Compression moulding of complex parts using randomly-oriented strands thermoplastic composites

LeBlanc, Dominic; Landry, Benoit; Levy, Arthur; Hubert, Pascal; Roy, Steven; Yousefpour, Ali

Publisher's version / Version de l'éditeur:

SAMPLE Seattle 2014, pp. 1-13, 2014-06-05

COMPRESSION MOULDING OF COMPLEX PARTS USING RANDOMLY-ORIENTED STRANDS THERMOPLASTIC COMPOSITES

Dominic LeBlanc[1], Benoit Landry[1], Arthur Levy[1], Pascal Hubert[1], Steven Roy[2], Ali Yousefpour[2]
[1]*McGill University, Department of Mechanical Engineering*
817 Sherbrooke street West
Montreal, QC H3A 0C3

[2]*National Research Council Canada, Aerospace Manufacturing Technology Centre*
5145 Decelles avenue, University of Montreal campus
Montreal QC H3T 2B2

ABSTRACT

Randomly-oriented strands composites offer the possibility to mould complex parts with fast processing cycle. In this paper, effects of pressure and strand size on the quality of a T-shape part were studied experimentally. Low pressure results showed strand size effects on the filling of a 25 mm rib cavity. Filling pressures for three strand sizes were obtained. 10 bar of pressure was enough to fully consolidate parts with smaller strands (3.17 mm × 6.35 mm). Analyzing parts processed at minimal filling pressure showed a void content in the rib feature no greater than 1.2 %. Processing at higher pressure reduced void content between 0.22 % and 0.44 %. Mechanical testing (ASTM D2344) showed similar strength for ribs processed at filling pressure and high pressure. This same trend was obtained for component testing of the T-shape. The main findings show that processing a complex feature at filling pressure P_{fill} was sufficient to reach nominal mechanical properties. This suggested that porosity was not detrimental to the mechanical performance for the given tests.

1. INTRODUCTION

With the need for lightweight structural parts in the aerospace industry carbon-fibre reinforced polymer (CFRP) has been the material of choice for several years. Lately there has been a developing interest in manufacturing complex components with tight radii, variable thickness and rib features using composites. Conventional continuous fibres (CF) offer the mechanical performance but they are very difficult to form. On the other hand, parts with complex features can be injection moulded using lower volume content of short fibres, but they will lack mechanical properties. Lying between these two material configurations are randomly-oriented strand (ROS) composites [1]. ROS composites are obtained from a bulk moulding compound comprised of strands of high fibre volume content unidirectional thermoplastic pre-impregnated tape that are compression moulded. The main advantage of this material is very high formability but also increased mechanical performance. Feasibility to manufacture complex parts with ROS has been recently demonstrated by Greene Tweed [2], Van Wijngarden [5] as well as Eguémann [3]. Simple shapes with constant wall thickness such as flat panels can be processed at 30 bar [1], whereas complex parts with intricate out of plane features are usually processed at above 100 bar [3,4].

While most of the literature studies on ROS composites address mechanical properties [1,6] or part feasibility [1-4], little work has been done on the effect of processing conditions on the forming of complex shapes. Van Wijngarden [5] quantitatively assessed the effect of pressure on the filling of a deep flange using ROS. Identifying the processing window for complex shapes is paramount in order to properly master the manufacturing of ROS composites. This paper focuses on the effect of pressure and strand size on the consolidation of a ROS composite rib feature and resulting mechanical properties. Parts were manufactured with ROS composite and also a hybrid of ROS and unidirectional (UD) prepreg material. The compaction quality was assessed by measuring the void content of each part with the help of X-ray computed tomography (micro-CT). Furthermore, mechanical performance of the rib feature was assessed by short-beam strength testing (ASTM D2344). Additionally, full component testing was performed on the parts to evaluate the effect of processing pressure and strand size.

2. EXPERIMENTATION

2.1 Processing

2.1.1 Material

The material used in this study was a carbon fibre/polyether ether ketone (AS4/PEEK) bulk moulding compound and a unidirectional tape. The fibre volume content is about 59%. Three strand sizes were investigated:

- 3.17 mm × 6.35 mm.
- 3.17 mm × 12.7 mm.
- 6.35 mm × 25.4 mm.

2.1.2 Equipment

The T-shapes were moulded using an instrumented fixture made with two H-13 steel platens of 101.6 mm × 101.6 mm, two inserts and a frame, as shown in (Figure 1). The platens were heated using four 500 W cartridges and controlled using two auto-tuning PID controllers from Watlow. The fixture was mounted on a 250 kN MTS test frame. For the purpose of this study, all tests were performed in load control mode, while platen displacement was acquired. The depth of the rib was 25.4 mm while its thickness was 3.17 mm. The fillet on each insert had a radius of 3.17 mm. Both inserts were bolted together to ensure constant rib thickness for all specimens. To prevent material flow out and produce net shaped parts, a shear edge of approximately 0.076 mm clearance was used between the upper male platen and the bottom frame. The final part is shown in Figure 2b.

