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DEVELOPMENT OF AN EPOXY CARBON FIBER REINFORCED ROOF FRAME USING THE HIGH PRESSURE RESIN TRANSFER MOLDING (HP-RTM) PROCESS

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Abstract

Composites technology for the automotive market continues to advance rapidly. Increasing knowledge of composite design, simulation tools, new materials and process equipment are all contributing to make composites better performing and more affordable for mass-produced vehicles. In particular, the high pressure resin transfer molding (HP-RTM) and related liquid compression molding (LCM) processes are enabling manufacturers to produce complex composite parts at shorter and shorter cycle times.

This paper describes the development of an epoxy carbon fiber roof frame targeted for future vehicle production. Several composite processes were considered for the roof frame. The case illustrates that when the (product) design, material and process are considered together, a high-performing, cost-efficient part can be produced. The resulting carbon fiber roof frame met all OEM performance requirements and economic targets while weighing 44% less than the original design in magnesium and 32% less on the overall assembly. The part was the first HP-RTM part successfully demonstrated in North America and stands as a model for future lightweighting developments.

Of equal significance, the development process for the part involved a unique collaboration of companies throughout the automotive composites value chain. Each company contributed their particular expertise to the project including resin technology, reinforcement solutions, engineering analysis, process simulation, tool construction, preforms and molding. The collaboration enhanced the speed and technical success of the overall development.

Background

A particular model of an OEM sports car offers several removable (i.e. targa) roof options to its retail customers. Customer options include a body color painted roof made with a lightweight sheet molding compound (SMC), a clear polycarbonate roof and an exposed weave carbon fiber offering. (Figure 1.) Shared by all three configurations is a cast magnesium frame that provides the structural support for the completed roof assembly. Adhesive is used to bond the exterior panel to the structural roof frame. (Figure 2.)

Figure 1: Exterior View of Carbon Fiber Reinforced Removable (i.e. targa) Roof Assembly for an OEM Sports Car. The assembly consists of an exposed weave Class A panel bonded to a structural high pressure die cast magnesium frame (shown below).

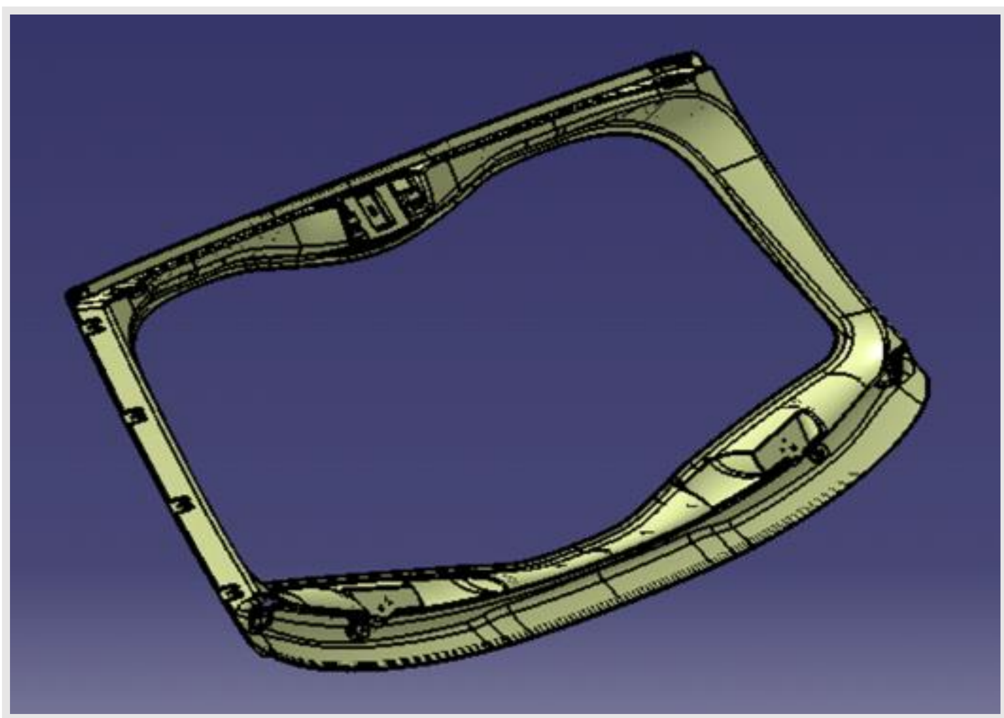


Figure 2: CAD View of the Original Magnesium Roof Frame.

The project goal was to replace the lightweight magnesium roof frame with a lighter weight epoxy carbon fiber design capable of being produced at high volume.

For several years, the vehicle manufacturer and tier 1 producer of the carbon fiber reinforced plastic (CFRP) version of the roof assembly discussed the possibility of converting the cast magnesium roof frame to an even lighter weight epoxy carbon fiber design using advances in technology for the resin transfer molding process.[1] The exposed weave carbon fiber offering would have both a carbon fiber panel and CFRP frame construction. If successful on the exposed weave carbon fiber option, the carbon fiber frame might also replace the magnesium frame on the other roof options offered on the vehicle. Motivations for converting the magnesium roof frame to a carbon fiber design included those shown in Table I.

Table I: OEM Motivations to Replace the Magnesium Roof Frame with an Epoxy CFRP Design.

Feature / Attribute	Benefit
Reduced part weight.	Easier for on / off customer handling
Improved part stiffness and dimensional stability	Eliminates "hand finessing" production line issues frequently encountered with cast magnesium part
Reduced weight from a high location on the car	Lower vehicle center of gravity for improved speed, performance and fuel economy
Roof frame design that reduces an excessive bond gap on the CFRP roof option	Improved performance and reduced cost due to less use of adhesive
Roof frame geometry is ideal candidate for the high pressure resin transfer molding process.	HP-RTM/LCM technology enables high volume production (e.g. >50,000 p.a.) of the roof frame as well as other composite part designs
HP-RTM is safe and proven technology for producing epoxy CFRP components	Eliminates safety and supply chain concerns related to die cast magnesium parts [2]

Forming the Project Team

An agreement to undertake the project was established amongst the OEM, tier 1 molder (Plasan Carbon Composites[3]) and thermoset resin system supplier (Hexion[4]). Cost and performance targets were provided by the OEM. The tier 1 and Hexion agreed to co-manage the project with each sharing costs, engineering knowledge and technical expertise. Fundamental to the success of the project was use of a newly-developed family of fast curing HP-RTM/LCM resins from Hexion whose cure times are capable of supporting high volume production programs. The tier 1 and Hexion recruited additional partners to the project team based on each company's real world experience with the high pressure RTM process. The supplier companies provided expertise in APQP project management, resin and binder technology, reinforcements, part design and analysis, preforming, tool design, process simulation, production and assembly system designs. In all, ten supplier companies plus the OEM participated to the project.[5]

Business Case to Determine Preform Assembly Approach

Experience dictated that it was important to establish first how the part would be constructed from the preforming perspective. The geometry of the roof frame called for one of two general approaches for assembling the preform. The first approach was to cut a "hole" from a single fabric stack, leaving the sides, and then molding the frame. The other approach was to assemble the individual "sides" of the frame, and then mold the frame. The team referred to these approaches as the "donut hole" versus "bacon strip" designs, respectively, each approach having its advantages and disadvantages. (See Table II.)

