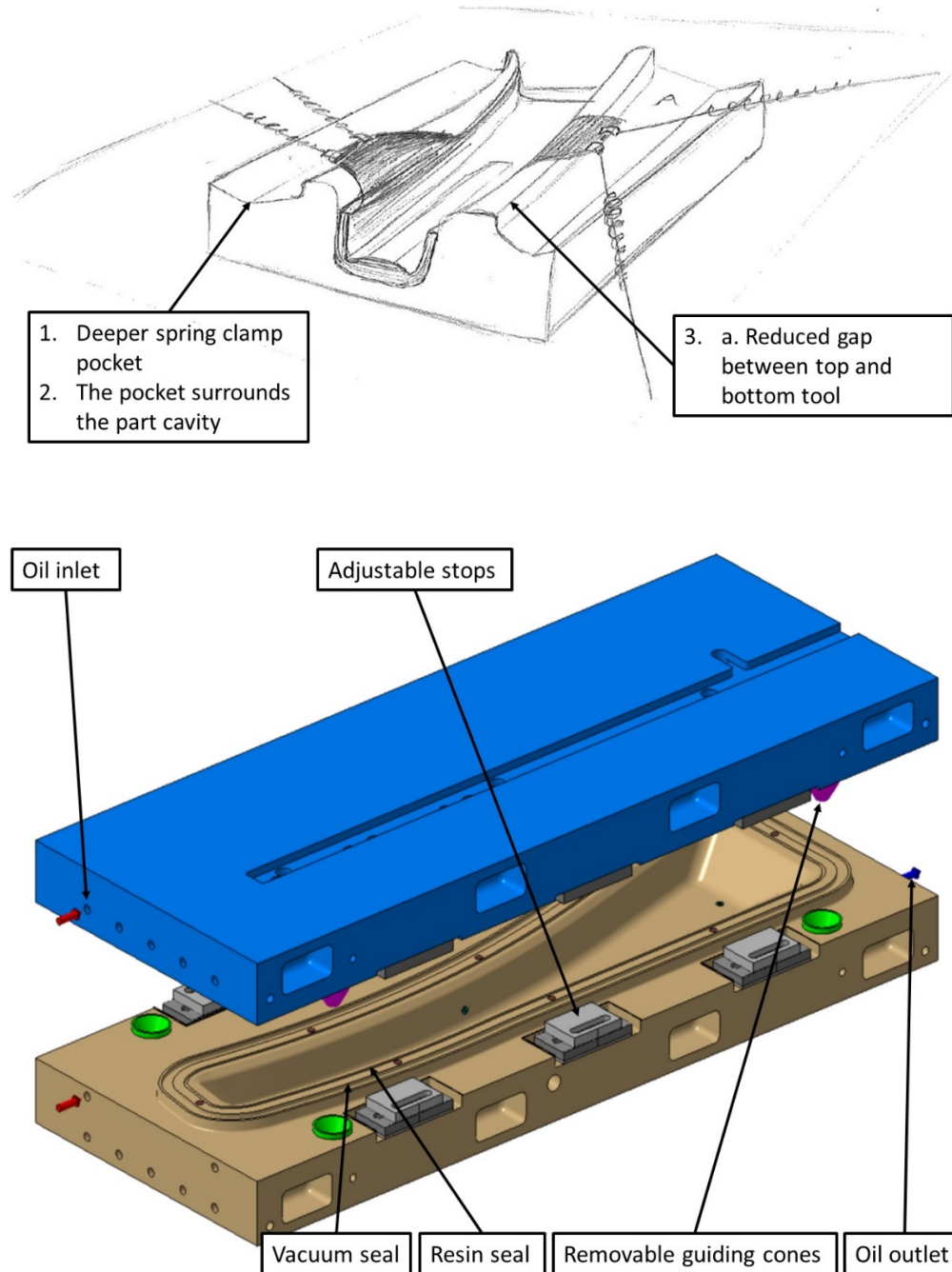


Figure 5: Challenge part design evolution

Once machined, the tool was installed in Solvay's application center in Heanor, UK, as shown on the Figure 6 below. The image highlights the presence of the automated blank shuttling rails on the left and right sides of the tool. The infrared (IR) preheat station is located at the back of the platen area.