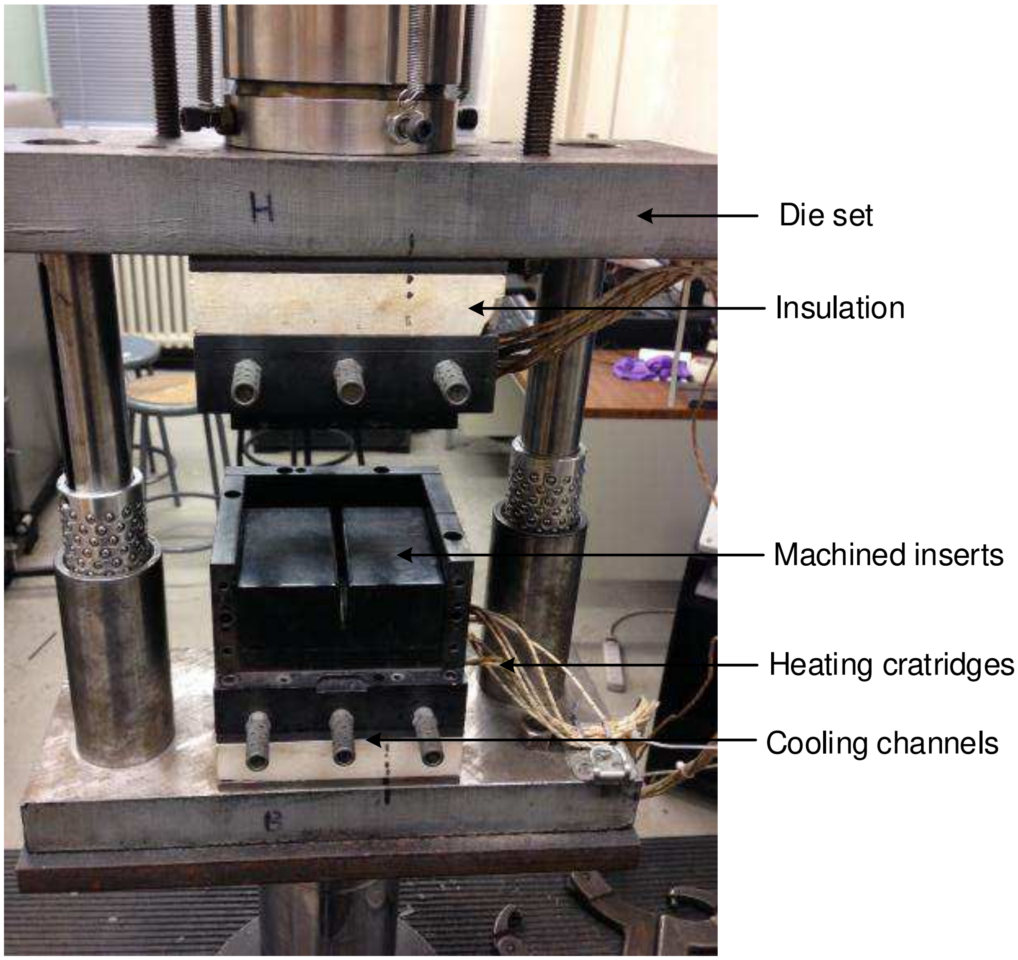

Figure 1. Instrumented fixture.

2.1.3 Procedure

Strands were manually placed in the mould in successive small batches in order to ensure a random in-plane distribution and minimize out-of-plane orientation (Figure 2a). A total of 50g of material was used for every trial. For the hybrid configuration 25 g of UD tape was placed on top the 25 g of ROS material in the mould cavity. In order to maximize material properties in all directions, a [0°/90°] layup was used. Bottom and top platens were heated to 425°C and 400°C respectively. The bottom platen was set to a higher temperature in order to compensate for the thermal mass of the inserts and heat loss around the frame. An initial contact pressure of 10 bar was applied during heating. When processing temperature was reached, full pressure was applied for a dwell of 15 minutes. The fixture was then brought to room temperature at a rate of 10 °C/min using compressed air flowing through cooling channels in the mould platens. A typical processing cycle can be seen in Figure 3. For pressures lower than 10 bar, full pressure was applied during the entire cycle. Pressure between 3 and 70 bar was applied.