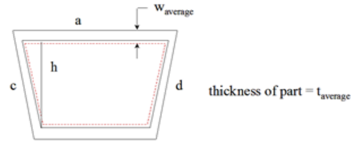
Table II: Advantages and Disadvantages of Different Roof Frame Preform Assembly Approaches

Preforming Approach	Advantages	Disadvantages
"Donut Hole" (Preform Cut from Single Plies)	• No overlapping joints • Less likelihood of "misaligned" preform • Faster preforming	• Large (costly) area of material cut from center of frame • Potentially difficult to form fabric to contours
"Bacon Strip" (Sides Assembled to Make Preform)	• More efficient use of material; material used to construct sides of frame only.	• Overlapping joints must be created to form frame • More assembly steps • Greater likelihood of "misaligned" preforms

The team's comparison concluded that the "bacon strip" preforming approach was more economical than the "donut hole" approach despite the higher likelihood of misalignments or scrap when creating the frame joints. Scrap material cut from the center of the donut hole approach also confirmed to be too great to offset from a cost perspective. Figure 3 shows the comparison of the two preforming approaches. Figure 4 shows the bacon strip preform layup concept along with its calculated scrap rates. Figure 5 gives a basic schematic of the overall preforming and molding process for the roof frame.

Roof Frame Preforming Model
Input & Summary Page
Last Updated: October 30, 2014

	Base Value	Input
Geometry		
Outer Width (inches)	50.0	50.0
Outer Height (inches)	34.0	34.0
Inner Width (inches)	36.0	36.0
Inner Height (inches)	16.0	16.0
Reinforcement		
Ply weight (grams per square meter)	150	150
Ply thickness (mm)	0.2	0.20
Number of plys	8	8
Reinforcement cost per sq. meter (complete laminate)	$8.50	$8.50
Scrap / Loss Rates		
Scrap Rate / Loss Single-Piece Cut-Out Approach	5.0%	5.0%
Scrap Rate / Loss Multi-Piece Assembled Approach	10.0%	10.0%
Process		
Cut-Out Approach		
Time to cut shaped plys (seconds)	18	18
Time to move plys from cutting table onto conveyor (seconds)	15	15
Time to transfer of stabilized preform(s) to RTM tool (seconds)	30	30
Assembled Approach		
Time to cut shaped plys (seconds)	120	120
Time to move plys from cutting table onto conveyor (seconds)	60	60
Time to transfer of stabilized preform(s) to RTM tool (seconds)	120	120
Cure Time		
Cure Time (seconds)	120	120



Result

	Cut-Out Approach	Assembled Approach
Material Cost per Part	$78.51	$54.79
Labor Cost per Part	$7.56	$9.28
Subtotal	**$86.06**	**$64.07**
Delta	*($22.00)*	---
	34%	
2 x 10hr @ 5 days	23,816	**19,401**
2 x 10hr @ 6 days	28,579	23,281

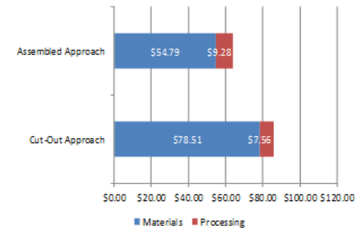


Figure 3: Composite Roof Frame (Directional) Preforming Cost Model Comparing "Donut Hole" Approach (cut-out from single fabric ply) to "Bacon Strip" Approach (sides of frame are assembled from individual fabric pieces.)

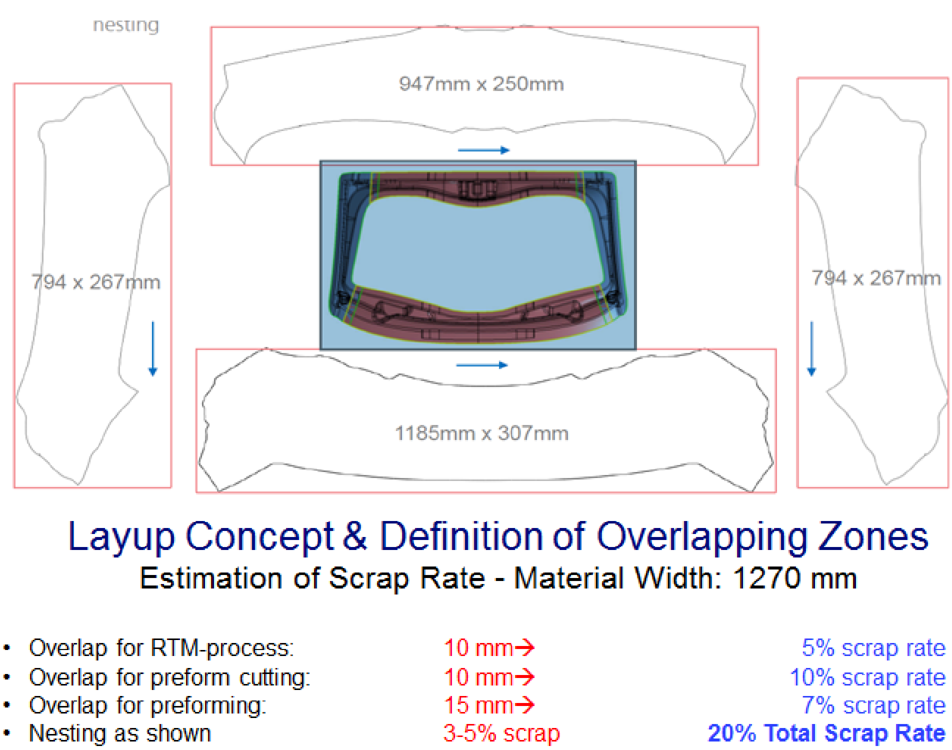


Figure 4: Roof Frame Preform Flattening of Fabric with CATIA® CPD (Composite Product Design) for Evaluation of Nesting and Scrap Rate.

