SUITABILITY OF CARBON FIBER COMPOSITES IN A HIGH-VOLUME PRODUCTION PROCESS FOR VEHICLE FRONT SUBFRAMES

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Abstract

This was a collaborative research project to investigate potential mass savings and highlight the technical opportunities and challenges presented by utilizing carbon fiber composites in a structural application to replace traditional stamped steel in a front subframe for the Ford Fusion.

Part design and manufacturing process were considered to aim for high-volume production capability. The subframe design predominantly used carbon fiber sheet molding compound (CF SMC) in two large compression molded thermoset composite parts including a clamshell shaped upper molding with over-molded steel reinforcements and a lower close-out panel. Both parts contained co-molded, non-crimped fabric patches for local reinforcement.

Compression molding was the selected manufacturing process to align with potential high-volume manufacturing capability. The cycle times for the initial prototype parts were approximately five minutes with the anticipation that design lessons learned, charge layup and other material handling automation will reduce the expected high volume cycle time by approximately 50%.

The resulting carbon fiber composite subframe weighs 18.8 kg and reduces the number of components from 45 to 8 (two molded parts with six steel over-molded inserts) as compared to the steel version. This represents a 28% mass savings from the production stamped steel subframe as well as an overall part reduction of 82%.

Projected tooling expenditures are in the neighborhood of US $4 million dollars, a substantial savings over tooling for a stamped and metal inert gas (MIG) welded steel subframe.

The estimated variable cost is approximately three to four times that of a surrogate steel subframe. The number and complexity of the current manufacturing and assembly operations drive the high variable cost. Use of carbon fiber composites in the automotive industry will become more prevalent as the cost of carbon fiber roving, and costs and complexity of composite manufacturing operations are reduced.

The mass reduction and mass redistribution offered by lightweight front subframes may currently be most applicable for performance vehicle applications until piece cost improvements can be achieved.

Background and Requirements

The high specific modulus and strength of carbon fiber thermoset composites make them an attractive material for lightweight structural automotive components. Table 1 presents the material properties for the carbon fiber thermoset composites used in the subframe. Some of the challenges associated with manufacturing complex carbon fiber composite components for high-volume automotive applications frequently lead to costs higher than desired for profitability. This research project investigates the manufacturing and cost opportunities and challenges associated with producing a carbon fiber thermoset composite structural subframe in this context.

Table 1: Carbon Fiber Thermoset Mechanical Properties with Reference HSLA Steel

Carbon Fiber plus Vinyl Ester EpicBlend ™ CFS-Z Composite Mechanical Properties					
	Density (g/cm^3)	Modulus (GPa)	Specific Modulus (1000 kN-m/kg)	Tensile Strength (MPa)	Specific Strength (kN-m / kg)
CFS-Z SMC 50 wt% CF	1.41	30	21.3	215	152
CFS-Z $0^o/90^o$ NCF 56 wt% CF	1.46	50	32.2	600	411
HSLA Steel	7.87	207	26.3	500	63.5

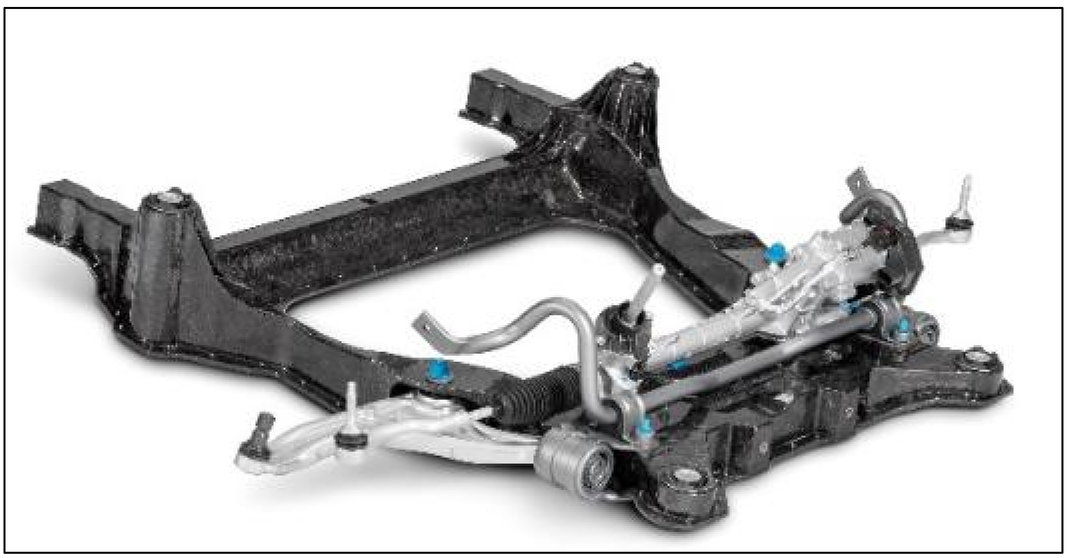
The subframe design, performance requirements and package space are described in companion SPE papers, see Bolar et al. [1] for design, Chen et al. [2, 3] for fatigue, strength and corrosion performance. The carbon fiber thermoset composite subframe met most of the requirements for a production stamped steel, metal inert gas (MIG) welded front subframe.