Figure 6: Challenge part tool setup in Heanor Application Centre

2.3 Spring frame configuration

Following the design concept for the challenge part tool, detailed in the previous section, the pocket location all around the tool cavity allows maximum freedom for spring clamps positioning. In order to have full flexibility on clamps location, angle, number and tension, adjustable brackets were manufactured for the challenge part spring frame. This enabled quick change in configuration and fine tuning such as the one illustrated on Figure 7. This modularity was key in the development of the press-forming process for the challenge part, as anticipated during the press-forming simulation stage [9], where a series of spring clamping and tension application were investigated in order to confirm or not the feasibility of this geometry. The conclusions drawn at that time were that some areas of the part would be prompt to generate defects, but that the dramatic variation in thicknesses did not allow full prediction of the forming behavior. Therefore, the physical trials are complementary to the simulation scenario investigated, and will help refine the model for better future prediction.

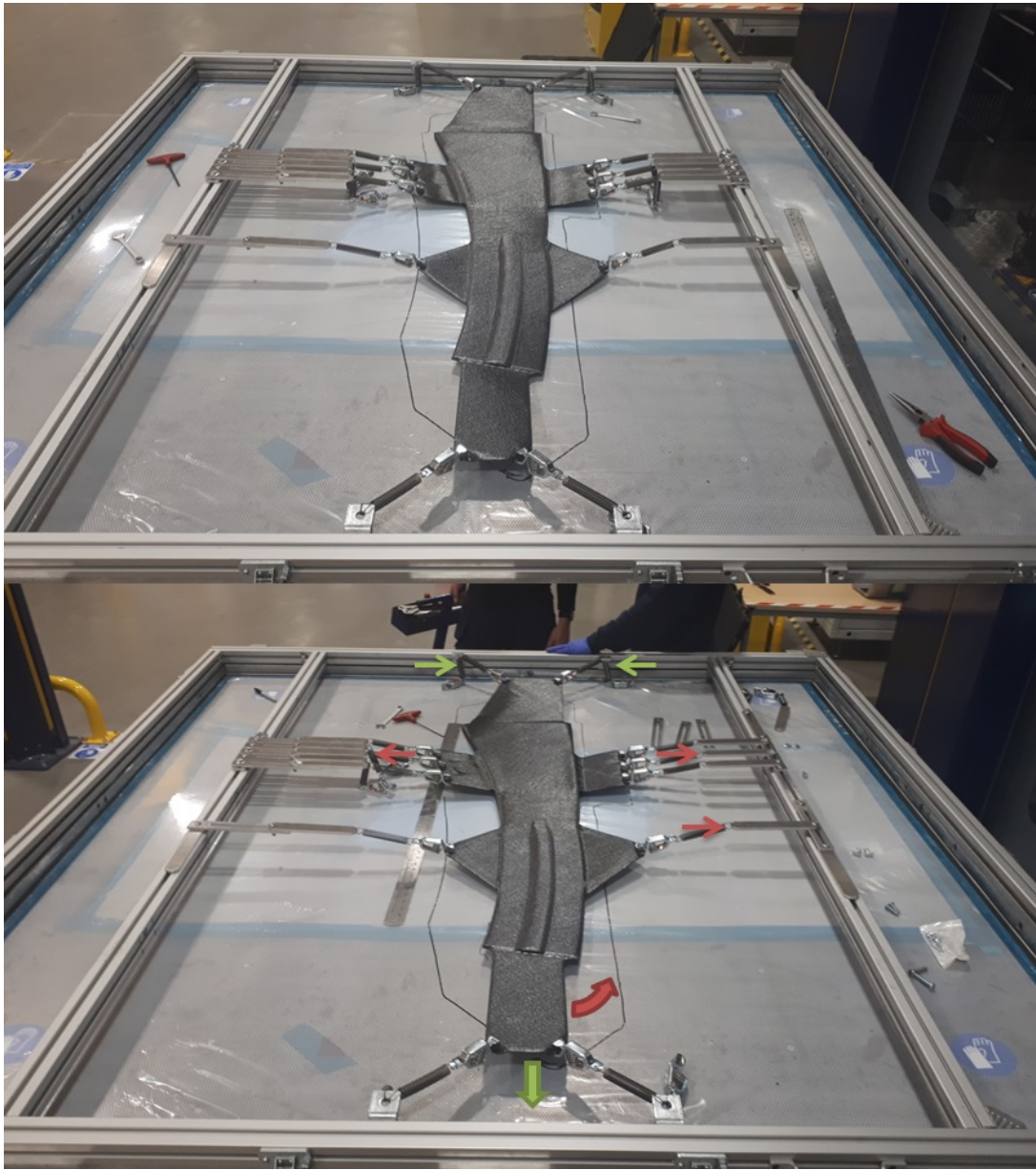


Figure 7: Example of spring frame adjustment from one trial to the next. The green arrows represent adjustments in location and the red arrows represent adjustments in tension

An example of predicted manufacturing defect through simulation was the fiber distortion observed in the thickest area of the part, resulting from multiple orientations curvatures applied to the 2D blank when forming into a 3D shape in one stage. Despite optimized IR preheat cycle which enabled the resin to be at minimum viscosity during the closing stage and therefore maximized slippage of plies, consistent fiber distortion was observed from one part to the next, in the same area of the part, predicted by the simulation model, as shown on Figure 8.

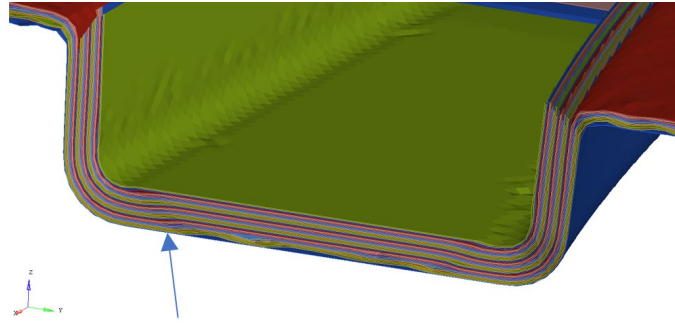
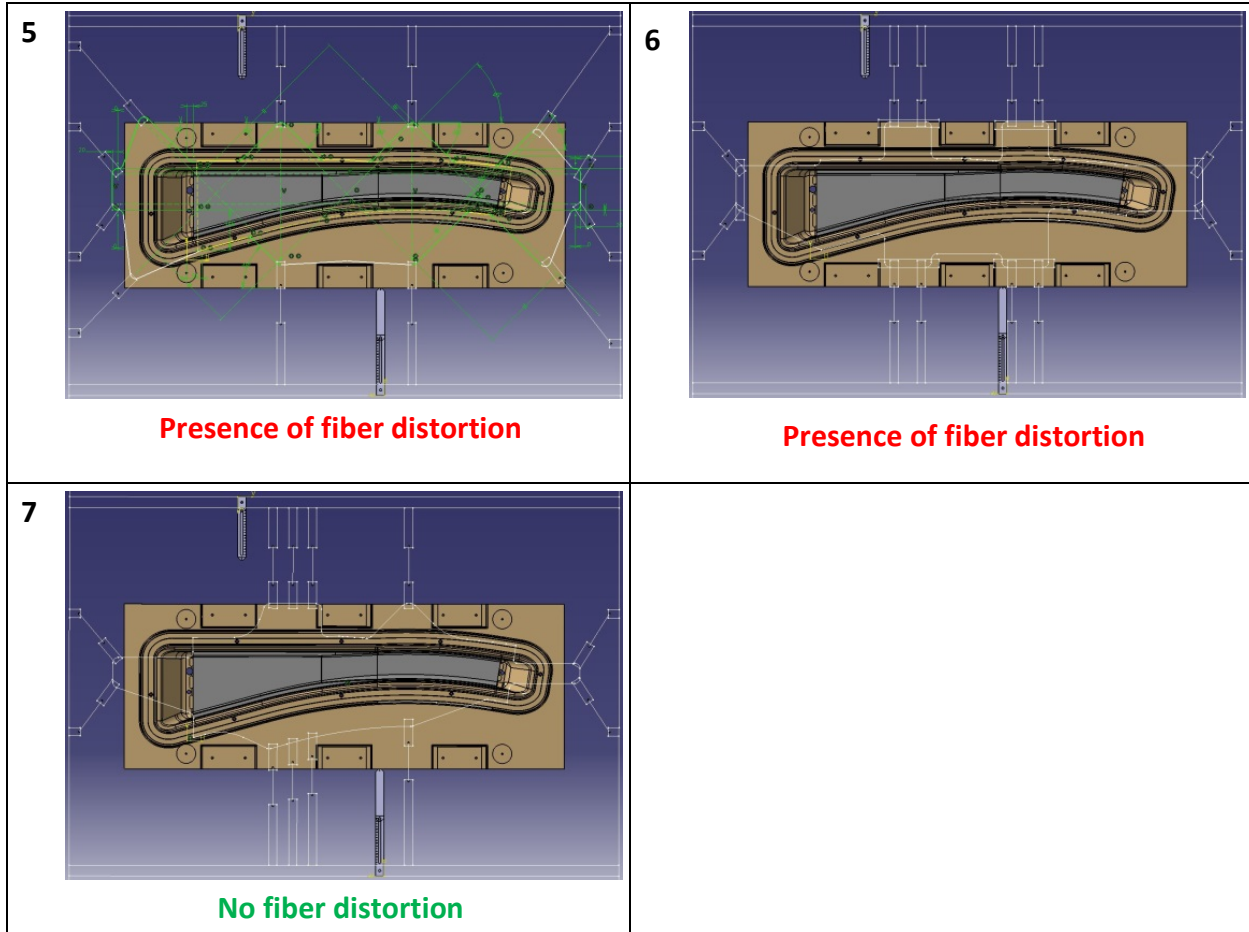