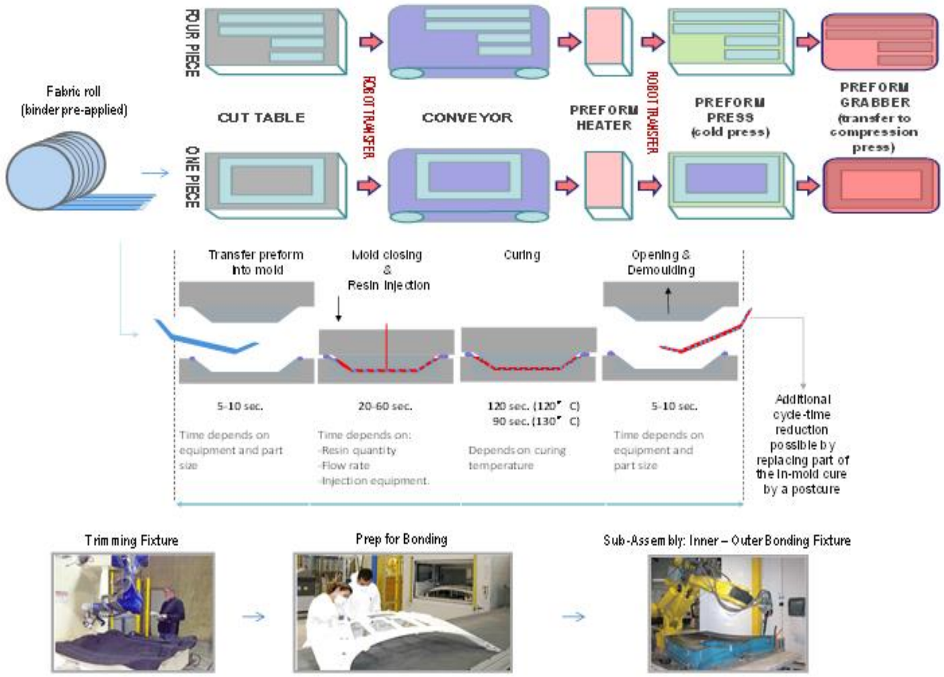


Figure 5: Schematic of Roof Frame HP-RTM Manufacturing Process, Bonding to Outer Panel.

Part Design

Having established the basic preform and processing approach, the team's next step was to tackle the detailed part design. Engineering and design analyses were performed by Forward Engineering, GmbH[6] and iXent GmbH[7] of Munich, Germany. Attachment points were resurfaced to make them more RTM process-friendly. All radii, for example, were increased to a minimum of 4 mm or wider where possible, overlap zones for the non-crimp fabric (NCF) reinforcement were determined and potential trouble spots identified for draping. (See Figures 6 and 7). The team conducted more than twenty design iterations to find optimal solutions satisfying the OEM design requirements for stiffness, deformation, and natural frequency targets at the least weight and cost. (See Figure 8). Table III shows the frame only analyses using combinations of 150 and 300 gram per square meter (gsm) non-crimp reinforcing fabrics provided by Sigmatex Carbon Textile Solutions[8] and Zoltek Corporation.[9]

The team's analysis found the possibility of reducing the frame-only weight by up to 62%. Further reduction on the overall roof assembly could be possible if the stiffness of the panel were also taken into consideration. Draping analyses and production considerations favored the use of 150 gsm fabric for the frame. The overall design could be reduced by an additional 0.9 kilograms if the exterior panel ply configuration changed to a $[+30^\circ_{150}\ -30^\circ_{150}\ 90^\circ_{190}]$s layup versus its current $[0^\circ_{190}\ 90^\circ_{190}\ 0^\circ_{190}]$s. However, the team settled on a [+30° 90° -30° 0°]s 150 gsm layup for the frame in combination with the currently produced exposed weave CFRP exterior panel. The weight savings of the final design replacing the cast magnesium frame with an epoxy carbon fiber design was 1.8 kg. (32%) on the total assembly comprehending a 44% weight savings on the frame itself and a reduction of more than 1 lb. (0.75 kg) in the use of adhesive due to a reduced bond gap between the CFRP frame and panel. See Table IV and Figure 9.

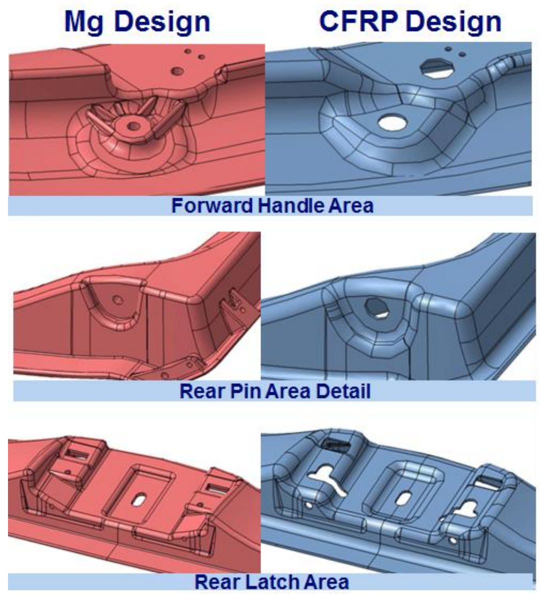


Figure 6: Redesign of Magnesium Roof Frame Features to Facilitate CFRP HP-RTM Manufacturing.