Design Description

The carbon fiber thermoset composite front subframe reduces mass and part count when compared to a production stamped steel subframe. At a weight of 18.8 kg it represents a 28% mass savings and is made up of only eight major parts, an 82% part count reduction from the 45 steel parts for a stamped steel subframe. Random chopped industrial grade carbon fiber compounded into sheet molding compound (SMC) comprises the majority of the two large compression moldings for the composite subframe. The upper clamshell uses 12.2 kg of random chopped carbon fiber SMC, 0.4 kg of non-crimped fabric $0^o/90^o$ laminate, and 1.8 kg of steel for the body mount sleeves, steering gear compression limiters and top hat washers. The lower close-out panel uses 3.4 kg of SMC, 0.5 kg of non-crimped fabric $0^o/90^o$ laminate, and 0.2 kg of steel for top hat washers at bolted connection points. The steel rivets and adhesive for the assembly add another 0.3 kg to the final subframe mass.

Figure 1 shows the carbon fiber composite subframe with and without the attached chassis components, i.e., front lower control arms, roll restrictor, and steering gear.

(a)



(b)

Figure 1: Carbon fiber composite subframe, (a) subframe alone, and (b) with attached chassis components. Images courtesy of Ford Motor Company.

Manufacturing Process Description

The multi-step manufacturing process begins with incoming composite materials. Both the random chopped carbon fiber SMC and the non-crimped fabric $0^o/90^o$ laminate arrive fully matured as either rolls or festooned in a returnable dunnage box. The SMC material is 2.4 mm thick, approximately one meter wide and has a carrier film on both sides of the sheet which must be removed prior to use. There is a limited open time for both materials, therefore on-site storage must be environmentally controlled. The first step is cutting the sheet material into the charge patterns. Due to geometric complexity, substantial part volume and to ensure structural integrity of the upper clamshell molding, a large number of individual SMC pieces were required to make a full charge pattern assembly. For the initial prototype dozens of individual pieces comprise the SMC charge. Work continues on optimizing the charge pattern and number of pieces for high volume production. Both the upper clamshell and the lower close-out panel incorporate reinforcement patches of the non-crimped 0º/90º laminate that are co-molded with the SMC.

For the upper clamshell molding, the four steel body mount sleeves and the two steel steering gear compression limiters are placed first into the female side of the mold. The lower close-out panel has no over-molded steel parts. The non-crimped 0º/90º laminates are then manually loaded into the mold. The larger, heavier SMC charge follows the laminate local reinforcements and is placed into the mold. These cutting, stacking and placement processes plus carrier film removal, would be automated with limited operator oversight or interventions for high volume production.

The compression molding press time could be as short as 150 seconds based on the 12.6 kg composite mass of the upper molding. Also, the high-volume manufacturing plan calls for a two-cavity mold to further increase the speed of production. The prototype build used a single cavity mold. Figure 2 shows the composite charges in the upper clamshell mold. The steel sleeves and compression limiters cannot be seen in Figure 2 although they are in the mold.

Figure 2: Charges in the upper clamshell mold. Image courtesy of Magna International.

The composite parts are transferred to a cooling fixture for de-flashing after molding. In this fixture, a robot or operator removes the plugs used to seal-off the body mount sleeves and completes removing any flash from the parting line at the clamshell flange. The molded parts then move to the machining area. Figure 3 describes the charge cutting, charge placement and molding processes for both the upper clamshell and the lower close-out panel.