Figure 8: Fiber waviness issue in the thickest area of the challenge part, as predicted by the simulation model [9]

In order to overcome the issue of fiber waviness predicted by the simulation model and confirm by press forming, the modularity of spring frame configurations allowed to generate an empirical solution, obtained purely from experimental combinations of location and tension applied to the blank, which itself was built from varying geometrical parameters. The summary of those combinations is shown in Table 2.

Table 2: Spring frame evolution

#	Configuration	#	Configuration
1	<p>Presence of fiber distortion</p>	2	<p>Presence of fiber distortion</p>
3	<p>Presence of fiber distortion</p>	4	<p>Presence of fiber distortion</p>



2.4 IR preheat

While 3 minutes were usually enough to ramp the temperature up and stabilize it in the IR preheat for the thin parts of the project (rib and beaded panel), the thicker parts required longer time spent in the IR preheat in order for the heat to transfer to the center of the blank and allow maximum slippage between the plies whilst not over-staging the resin before entering the mold.

On the challenge part, it was first attempted to use 4 minutes preheat, in order to minimize the cycle time. It then had to be extended to 8 minutes, 16 minutes, and 30 minutes. Heating the top skin stronger than the bottom skin has also provided some positive effect. A sample of the temperature profiles considered is shown in Figure 9.