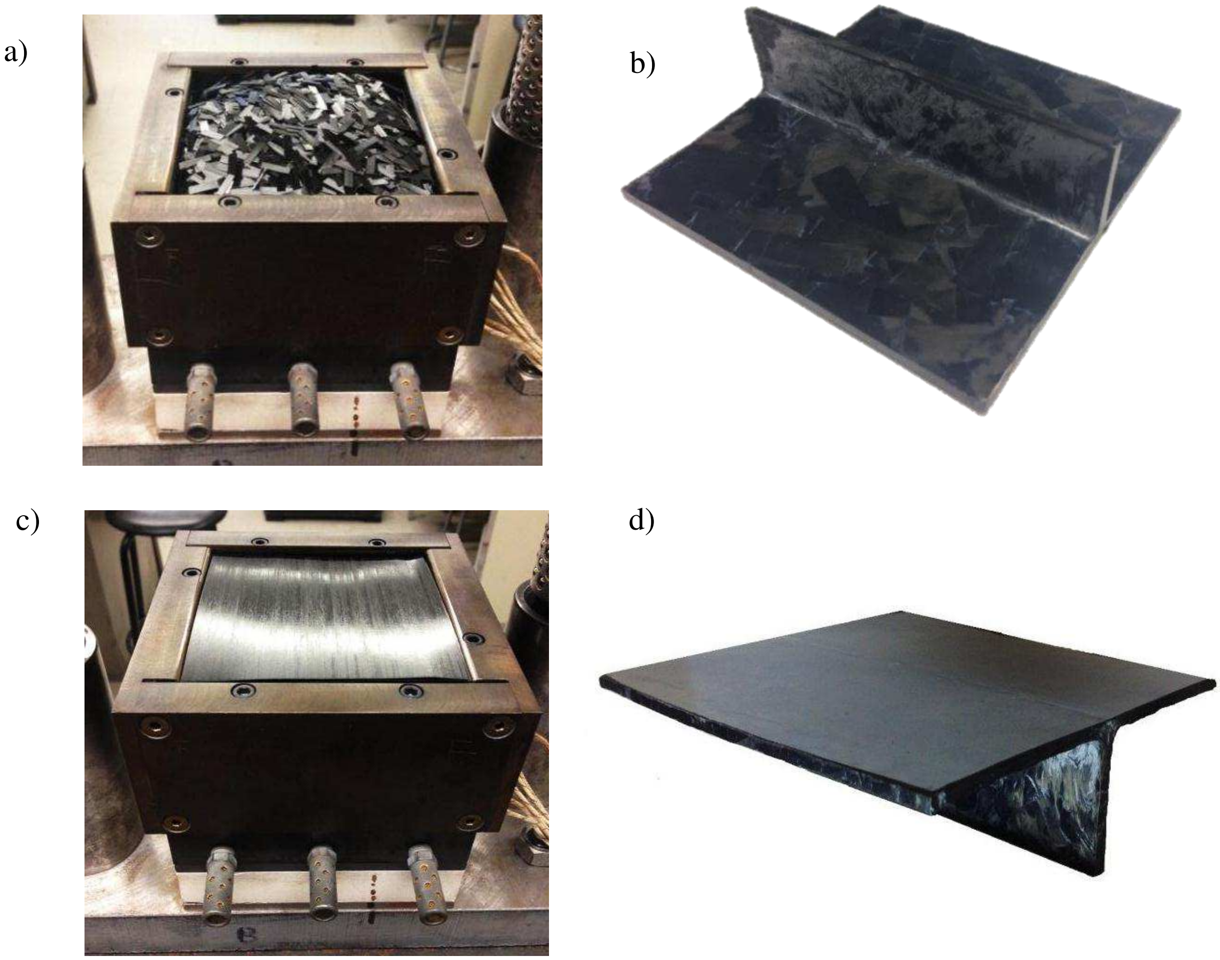

Figure 2. a) Cavity filled with 3.17 mm × 12.7 mm strands. b) ROS T-shape. c) Cavity filled with ROS + UD tape [0°/90°]. d) Hybrid T-shape

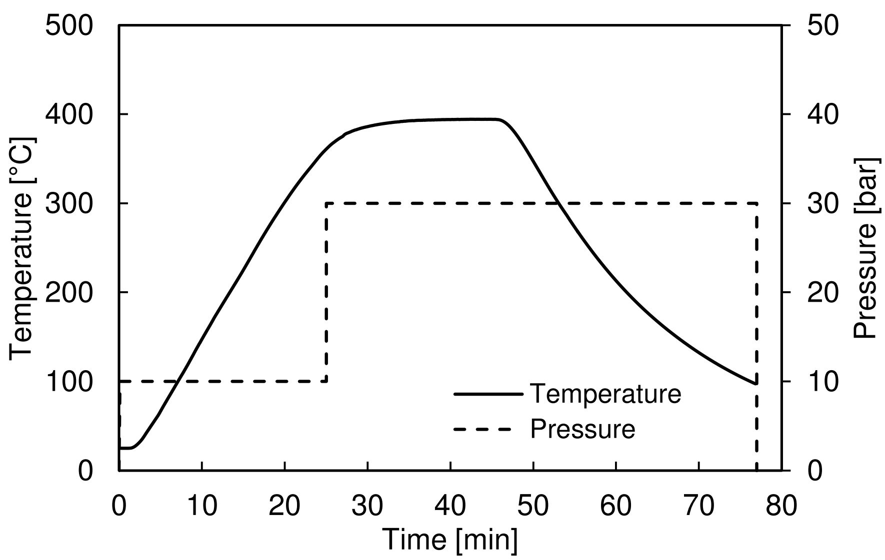

Figure 3. Typical processing cycle.

2.2 Characterization techniques

2.2.1 Rib filling

For all low pressure trials, i.e. below 30 bar, the percentage of the rib filled with ROS was calculated using ImageJ, an image processing software. This method provided an indication of the minimal pressure (P_{fill}) required to fill the 100 mm × 25 mm × 3.17 mm rib cavity.

2.2.2 X-Ray tomography

X-ray tomography is a non-destructive inspection that allows the study of the microstructure of materials. The void content in each part was measured using micro-CT. It has been showed by Little et al [8] that micro-CT is the most accurate and reliable technique for void characterization in composite materials. ROS T-shape specimens were scanned using an XTek HMXST 225 computed tomography system in order to determine the void content in the rib region. All samples were scanned under the same conditions, using an acceleration tension of 45 kV and a current of 345 μA. No filters were used during the scan. The scanning resolution was 15 μm which is in the appropriate range to measure voids in CFRP [8]. CT Pro was used to reconstruct the samples geometry and ORS Visual to visualize and analyze the data. One cross sectional sample of each T-shape was scanned. The samples were taken at the center of the part and their width varied between 2 to 3 mm. Finally, thresholding was used to calculate void content, keeping the parameters constant between parts for consistency in the results.

2.2.3 Short-beam strength

Mechanical performance obtained for each processing conditions were compared by means of their short-beam strength, performed in accordance with the ASTM D2344 standard [7]. Solely the rib section of the ROS T-shapes was tested using this method. In order to assess the in-plane isotropy of the material, two directions were tested as defined in Figure 4. To prevent edge effects, samples were taken at least 12 mm from each side. Sample size was approximately 3.17 mm × 6.35 mm ×19.05 mm as per ASTM D2344 standard. A total of 4 samples were tested per configuration.

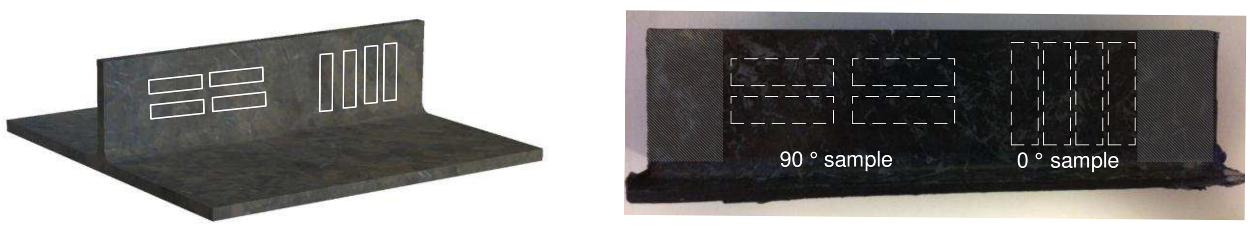

Figure 4. Short-beam strength testing samples.