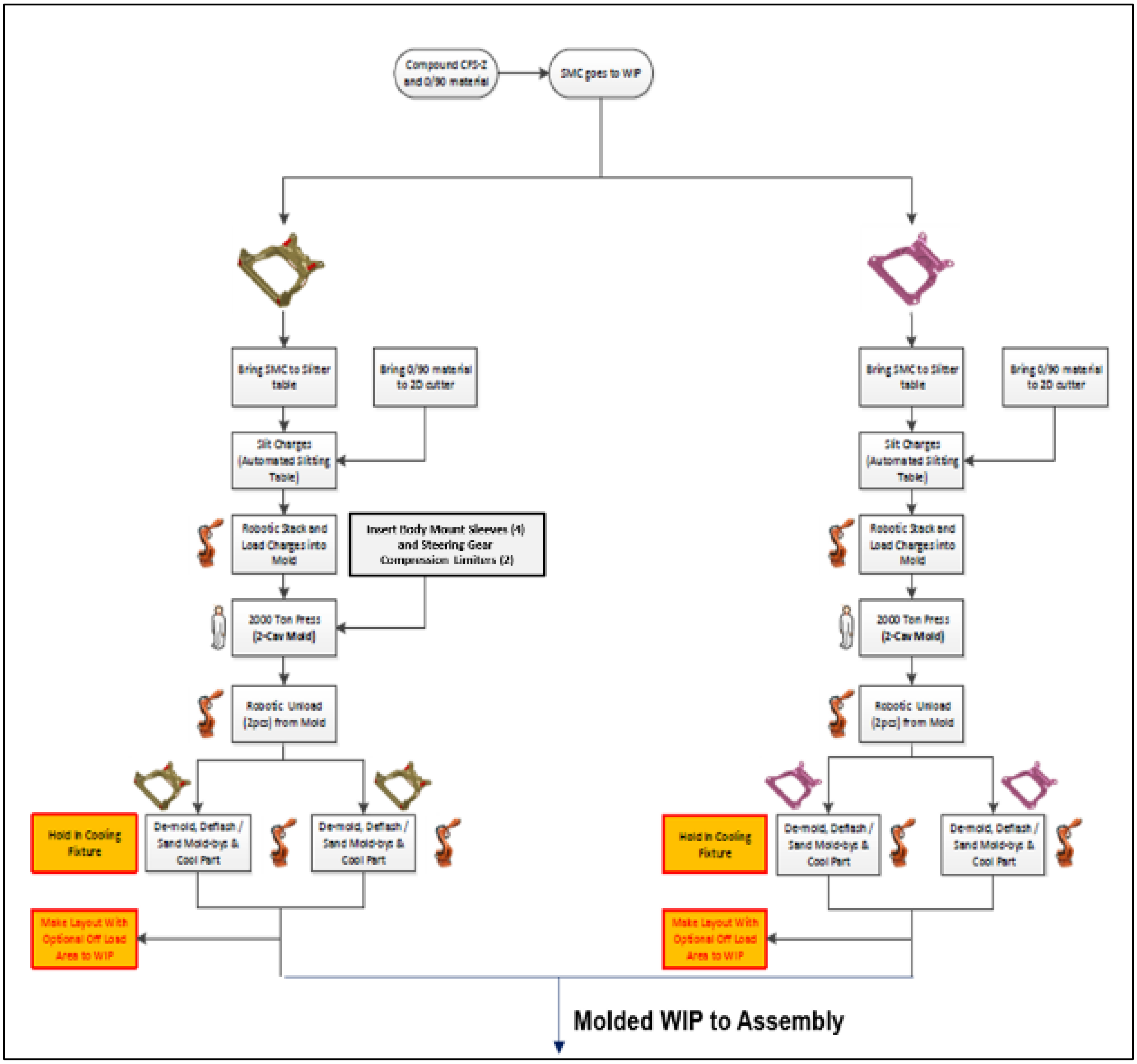


Figure 3: Process flow for carbon fiber composite moldings. Image courtesy of Magna International.

The machining operations on the upper clamshell molding include cutting clearance holes for the roll restrictor and the front attachment of the lower control arm pockets. On both the upper clamshell and the lower close-out panel moldings, the top and bottom surfaces of the steering gear compression limiter and the rear attachment of the lower control arm are spot-faced to meet required tolerances. Machined surfaces received a sealer application to reduce the potential for loose carbon fiber filaments from falling off the part and thus mitigating electrical conductivity concerns. After machining and sealing, the top hat washers are adhesively bonded into the composite moldings and pressed into place.

The parts then move to the final joining assembly operation. The upper clamshell and the lower close-out moldings are clamped together and rivet pilot holes are drilled. A total of approximately 140 rivets hold the moldings together. The surfaces receiving adhesive are then cleaned to remove any dust or debris prior to robotic adhesive application to the lower close-out panel.