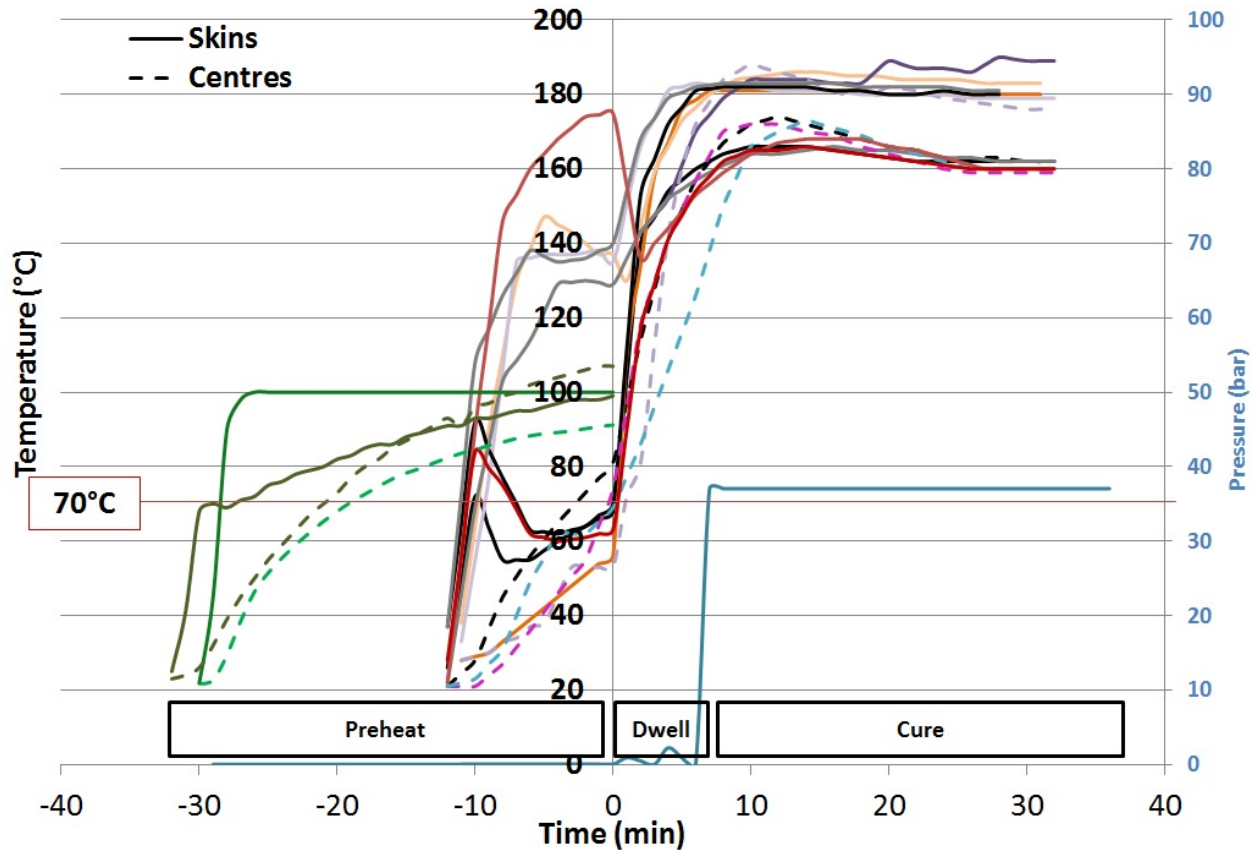


Figure 9: Examples of temperature profiles considered for the challenge part

The sample of temperature profiles shown in Figure 9 was captured when attempting to limit the IR steady state set temperature time to 8 minutes, resulting in around 11 minutes total IR time including the ramp. It was experimentally observed that providing top skins with strong preheats while letting the bottom skins cool down below 70°C after an initial peak of heat enabled within those 11 minutes the center to reach a temperature high enough to minimize the resin viscosity. The improvement was observed in terms of porosity and wrinkle comparison between parts #16 and #17 (Figure 10). When remaining below 70°C, the bottom skin is stiffer than the rest of the blank, which helps it not to distort, as it is the one subject to the highest tension during draping. This way the drapability of the blank is increased in comparison to a homogeneous preheat of the same duration. However, increasing the preheat time to 30 min allowed the temperature in the blank to be homogeneous from skin to center whilst remaining cold enough to not over-stage the blank before entering the mold.

Thirty minutes preheat is a strong cycle time penalty, as it doubles the takt time if preheat and on-tool-time happen in series. However, it is not a penalty if the press equipment allows those two steps to happen in parallel.