2.2.4 Component testing

Component testing of the T-shape was also done using a custom rib pull-out fixture shown in Figure 5. T-shapes manufactured with ROS and a hybrid of ROS and UD [0°/90°] were investigated. Specimens were 25 mm wide slices of the full T-shape. In order to prevent edge effects, specimens were cut 12 mm away from the edge of the original T-shape part. Tension was applied on the rib resulting in bending of the flange section between rollers. A displacement rate of 1 mm/min was employed. The diameter of the rollers was 3.18 mm, and a span of 38.1 mm was used. To properly grip the T-shape, tabs were bonded using Loctite 9340 epoxy adhesive. The fixture was installed on a MTS 100 kN equipped with pneumatic grips. A total of three specimens were tested for every processing trial.

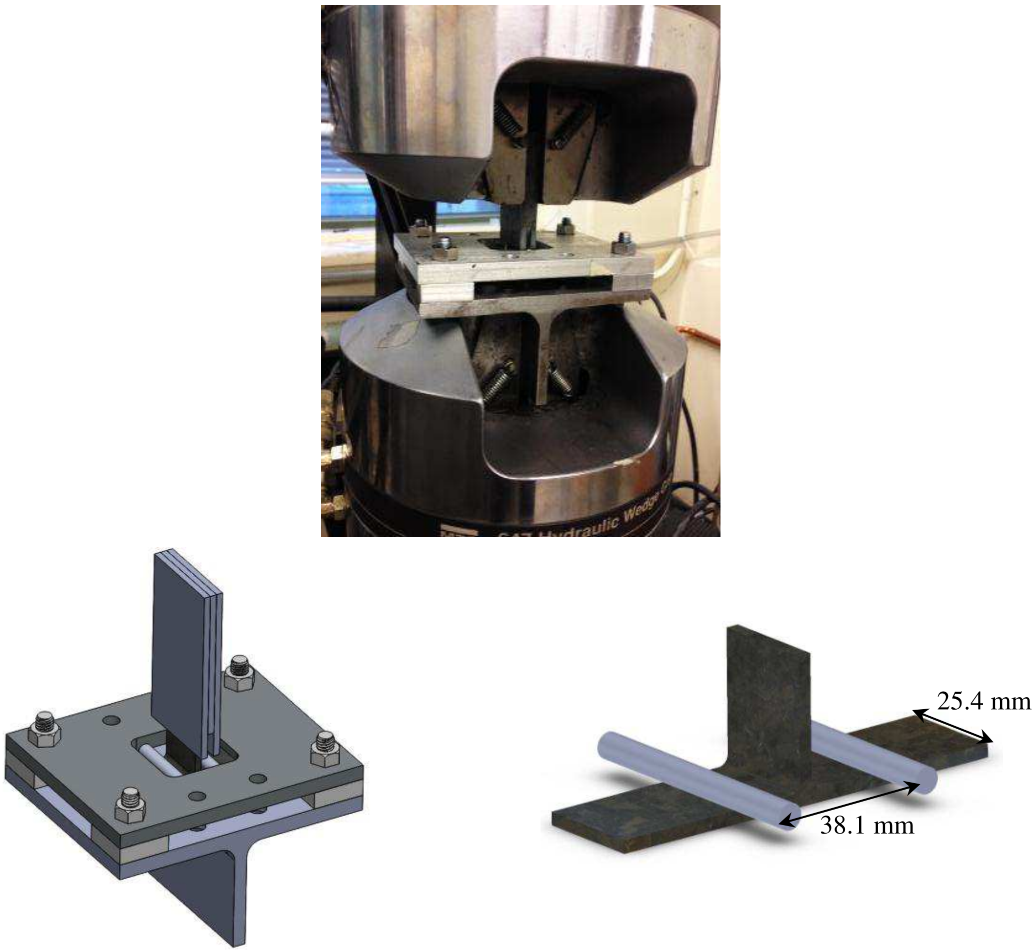

Figure 5. T-shape component test fixture.

2.3 Text matrix

A global test matrix for all of the characterization techniques can be found in Table 1.

Table 1. Processing pressure [bar] for ROS rib characterization.

Strand size	Rib filling	ASTM D2344	Component testing	Micro-CT
3.17 mm × 6.35 mm	3, 5, 10	10, 60, 70	10, 70	10, 20, 60, 70
3.17 mm × 12.7 mm	3, 5, 10, 20	20, 60, 70	20, 70	20, 60, 70
6.35 mm × 25.4 mm	3,5 ,10 ,20 ,30	30, 60, 70	30, 70	30, 60, 70
Hybrid (3.17 mm × 12.7 mm)	N/A	N/A	70	N/A
Hybrid (6.35 mm × 25.4 mm)	N/A	N/A	70	N/A

3. RESULTS

3.1 Rib filling

Rib filling versus processing pressure is plotted in Figure 6 for three different strand sizes. Strand size effects can be observed especially for 3.17 mm × 6.35 mm. The rib processed with the smallest strands undergoes complete filling at a much lower pressure, approximately 10 bar. The largest strand size (6.35 mm × 25.40 mm) necessitated the highest pressure to completely fill the rib cavity. The minimum pressure to fill the rib cavity (P_{fill}) for each of the three strand sizes can be found in Table 2.

Table 2. Rib filling pressure [bar].