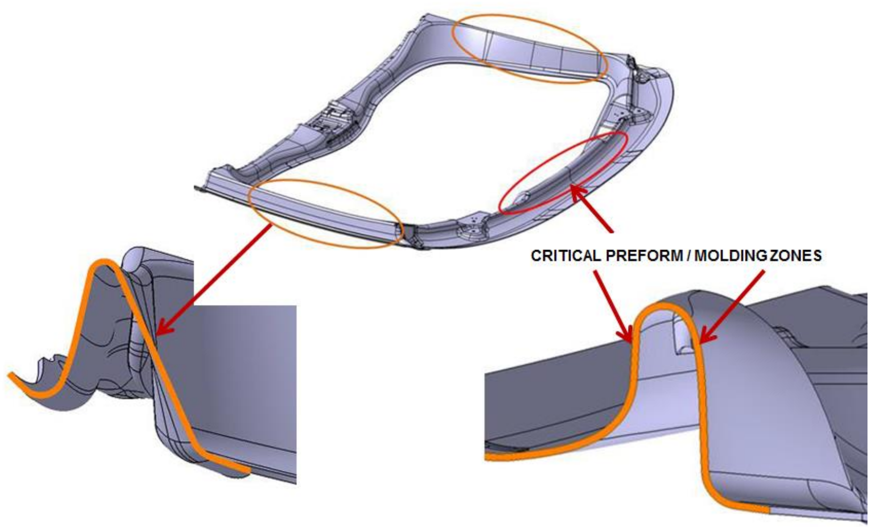


Figure 7: Identification of Challenging Preform Areas / Molding Zones of CFRP Part Design.

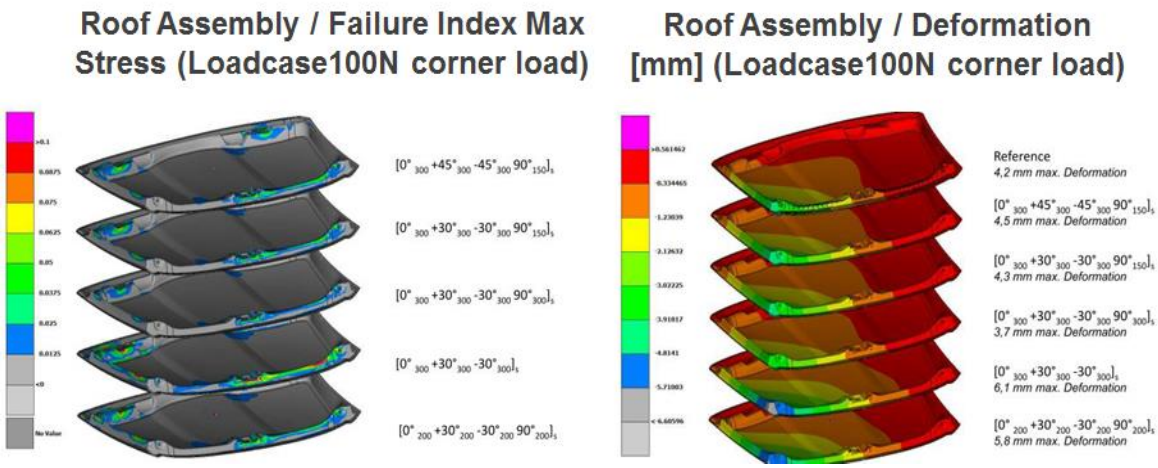


Figure 8: Finite Element Analysis Iterations to Identify Optimum CFRP Roof Frame Design vs. Assembly Stress and Deformation Limits.

Table III: Summary of Predicted Corner Load Deformation as a Function of Laminate Design.

Frame Material	Variant	Wall Thickness (mm)	Roof Frame Mass (kg.)		Corner Load Deformation (mm)	
Magnesium	Reference	~3 mm nominal	2.740	100%	4.2	100%
CFRP	Initial Design: 300 gsm plies [0°,+30°,-30°]s.	1.8	1.446	53%	6.1	145%
CFRP	300+150 gsm plies: $[0°_{300},+30°_{300},-30°_{300},90°_{150}]s$	2.1	1.687	62%	4.3	102%
CFRP	300+150 gsm plies: $[0°_{300},+45°_{300},-45°_{300},90°_{150}]s$	2.1	1.687	62%	4.5	107%

Table IV: Projected Weight Savings of CFRP Part Design.

Frame Material	Outer Panel Type	Description	Total Mass with Hardware w/o Adhesive	Weight Savings (%)
Magnesium (Mg) ~3.0 mm nominal	CFRP; Current Skin $[0^\circ_{190}\ 90^\circ_{190}\ 0^\circ_{190}]s$	Current Mg/CFRP Roof	4.9 kg (3.2 kg + 1.7 kg)	Reference
CFRP Lightweight $[+30^\circ_{150}\ 90^\circ_{150}\text{-}30^\circ_{150}\ 0^\circ_{150}]s$	CFRP; Current Skin $[0^\circ_{190}\ 90^\circ_{190}\ 0^\circ_{190}]s$	Lightweight Frame with current outer skin	3.5 kg (1.8 kg + 1.7 kg)	Frame - 44% Assembly - 29%
CFRP Lightweight $[+30^\circ_{150}\ 90^\circ_{150}\text{-}30^\circ_{150}\ 0^\circ_{150}]s$	CFRP; Optimized $[+30^\circ_{150}\text{-}30^\circ_{150}\ 90^\circ_{190}]s$	Fully Optimized Lightweight Roof Assembly	2.6 kg (1.2 kg + 1.4 kg)	Frame - 62% Assembly - 47%

Attribute	Baseline (Mg Frame / CF Skin)	Redesign CF Frame / CF Skin	Weight Savings
Frame Mass (kg)	**2.74**	**1.69**	**38%**
Panel Mass (kg)	1.66	1.66	---
Adhesive Mass (kg)	0.91	0.16	82%
Hardware (kg)	0.40	0.40	---
Total Assembly (kg)	**5.71**	**3.91**	**32%**
F_n – Assembly (Hz)	34.5	~34.0	

Additional Opportunities

- Optimized outer skin
- Structural adhesive
- Hardware / attachment build-ups

Final Weight Savings: 1.8 kg (32%)

**Final design selected was not fully optimized design. Design assumes carryover outer panel versus potential for optimized redesign. Final weight includes hardware and lower adhesive mass due to reduced bond gap.*

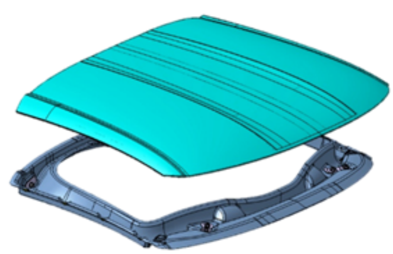


Figure 9: Projected Weight Savings of Final Redesigned Roof Frame – Total Assembly.