Figure 10: Comparative C-scan analysis between parts #16 and #17, highlighting the positive effect of asymmetrical IR preheat done on part #17

2.5 Thickness variation challenge

One of the specificities of the challenge part in comparison to the previous geometries investigated is to present a thickness variation which is an order of magnitude larger. On one end of the part the section is 3.9 mm thick (0.15 in) and it transitions to 12.8 mm (0.50 in) through a distance of only a few inches (Figure 3). The thickness is more than tripled, whilst the strongest ratio so far in the project was on the beaded panel, where the thickness of approximately 3 mm was transitioning to 6 mm (0.12 in to 0.24 in).

The bulk factor of CYCOM[®] EP2750 is smaller than CYCOM[®] 5320-1, due to higher impregnation level (Table 1). In the case of a blank with strong thickness variation, this represents a difference in absolute bulk value. As a consequence, in the mold closing sequence, the top tool enters in contact with the thick part of the blank earlier than with the thin part of the blank (Figure 11).



Figure 11: The top tool is first in contact with the thick part of the blank due to bulk factor

This can represent a considerable force, depending on the thermal history of the blank. This force results in the flow of the resin contained in the thick area. This has several detrimental effects:

- Creation of resin bulk outside of the blank, with a risk of exothermic reaction
- Tool rocking
- Uneven pressure through the part

- Uneven temperature through the part
- Resin starvation in the thick area, resulting in an increase of V_f in the thick area and creation of porosity
- Transfer of the resin from thick to thin area, resulting in a decrease of V_f in the thin area

Those points are problematic in the case of the challenge part because the difference in cure ply thickness (CPT) it induces between thick and thin areas prevents the part from reaching the specs. Three factors have shown to be particularly influential in bring CPT within the specs boundaries:

- Debulk method, either:
 - o Full debulk at room temperature for 20 minutes
 - o Partial debulk, including only the thick area of the part
 - o No debulk
- Dwell time
- Dwell force

It was observed that the absence of debulk had a positive effect on reaching the correct CPT. However this can have a detrimental effect on porosity and heat transfer consistency. It was also observed that the dwell time needs to be below a certain threshold in order to allow the excess resin contained in the thin area to exhaust. This also does not solve the porosity issue in the thick area, as the resin which has overflowed from it does not go back to it.

It is important to limit the flow of resin away from the thick area in the first place, by limiting the force applied to the thick part during the dwell. This comes from a combination of parameter including:

- IR temperature
- IR time
- Spring tension
- Dwell gap

The dwell gap has shown better results when being deliberately greater than the bulk, therefore not entering in contact with the part at all. However, this causes non-homogeneous temperature distribution through the part.

The first thirty-seven parts were made using a “double-dwell”, which consist in splitting the tool closing sequence into two steps. This way the pressure application profile is following the viscosity profile and allows better consolidation and smaller air entrapping. This is visible on C-scan and microscopy analyses: the lowest porosity levels are obtained using the double-dwell. When switching to a deliberately wider opening of the tool during the dwell in order to obtain correct CPTs, the porosity levels would not be able to drop as low as with a double dwell.

The antagonism between dimensional specifications and part quality can be illustrated through the comparison between parts #28, #33, and #49 (Figure 12). Part #28 presents the best C-scan signal

and lowest porosity level in all points of the part. However, this part is out of CPT specifications. Part #33 presents CPT within specifications thanks to removing the debulk stage. However the C-scan analysis shows a knock down in quality. Part #49 was manufactured with removed double-dwell, which also affects part quality negatively, but brings it within dimensional specs. A combination of process adjustments were required to lower its porosity level to a minimum, but still not matching the ones previously obtained with part #28.