Strand size	P_{fill} [bar]
3.17 mm × 6.35 mm	10
3.17 mm × 12.7 mm	20
6.35 mm × 25.4 mm	30

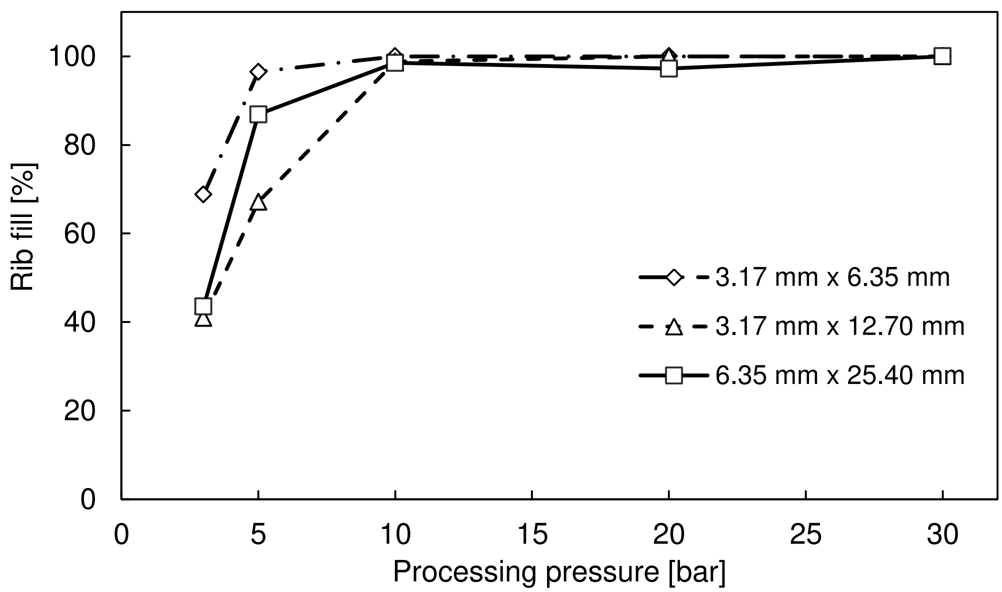

Figure 6. Low pressure ROS rib filling.

The flow front profiles of in the rib feature at low pressure can be seen in Figure 7. In this pressure range, material flow is more important in the center than along the edges. This can be explained by the fact that during the processing dwell, a temperature difference in the range of 15 °C was measured between the center of the rib and its edges. The ROS material at higher temperature had a lower viscosity, thus resulting in the higher flow observed.

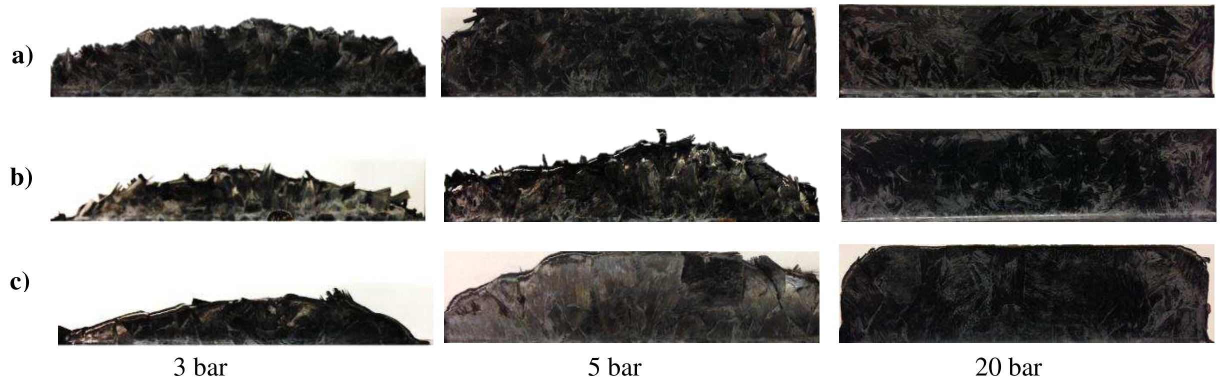

Figure 7. Low pressure rib profiles. a) 3.17 mm × 6.35 mm. b) 3.17 mm ×12.70 mm. c) 6.35 mm × 25. mm.

3.2 Void content analysis

All ribs processed at P_{fill} (Table 2) and higher were scanned using micro-CT. A three-dimensional rendering of the rib is shown in Figure 8. A representative cross section of a scanned rib is shown in Figure 9. Although micro-CT is a volumetric analysis, only a single slice of the scanned part is represented in the figure. The volumetric void content measured from micro-CT for the various processing pressures and strand sizes can be found in Figure 10. The measured void content at P_{fill} for strand sizes from smallest to largest was 1.2 %, 0.8 % and 0.6 % respectively. Note that P_{fill} is a material dependant pressure and varies with strand size. In most cases, voids were not distributed homogeneously, as localized higher void content regions were observed. As pressure was increased to 70 bar, the void content reduction was apparent for all strand sizes. The lowest void content, 0.17 % was measured for the 6.35 mm × 25.4 mm strand size processed at 60 bar. The void content at high pressures was inversely proportional to strand size.

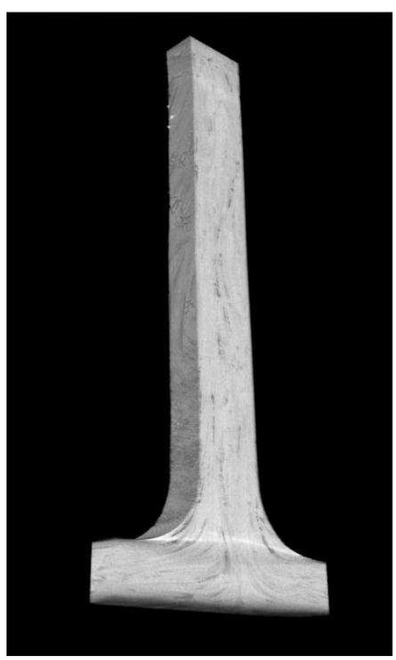

Figure 8. Micro-CT rib three-dimensional rendering.