The upper clamshell and the lower close-out panel are then mated together for riveting. Three robots insert the rivets connecting the two moldings. For high-volume production the manufacturing process plan does not call for any heat curing of the adhesive. The transfer racks and dunnage are planned to be capable of maintaining dimensional requirements as the adhesive cures. For the prototype builds, the assembled subframes cured for an hour in an oven while in a curing fixture. Figure 4 shows the machining and final assembly operations.

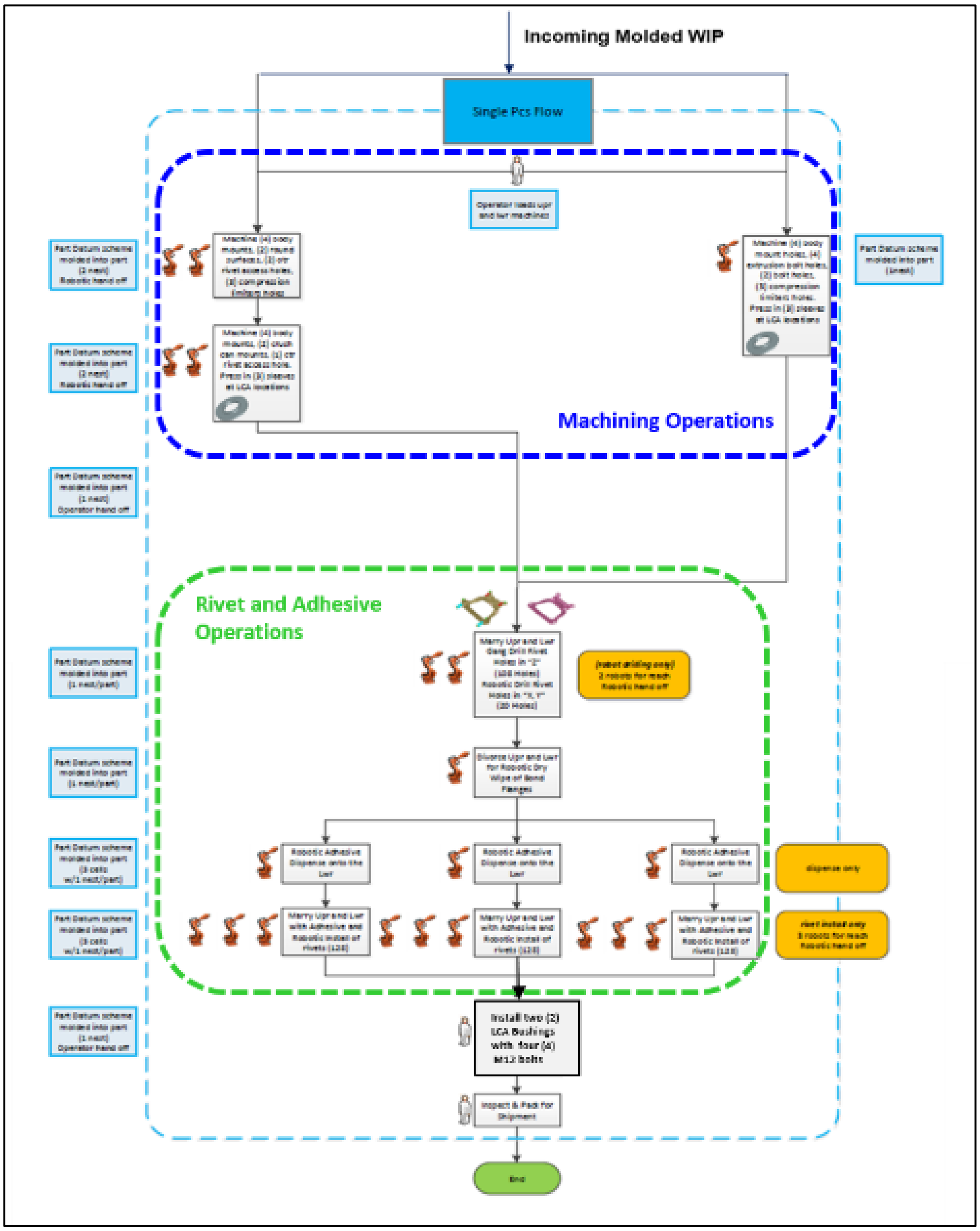


Figure 4: Process flow for assembling the two carbon fiber composite moldings into a front subframe. Image courtesy of Magna International.