Process Simulation and Mold Tool Development

An extremely useful tool for the rapid development of composite parts is mold flow process simulation. Software such as the ESI Group's PAM-COMPOSITES simulation suite[10] is especially useful for continuous fiber thermoset molding where numerous factors such as permeability of the reinforcement, time and temperature-dependent resin properties must be taken into account. While there is no substitute for real world behavior, computer simulations can detect potential issues early in development saving time and money compared to "traditional" methods. The team took advantage of the PAM-RTM simulations in evaluating the composite roof frame design.

Work began right away constructing the HP-RTM mold for the roof frame once the part design was complete. Tool design was led by Alpex Technologies, GmbH[11], an experienced maker of HP-RTM tools and expert about such aspects as the tool mating details, seal design, injection schemes and temperature management. Process simulations were conducted in parallel with the tool build; each activity keeping the other informed along the way.

The team's initial injection scheme had a single center injection point with runners feeding resin to each of the four sides of the roof frame and flowing from the inner to outer diameter of the part. At first, the simulation showed difficulty filling the complete part. Resin filled portions of the frame sides but then had difficulty to flow beyond the overlap areas leaving some portions at the outer edges of the part unimpregnated. The team made several simulation iterations before it occurred rather than fighting the resin at the overlap areas, perhaps filling these areas first would be a better approach. By changing placement of the runners and vacuum locations, the team arrived at an approach that essentially "flooded" the overlap areas of the roof frame first. Then, resin would flow to the outer edges of the part with less resistance. The tool was changed accordingly and this approach proved to be successful in the actual molding trials. (See Figure 10.)

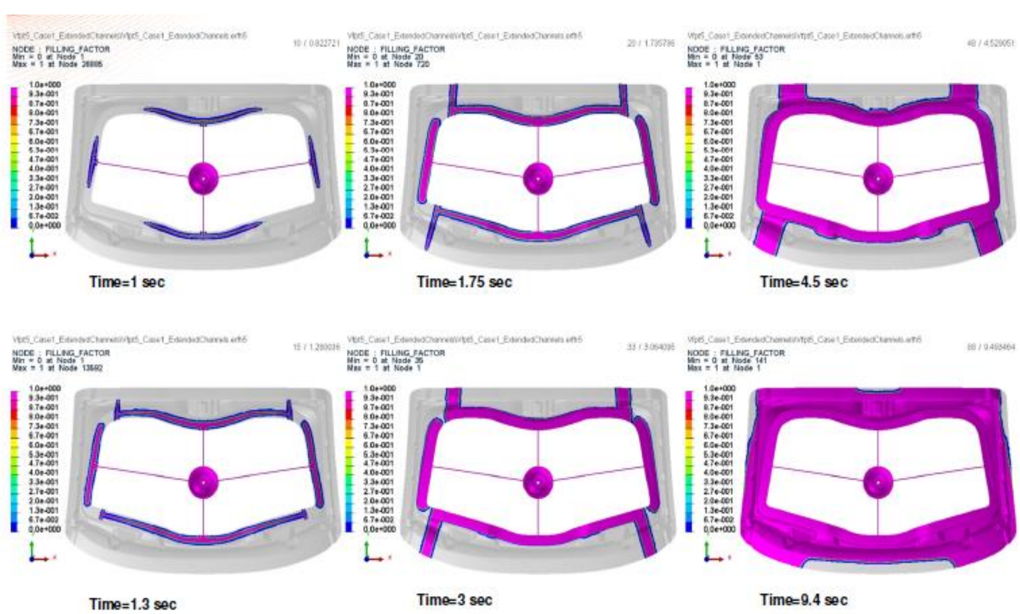


Figure 10: ESI Group's PAM-RTM Filling Simulation of Roof Frame Comprehending Cure Characteristics of the EPIKOTE™ / EPIKURE™ TRAC 06170 Fast Cure Epoxy Resin System.

Preform Production and Molding Trials

As only a limited number of parts were needed for molding trials and testing, the roof frame preforms were made by "hand" using soft tools. The preforms required tolerances to within +/- 1.0 mm to mold successfully. EPIKOTE™ TRAC 06720, a curable powder binder designed for the HP-RTM process, was manually applied to the layers of 150 gsm non crimp fabric. The fabric preforms were formed under heat in an aluminum tool (Figure 11) into their design shapes, then received final trimming with a robotic ultrasonic cutter provided by Diffenbacher[12] to ready the four overlapping preform sections for molding. (See Figures 12 and 13).

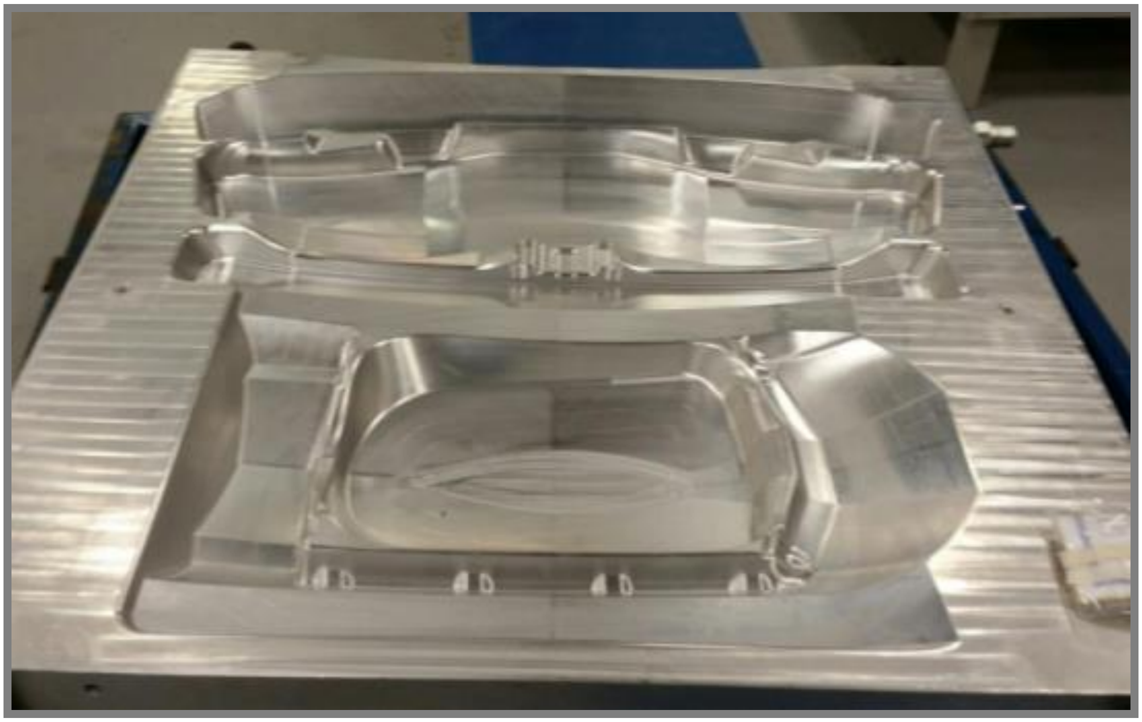


Figure 11: Heated Aluminum Tool for Forming / Stabilizing CFRP Roof Frame Preforms.