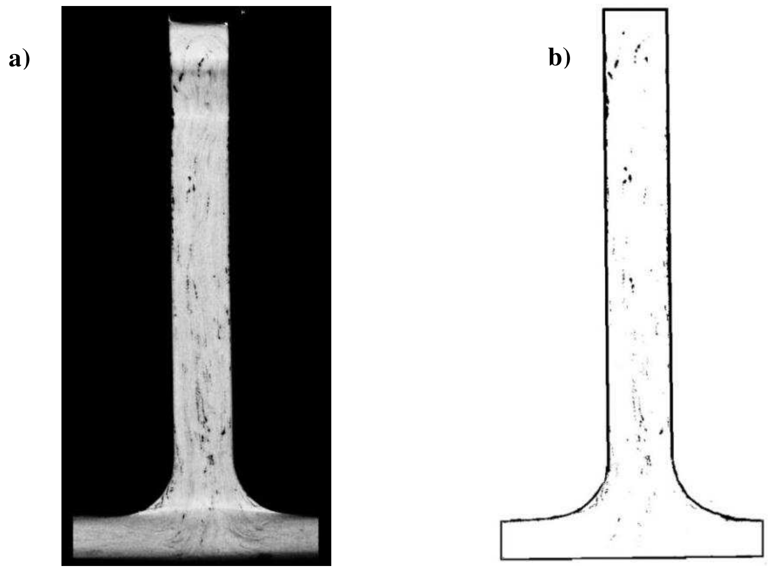

Figure 9. a) Micro-CT rib cross section processed at 30 bar, 3.17 mm × 12.7 mm strand size. b) 2-D representation of voids obtained with thresholding.

In this study, independent of the processing pressure, a white surface discoloration on the rib area was always apparent (Figure 2). These regions had a mat and rough surface, as opposed to the flange of the T-shape which was smooth and shiny. As mentioned by Landry and Hubert [9], these white regions were found to be an artifact of a loss of pressure during cooling that occurs when the pressure applied on the material during cooling is not sufficient to compensate for the transverse material shrinkage. Due to the geometry of the T-shape and its mould, no pressure could be applied in the transverse direction of the rib feature during cooling, hence a loss of pressure, resulting in a void content between 0.2 % and 0.4 % for pressure between 60 and 70 bar.

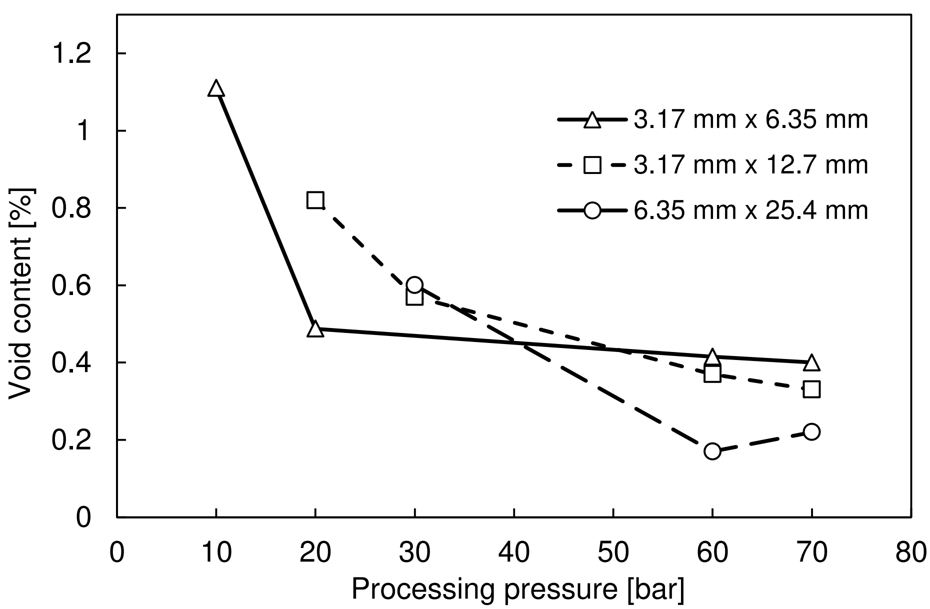

Figure 10. Rib section void content.

3.3 Mechanical testing

3.3.1 Short-beam strength

The results from short-beam strength testing of the rib section are presented in Figure 11. Flat panels were also manufactured to create a baseline for comparison for each strand size and were moulded at 70 bar. The results show that the normalized strength measured along the flow direction (0°), and perpendicularly (90°), were similar. This suggests that there was no significant mechanical anisotropy and limited flow induced orientation. Only a slight difference was observed for the 3.17 mm × 12.7 mm strands, where the transverse strength was noticeably smaller than the longitudinal strength at 60 and 70 bar. These small and slender strands probably resulted in enhanced flow and orientation. The short-beam strength of the rib sections processed under pressure P_{fill} (Table 2), 60 bar and 70 bar were also similar. These results suggested that processing at lower pressure, simply allowing a cavity fill might be sufficient to obtain nominal mechanical properties. A less constrained processing window could therefore exist compared to existing high pressure processing [3-5]. Averaging the short-beam strength from smallest to largest strand size (Figure 12), a reduction of 12 %, 8 % and 7 % was observed between the rib section and baseline results.