Tooling Cost Estimate

Both Magna International and Ford Motor Company investigated the costs for the carbon fiber composite front subframe. The tooling costs to produce 100,000 composite front subframes per year totals approximately US$4 million dollars. This is less than half the tooling cost to manufacture the same number of stamped steel, MIG welded front subframes. While the compression molding tool costs of over 1.5 million dollars for the upper clamshell and the lower close-out panel tools drive the total tooling cost, the savings compared to stamped steel subframe tooling lie in the part reduction count from the over forty stamping dies. The machining and assembly fixtures for the carbon fiber composite subframe are different but comparable to those for a stamped steel, MIG welded subframe.

Piece Cost Estimate

Magna International and Ford Motor Company cooperated to estimate the piece cost for the carbon fiber composite front subframe. At an assumed annual volume of 100,000 subframes, the estimated piece price is US$350 based on carbon fiber at $5/pound.

Although industrial grade carbon fiber 50k tow roving drives most of the material costs, it is not solely responsible for the estimated part cost. For this investigation, the target cost of US$5/pound was assumed as per the US Department of Energy, see Warren [4], US-DOE [5], and Schutte & Joost [6]. Currently, the spot price of carbon fiber is significantly higher than the US$5/pound target.

Of the total 18.8 kg subframe weight, carbon fiber composite, both SMC and non-crimped fabric, make up 16.5 kg with approximately a 50 wt% carbon fiber loading. Assuming only 10% scrap from the rolls of SMC and non-crimped fabric composite, this implies slightly over 20 pounds of carbon fiber per subframe. In addition to the US$100 cost for the carbon fiber roving per subframe, the remaining US$250 are derived from resin and composite compounding costs as well as the additional parts assembled in the subframe, i.e., body mount bushings and steering gear compression limiters, sealer, plus the consumables, the adhesive and rivets, plus labor, overhead, selling, general administrative expenses (SG&A) and profit.

If solely looking at price, the US$350 assumed cost of the prototype subframe compares to about US$100 for its stamped steel equivalent. This calculation does not take into consideration the significant weight savings achieved that support the continued need to reduce overall vehicle weight affecting range and fuel consumption.

Summary and Next Steps

This collaborative research project successfully demonstrates that a carbon fiber composite subframe can be manufactured using processes capable of high-volume automotive production. Prototypes processed at approximately five-minute cycle times show the opportunity and a pathway to reach a 150 second cycle time. To achieve faster cycle times, larger molds are required to produce two parts at a time and automated material handling needs to be instituted.

The substantial 82% part reduction enables a total tooling cost lower than what is typical for stamped steel MIG welded subframes. The tooling cost includes the primary upper and lower part compression molding tools plus the fixtures required for machining and assembly operations. The current estimated piece cost of each carbon fiber composite subframe is approximately three and a half times the cost of a typical stamped steel MIG welded subframe. Some of the cost differences arise from materials, resin and compounding operations as well as the number and complexity of the manufacturing steps involved. All these components would need further investigation to determine the best path forward to affect the high volume use of carbon fiber composite in the automotive industry.

Acknowledgements

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Suitability of Carbon Fiber Composites in a High-Volume Production Process for Vehicle Front Subframes

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SPE Automotive Composites Conference & Exhibition

September 6, 2019

Agenda

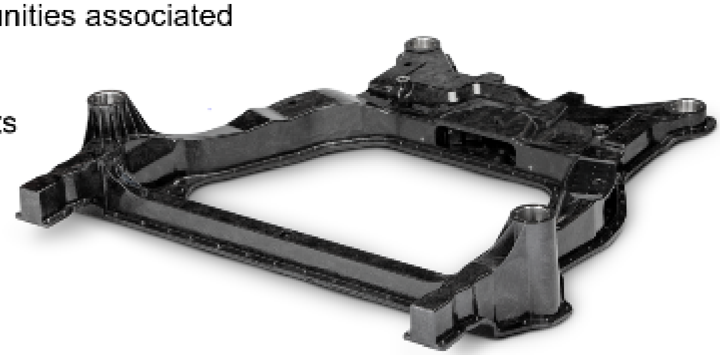
- Project Goals
- Design Overview
- Manufacturing Process
- Tooling Cost Estimate
- Piece Cost Estimate
- Summary

Executive Summary

- Collaborative R&D effort between Ford and Magna investigating challenges and opportunities with Carbon Fiber Composites for subframes
- Lightweight front perimeter subframe for unibody vehicles
- Baseline design is front Ford Fusion steel subframe