Figure 12: Robotic Roof Frame Preform Precision Trimming Station (Diffenbacher). Stabilized and Trimmed Preforms Ready for Molding

Figure 13: Preforms Sections Assembled Into Complete Roof Frame.

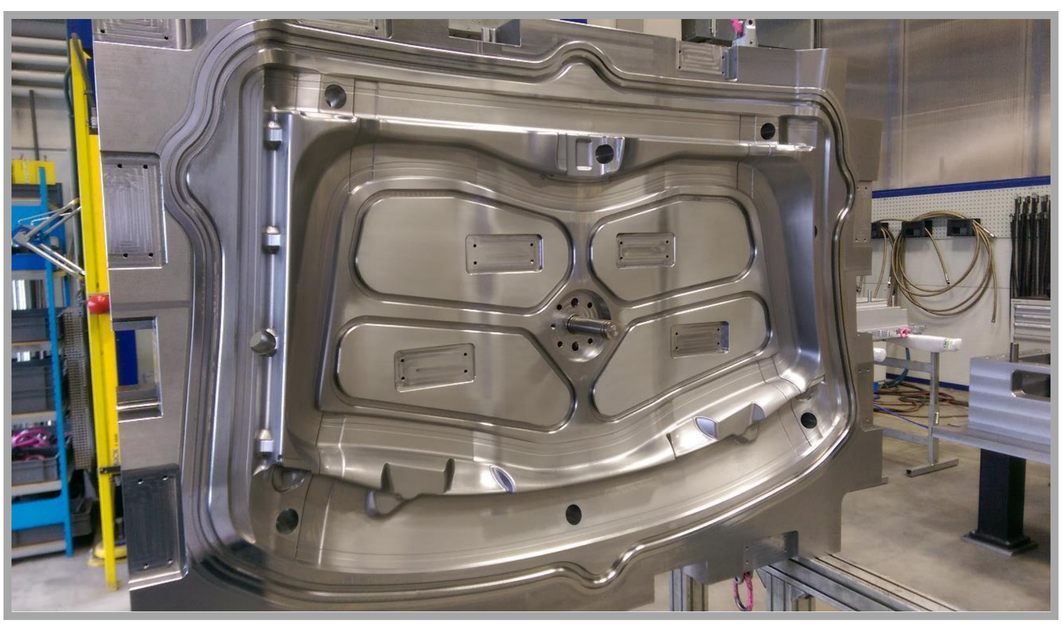


Figure 14: HP-RTM Roof Frame Tool

Initial molding trials were conducted at the Fraunhofer Institute for Chemical Technology[13] (ICT) in Pfinztal, Germany facilitated by a KraussMaffei HP-RTM injection system.[14] Parts were molded successfully on the first day of trials at a cycle time of less than 5 minutes per part. Following minor modifications, the tool (Figure 14) was shipped to the Fraunhofer Project Centre in London Ontario, Canada where parts were successfully molded in front of an audience of OEM representatives in just over 3 minutes per part. (Figures 15 and 16). The part was the first HP-RTM produced, fully engineered component successfully molded and demonstrated in North America.

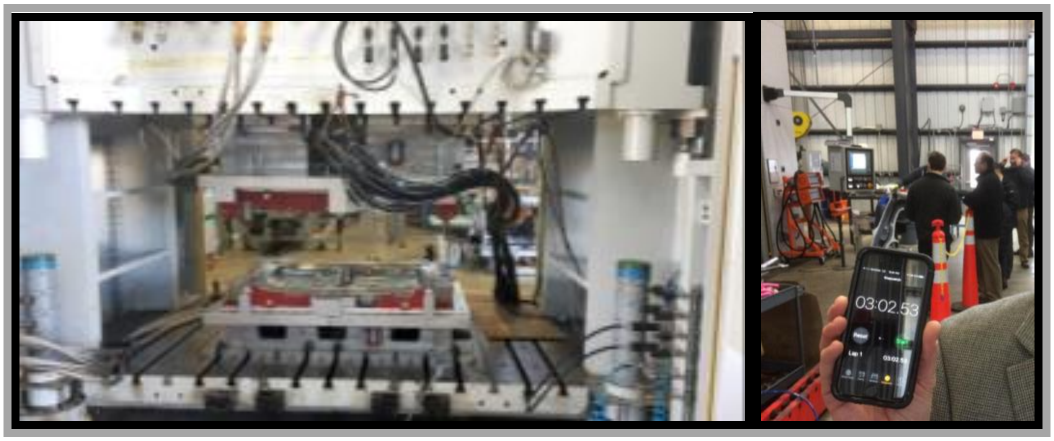


Figure 15: HP-RTM Roof Frame Tool in Press during Demonstration Molding Trials at Fraunhofer Project Centre, London, Ontario, Canada. Cycle times without optimization were just over 3 minutes per part.

Figure 16: Molded HP-RTM CFRP Roof Frame (Untrimmed)

Final Part Testing and Material Qualification Approach

Several CFRP roof frame parts molded using the HP-RTM production intent process were delivered to the OEM to conduct key component tests. The first test was a static deflection test on the bonded assembly. Figure 17 shows the test fixture to evaluate the deflection of one corner of the roof assembly when subjected to a 100 N corner load. The second test was a shear deflection test also shown. The third and fourth tests involved behavior of the roof assembly under dynamic crash situations. These included the side impact rigid pole test and frontal impact test configurations shown in Figure 18. The CFRP roof frame assemblies passed all the OEM's required static and dynamic tests.