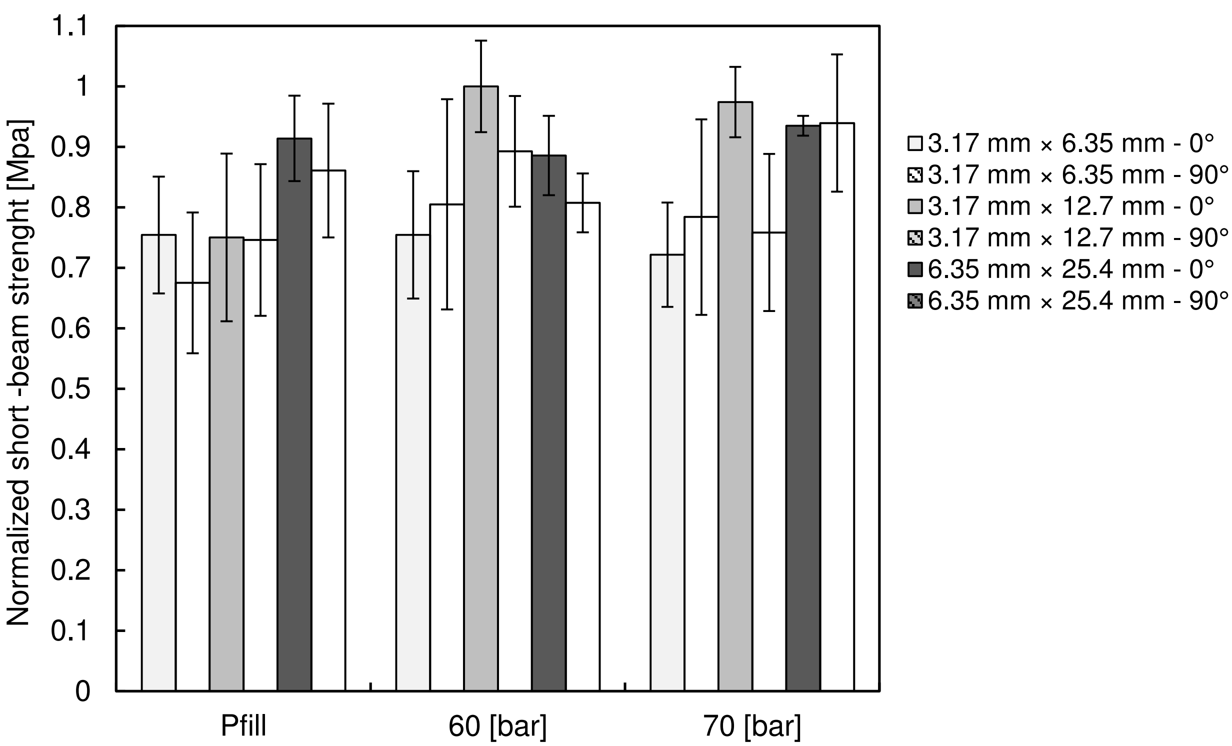

Figure 11. Normalized short-beam strength of rib sections measured in the direction parallel (0°) and transverse (90°) to flow direction.

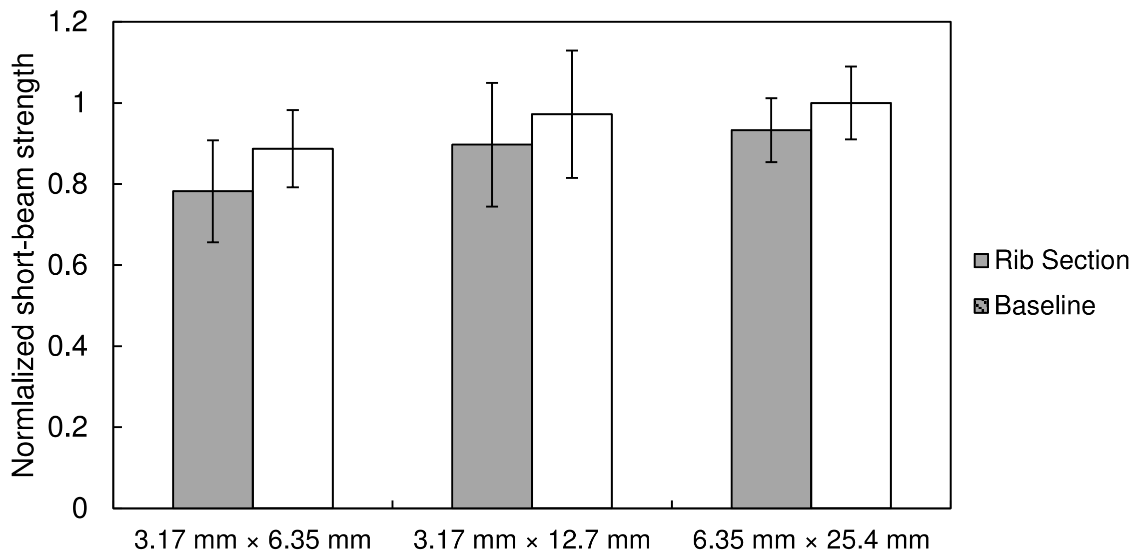

Figure 12. Averaged short–beam strength of rib sections.

3.3.2 Component testing

The component testing results are shown in Figure 13. The strength was measured based on the net section of the rib. The failure for all T-shapes occurred near the radius feature, where delamination of the strands was observed near the surface of the part, as shown in Figure 14. Figure 13 shows that the normalized strength of the components processed at P_{fill} and 70 bar were similar. This shows that the optimal component strength can be obtained with pressure as low as P_{fill}. Furthermore, effect of strand size was not apparent. A possible explanation for the similarity in these results was a high stress concentration at the radius (K_t ~ 5) for this loading configuration. This stress concentration is localized and thus initiated failure independently of strand size. For the hybrid configuration, the strength was increased (45 %) as the in-plane stiffness of the flange was increased with the [0°/90°] layup.

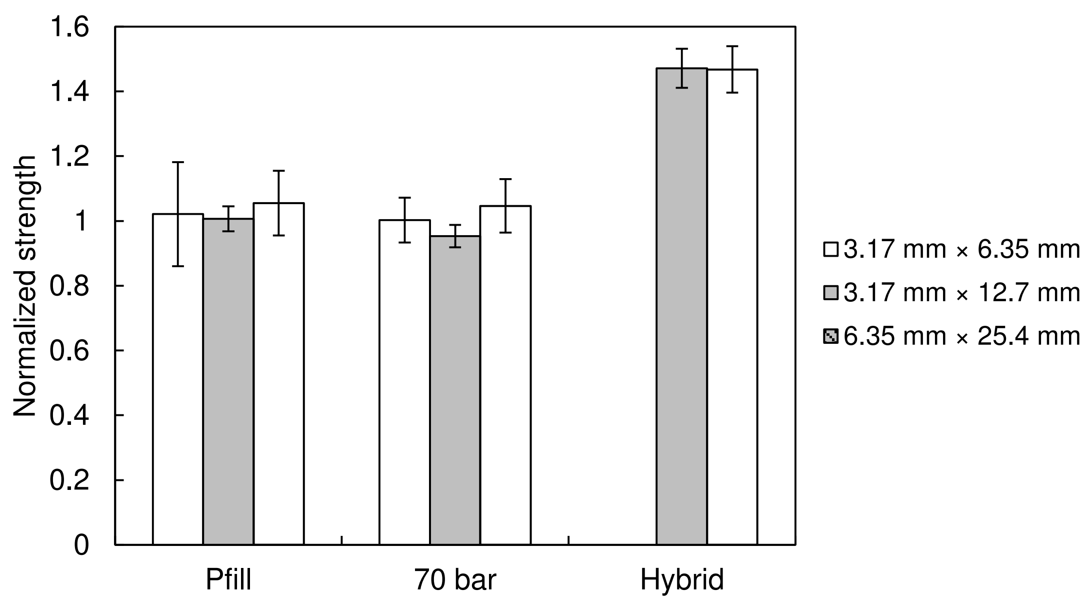

Figure 13. Component testing Results. Hybrid parts processed at 70 bar.