Project Goals

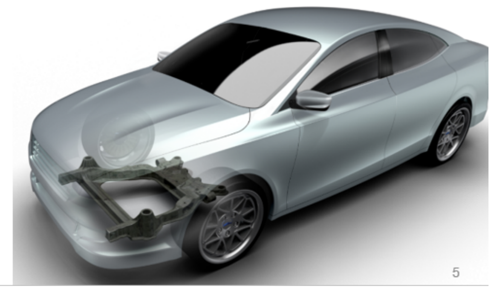
- Investigate carbon fiber thermoset composite for chassis components
- Design, analyze, prototype and test a front subframe
- Identify challenges and opportunities associated with high volume production
- Estimate tooling and piece costs



CFRP Subframe Development

Objective

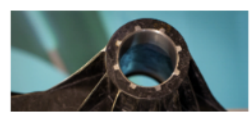
- Design carbon fiber intensive front subframe for a CD sized sedan to meet:
  - Package
  - Stiffness
  - Durability
  - Safety attributes
- High volume production manufacturing capable
- Cost estimate for future production vehicle

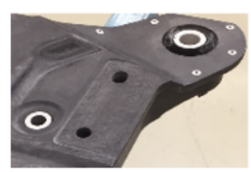


CFRP Subframe Development

Metrics

- Mass reduction
- Match or exceed the following parameters:
  - Package
  - Stiffness
  - Strength
  - Durability
  - Safety
  - Corrosion attributes
- Manufacturing feasibility for high volume production





CFRP Subframe Development

Collaboration

- Ford Motor Company
- Magna International
  - Magna Exteriors (materials & manufacturing)
  - Cosma International (engineering)

Key Deliverables

- Designs for front carbon fiber intensive subframe with manufacturing plan and production cost estimates

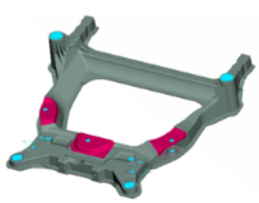
Timing

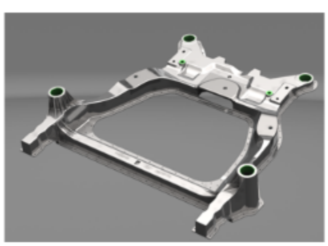
- First subframes in early 2018
- Prototype testing completed March 2019

CFRP Subframe Development

Data

- Design completed
- Prototypes built
- Subframes tested
- Tooling cost estimate ~ US $ 4 Million
- Piece cost estimate ~ US $ 350





Baseline Weight	26.1 kg
Proposed CF Weight	18.8 kg
CF Weight Savings	7.3 kg (28%)
Stiffness	Pass
Strength	Marginal
Durability	Pass
Safety	Pass
Random CF SMC	15.5 kg
Oriented CF Pre-Preg	0.8 kg
Steel & Rivets	2.4 kg
Adhesives	0.1 kg

Design Summary

Composite Subframe Highlights

Mass reduction:

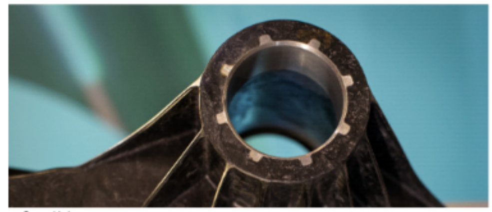
- 7.3 kg versus baseline steel design
- 28% mass savings

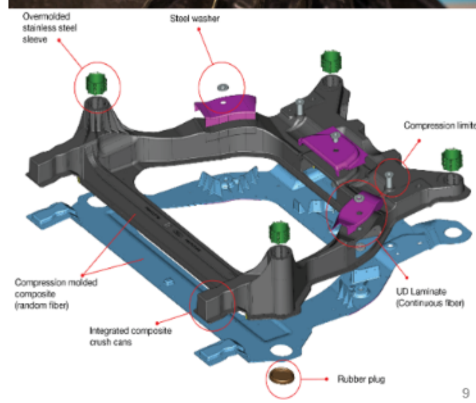
Part Consolidation:

- 45 steel parts replaced by two (2) molded parts and six (6) steel parts
- 82% part reduction count

Design:

- 83% carbon fiber composite material by mass





Manufacturing Process Highlights

Prototype Location:

- Magna Exteriors Composites Centre of Excellence

Materials:

- Industrial grade 50k tow carbon fiber
- Vinyl ester resin
- CFS-Z random chopped SMC (~ 50 wt.%)
- CFS-Z 0°/90° NCF (~ 56 wt%)

Compression Molding:

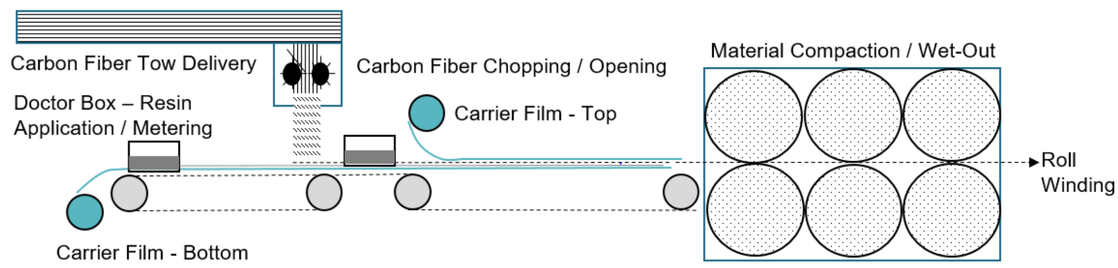
- Co-molding of NCF patches and steel parts in SMC
- SMC charge developed for prototype
- 2500 ton Dieffenbacher press

Final Assembly:

- Steel rivets and urethane adhesive to join upper and lower moldings

Composite Material Compounding

Carbon Fiber SMC Compounding



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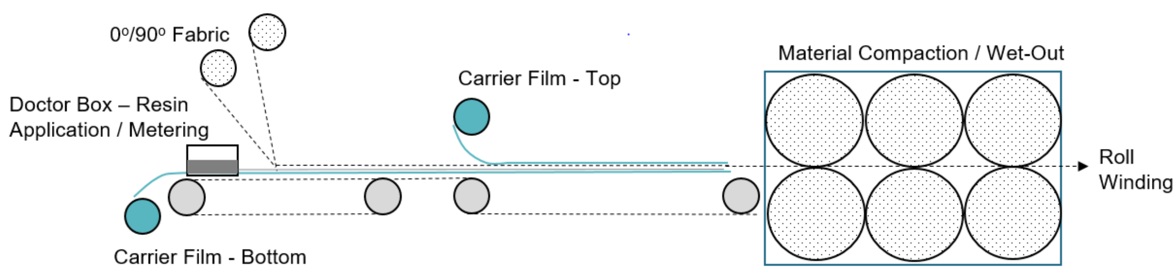
Composite Material Compounding

Carbon Fiber Non-Crimped 0°/90° Fabric Compounding



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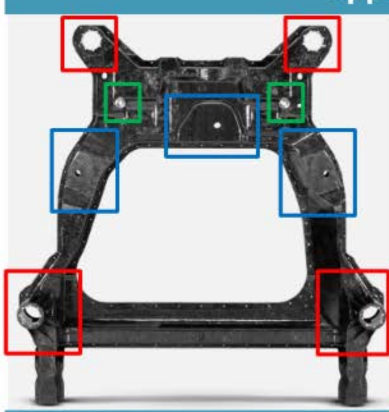
Co-Molded Elements

Upper Subframe Molded Component

Topology Directed Internal Ribbing
(as-molded upper, pre machining)