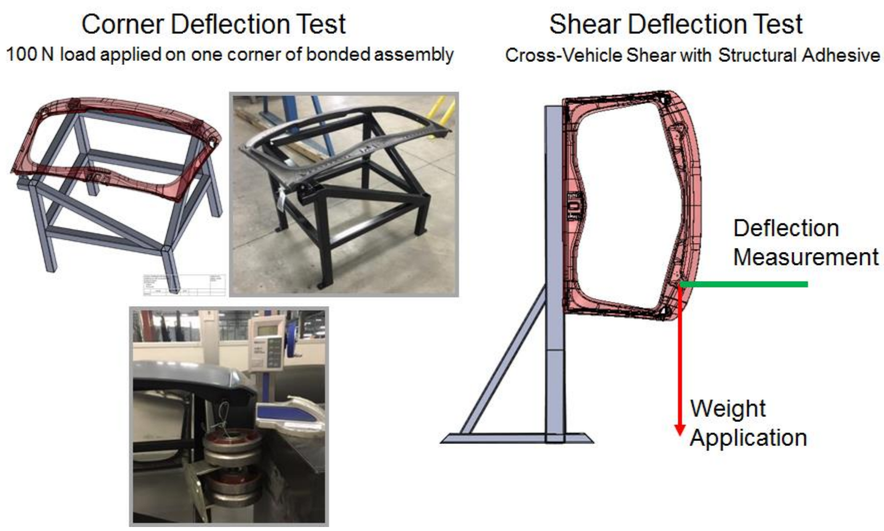


Figure 17: Corner and Shear Deflection Tests for Roof

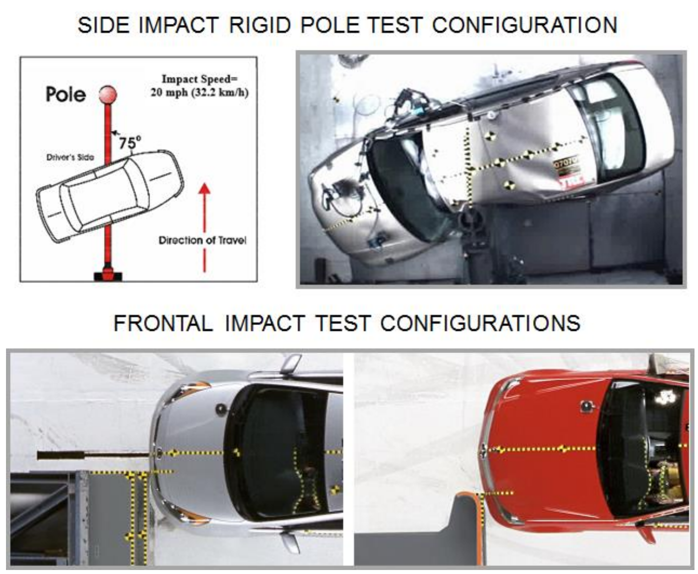


Figure 18: Side and Frontal Impact Vehicle Tests Involving Roof Frame Assembly.

One of the objectives in pursuing the carbon fiber roof frame was to expand the HP-RTM technology to future applications. The team offered an approach for a material qualification plan that could be transferable to other HP-RTM-produced parts (Figure 19). Normally, composites must be qualified according to the complete reinforcement laminate schedule and the specific application case – a conservative approach. If computer models can accurately predict laminate behavior based on lamina (single-ply) behavior, however, then there can be confidence in extrapolating test results from single ply testing data to establish preliminary specifications. This approach can save significant time and money related to the material qualification phase of composites application development.

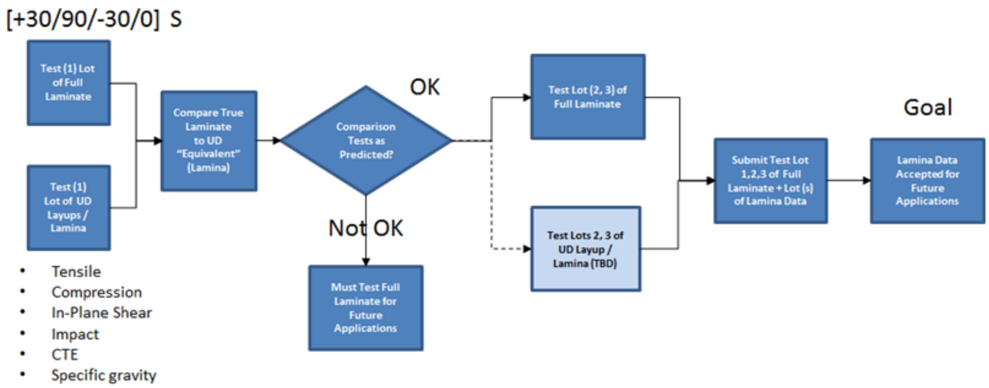


Figure 19: Plan for Material Qualification Applicable to CFRP Roof Frame and Similar Future Applications (even if laminate design differs).

Figure 20: Final Exposed Weave CFRP Roof Assembly Fitted with Lightweight CFRP Roof Frame on Reverse Side.

Summary

The final HP-RTM produced carbon fiber roof frame met the key performance criteria of the incumbent magnesium roof frame design while reducing weight (Figure 20):

- *Redesigned lightweight epoxy carbon fiber epoxy roof frame versus original die cast magnesium*
    - *CFRP = 1.8 kg. versus magnesium = 3.2 kg. including hardware*
    - *A 44% weight savings on the roof frame itself; 32% weight savings on overall assembly*
- *Prototypes successfully produced on production scale HP-RTM equipment with a demonstrated cycle time of 3 minutes per part - unoptimized*
- *Met OEM roof frame static stiffness specifications*
- *Passed OEM dynamic side pole and frontal impact tests*
- *HP-RTM material qualification plan transferable to similar parts and applications*

Concerning the economics of the project, the approximate cost to implement the CFRP roof frame solution including tooling and fixtures was estimated at $660,000 to produce up to 10,000 parts. The redesigned CRFP roof assembly would add an estimated $300 to the piece cost of the magnesium design. In the end, the project showed the successful collaboration by several expert supply chain partners to develop a lightweight composite part made using the high pressure resin transfer molding process. The experience and lessons learned can be applied to similar parts of interest to the OEM.