a) b)

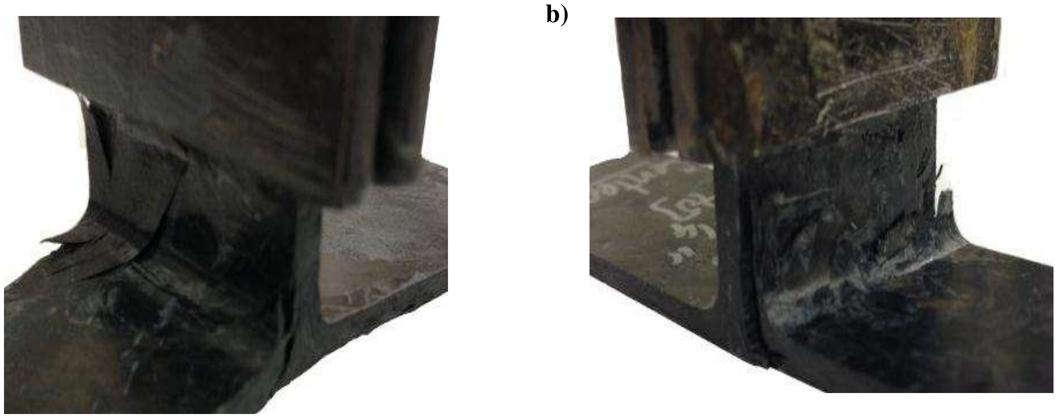

Figure 14. ROS component failure. a) 6.35 mm × 25.4 mm strands. b) 3.17 mm × 6.35 mm strands.

4. CONCLUSIONS

This project investigated the effect of processing conditions on the quality of a complex ROS part. The work resulted in the following findings:

- Filling pressure, P_{fill}, of a 25.4 mm deep rib cavity was obtained and showed strand size dependence.

- A processing window of void content vs. processing pressure was obtained. The void content of a consolidated rib at P_{fill} was below 1.2 % for all tested strand sizes. Increase in pressure lowered void content to a range between 0.2 % and 0.4 %.

- Averaging the short-beam strength of the strand sizes, from smallest to largest, a reduction of 12 %, 8 % and 7 % was observed between the rib section and baseline results. No significant difference was observed between the strength measured in the direction parallel (0°) and transverse (90°) to flow direction.

- Component testing showed similar results for all strands sizes at P_{fill} and high pressure. Use of hybrid configuration increased strength by about 45 %.

The main findings show that processing a complex feature at filling pressure P_{fill} was sufficient to reach nominal mechanical properties. This suggested that porosity was not detrimental to the mechanical performance for the given tests.

5. ACKNOWLEDGEMENTS

The authors would like to greatly acknowledge financial support provided by the industrial partners: Bell Helicopter Textron Canada Limited, Bombardier Inc., Pratt and Whitney Canada Corp, Marquez Transtech Limited, Delastek Inc. and Avior Integrated Products Inc. B.L thanks the National Sciences and Engineering Research Council of Canada (NSERC). D.L and B.L thank McGill University for financial assistance.

6. REFERENCES

1. Selezneva. M, Picher-Martel. G.-P, Landry. B, Trudel-Boucher. D, Roy. S, Khoun. L, Hojjati. M, Lessard. L, Hubert. P. "Compression moulding of discontinuous-fibre Carbon/PEEK composites: study of mechanical properties", *Proceedings of International SAMPE Tech. Conf.* Baltimore, USA, 2012. Society for the Advancement of Material and Process Engineering.
2. Xycomp ® DLF high-performance thermoplastic composites aerospace brackets.
3. Eguémann. N, Giger. L, *et al.* "Manufacturing and recycling of complex composite thermoplastic parts for aerospace applications". *Proceedings of SAMPE Europe SETEC 12 International Conference,* Lucerne, Switzerland, 2012. Society for the Advancement of Material and Process Engineering.
4. Eguémann. N, Giger. L, *et al.* "Compression moulding of complex parets for the aerospace with discontinuous novel and recycled thermoplastic composite materials". T*he 19th International Conference on Composite Materials*, Montreal, Canada, 2013.
5. Van Wijngaarden. M, Jongbloed. A. M *et al.* "Thermoplastic compound compression molding." *Proceeding of the International SAMPE Symposium and Exhibition,* Seattle WA, USA, 2010. Society for the Advancement of Material and Process Engineering
6. Feraboli. P, Peitso. E, *et al.* "Characterization of prepreg-based discontinuous carbon fiber/epoxy systems". *Journal of Reinforced Plastics and Composites*, Vol. 28, No. 10, pp 1191-1214, 2009
7. ASTM D2344-07. Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates1. *Annual Book of ASTM Standards*, Vol. 15.03, 2007.
8. Little. J, Yuan. X, M.I Jones, "Characterization of voids in fibre reinforced composite material". NDT&E International 46, pp.122-127, 2011
9. Landry. B, Hubert. P. "Processing effect on the damage tolerance of randomly-oriented strands thermoplastic composites". *The 19th International Conference on Composite Materials*, Montreal, Canada, 2013.