Co-Molded Elements

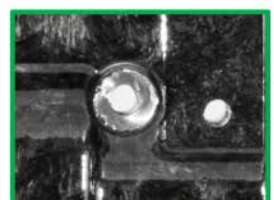
Upper Subframe Molded Components



Co-Molded NCF Patches, Steel Bushing Sleeves, Steering Gear Compression Limiters

NCF Patches As-Molded

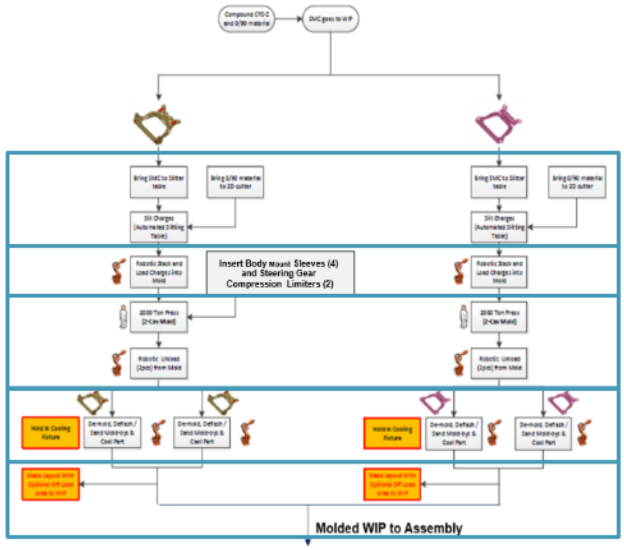
Bushing Sleeves



Compression Limiters

Upper and Lower Molding Steps

1. Cut SMC charges, cut NCF charges
2. Remove carrier films from SMC pieces
3. Arrange charges for upper and lower
4. Insert body mount sleeves and steering gear compression limiter in upper mold
5. Locate NCF patches in molds
6. Place SMC charge in molds
7. Mold in 2000 ton press
8. Unload moldings from tools
9. Place moldings in cooling fixtures
10. De-flash moldings
11. Transfer to assembly



Final Assembly

Machining

Upper: LCA and roll restrictor openings
LCA and roll restrictor bolt holes
LCA bracket face

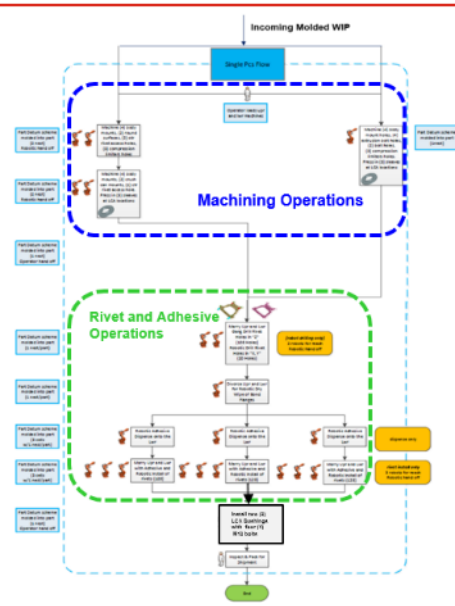
Lower: LCA and roll restrictor bolt holes

Seal machined surfaces

Bond top hat washers in place

Rivets & Adhesive

1. Wipe bond line flanges
2. Apply adhesive along perimeter bond line
3. Clamp upper and lower together in fixture
4. Drill rivet holes
5. Insert rivets



Tooling Cost Estimate

Total Estimate: ~ US$ 4 Million

- Compression molding tools for upper and lower
- Cooling fixtures
- Machining fixtures
- Bonding & riveting fixture

Compression Tools

Upper Close-Out

Lower Close-Out

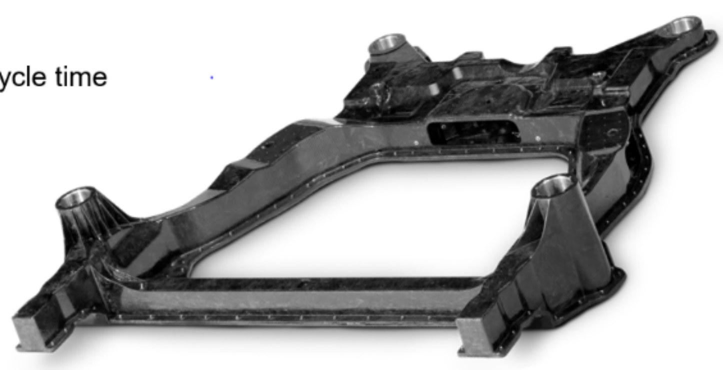
Bonding & Riveting Fixture

Machining Fixtures

Piece Cost Estimate

Piece Cost Estimate: ~ US$ 350

- Approximately 20 pounds (US$ 100) of carbon fiber*
  * based on US-DOE target cost
- Approximately 20 pounds of vinyl ester resin
- Assuming 10% composite scrap
- Assuming 150 second molding cycle time
- Four steel body mount sleeves
- Two steel compression limiters
- 0.25 pounds of adhesive
- 140 rivets



MAGNA

Successful Collaborative Research Project

- Joint development of a carbon fiber composite subframe that meets most performance requirements
- 28% weight reduction
- 82% part count reduction
- ~ US$ 4 Million tooling cost
- ~ US$ 350 piece cost

Acknowledgements

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Magna International, Magna Exteriors, Cosma Engineering, Magna Exteriors Composites Centre of Excellence

Zoltek, a division of the Toray Group, Tycos Tool and Die, CTS Composites Group, CTG Bel-Kur Inc., Barron Industries, Crawford Products, Ashland LLC

Questions?