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Appendix

Project co-lead; Tier1 Molder

Project co-lead; Resin System

HP-RTM Injection System

Carbon Fiber

Non-crimp Fabric

Engineering and FEA

Prototyping Facilities

Process Simulation

Tooling

Preforming Solutions

Figure A1: CFRP Roof Frame Project Team – Represented Companies

(With automotive applications in mind)	SMC	PCM	HP-RTM	LCM	Filament Winding	Pultrusion
DESIGN						
Suitable for 3-dimensional geometries	Yes	Yes for compatible contours	Yes	Yes for compatible contours	Yes	No. Generally requires constant cross section
Suitable for window-frame / open geometries	Yes	Yes, if at low volume; no scrap	Yes	Yes	No	No
Suitable for omni-directional loading (e.g. node)	Yes	Yes if suitablly designed	Yes if suitablly designed	Yes if suitablly designed	Yes	No
Suitable for directional loading	Less efficient	Yes	Yes	Yes	Yes, in hoop loading	Yes, in line direction
PROCESSING						
Format allows for continuous feed production	Yes	Yes	Yes - if automated	Yes - if automated	Yes	Yes
Same material input can be used on multiple parts	Yes w/ new die and tailored blank	Yes w/ new die and tailored blank	No. Requires new custom preform	Yes w/ new die and tailored blank	Yes w/ new mandrel	Yes w/ new die
Requires preforming	No	Yes - Tailored blank	Yes	No	No	No
Requires on-site mixing	No	No	Yes	Yes	Yes	Yes
Requires high tonnage press	Yes	Yes	Yes	No	No	No
Can use recycled fiber as input	Yes	Yes in combo with UD, fabrics or mats	No	Yes in combo with UD, fabrics or mats	No	Yes in combo with UD, fabrics or mats
Requires staging / maturation	Yes, unless Direct SMC process	No	No	No	No	No
Raw materials require refrigeration	No	Yes	No	No	No	No
In-mold cycle time	~1' - 2'	2' - 5' minutes	1' - 5' minutes	~1'	Depends on size and geometry	Continuous

Figure A2: Qualitative Comparison of Automotive Composite Processes Considered for CFRP Roof Frame (Hexion Inc.)

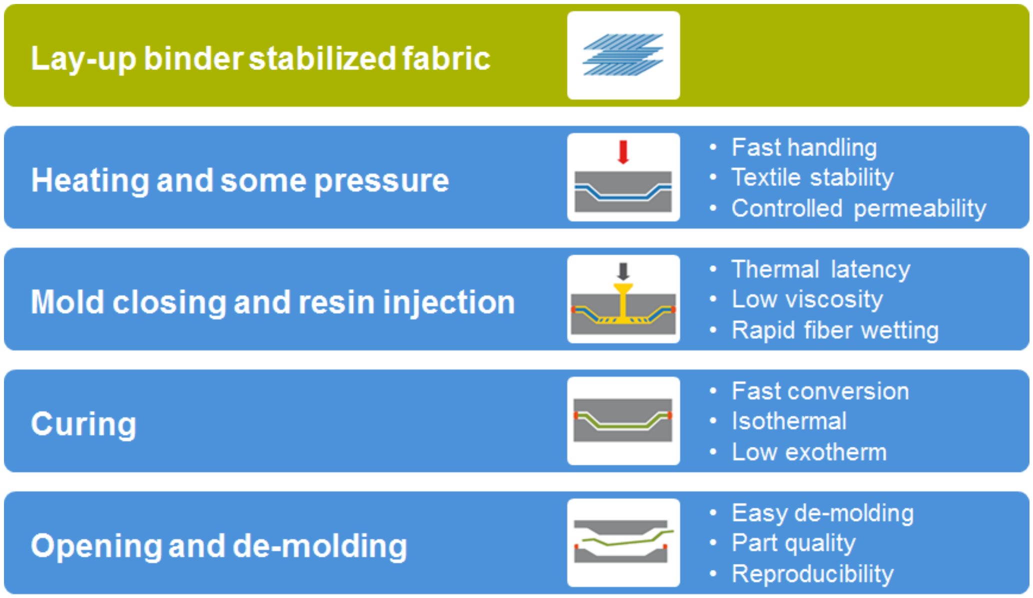

Figure A3: Outline of High Pressure Resin Transfer Molding Process (HP-RTM)

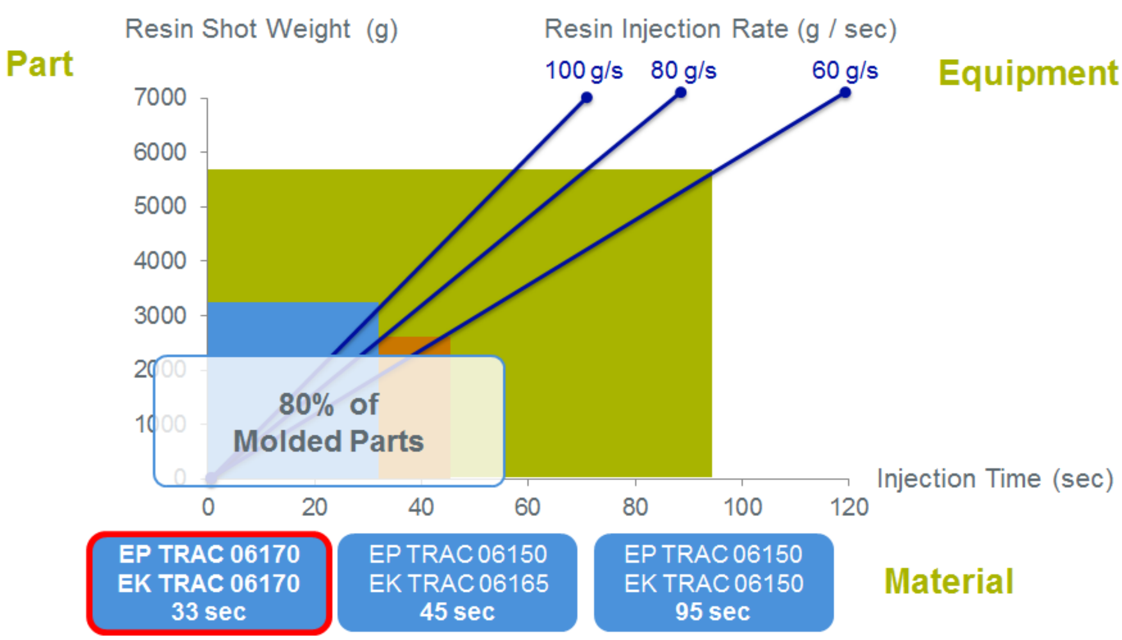

Figure A4: Part Size and Equipment Determine the Material Processing Window.
The CFRP roof frame utilized the EPIKOTE / EPIKURE TRAC 06170 fast curing epoxy resin system.