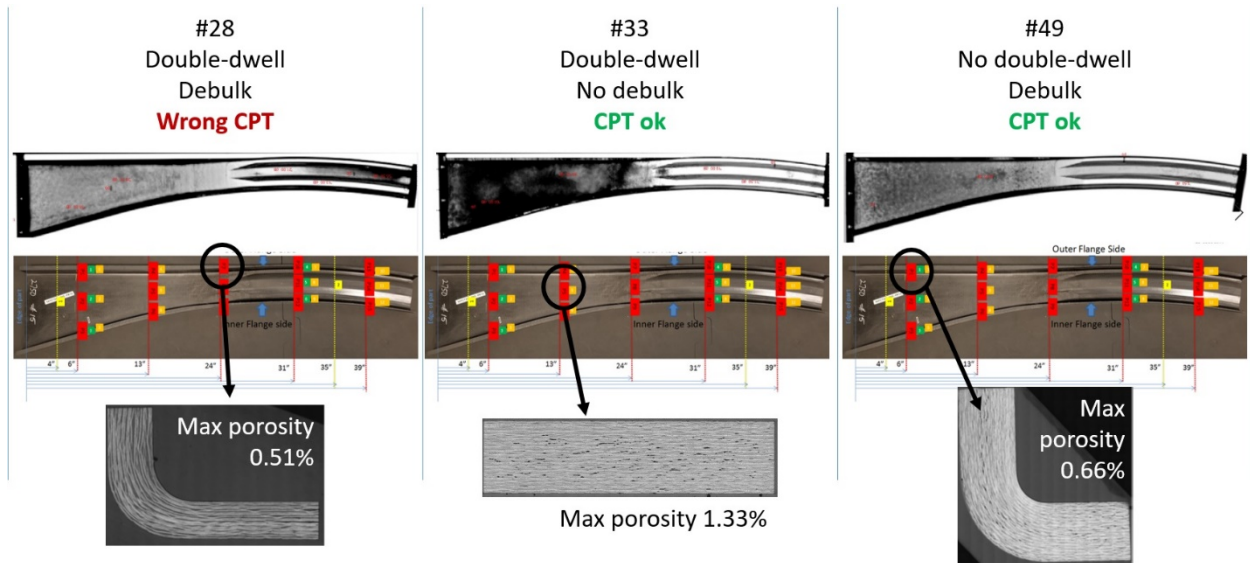


Figure 12: comparative NDI and destructive analysis of parts #28, #33, #49. CPT and porosity specs are antagonistic due to severe thickness variations in the part

3. CONCLUSIONS

The challenges of high-rate compression molding were taken to a new level with the TS-RAPM-007 “challenge part” geometry. In particular, the radical variations in thickness have revealed the necessity to face engineering tradeoffs, which had not been experienced before. The main tradeoffs was the antagonism between porosity levels and CPT consistency: there was a need to compromise on one of them in order to achieve the other. And it is only through educated fine tuning of the

process, and accumulated learning from previous studies, that the specifications were met. This is both in terms of:

- CPT / V_f evenness
- Fiber distortion
- Porosity level
- Dimensional accuracy

The mechanisms which enabled achieving those specifications were:

- Material development: CYCOM[®] EP2750 and its high impregnation / low bulk factor was particularly effective in the manufacturing of the challenge part. Its higher resin content also added some forgiveness and repeatability, in comparison to traditional processes resin systems. This is why CYCOM[®] 5320-1 benefitted from added resin via the “Transformer film”, locally applied to support fiber wetting through the process and acting as a liquid shim to guarantee hydrostatic pressure conditions.
- Process: IR preheat cycle and pressure application sequences were particularly influent in maximizing part quality whilst meeting the other specs. The ply geometry parameters combined with spring frame tension and location also played a major role.
- Tooling: The modularity of the spring frame was made possible through improved tool design, alongside with better resin channeling, resin sealing, guiding mechanism, and temperature homogeneity.

Boeing and Solvay have built a deep understanding of the compression molding technology, applied to high rate and low cost aerospace structural parts. The collaborative RAPM program has allowed to generate confidence in our capacity to manufacture highly complex parts with a 30 minutes takt time, and with high degree of control and repeatability. The applications for this technology reside in the civil and unmanned aircrafts industrial landscapes, and will be determinant in enabling cost effective and high volume.

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