LAMBORGHINI “FORGED COMPOSITE®” TECHNOLOGY FOR THE SUSPENSION ARMS OF THE SESTO ELEMENTO

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ABSTRACT

Recent composite technology research and development efforts have focused on new out-of-autoclave material forms, and automated processes that can markedly increase production efficiencies. In a fashion similar to the aviation industry, manufacturers of high performance automobiles are moving away from costly manufacturing processes based on manual lay-up of prepreg and autoclave cure. Since 2007, the research and development efforts at Lamborghini have aimed at reducing composite part cost and increasing production rate. This effort has culminated in the development of *Forged Composite®* technology, which is an advanced compression molding technique that utilizes carbon fiber sheet molding compounds. This publication constitutes the first public technical disclosure of both Forged Composite® and of the control arms manufactured using this technology. The process, which uses high pressures but conventional temperatures, is used to manufacture parts with complex geometries and subject to combined loadings, which were typically manufactured as aluminum and titanium forgings. This technology was used to manufacture the inner monocoque and the suspension control arms of the *Sesto Elemento*, a multi-million dollar composite technology demonstrator vehicle unveiled in September 2010 at the Paris Autoshow. This paper focuses on the development of the suspension control arms, which aim at a 30% weight reduction, as well as a cost and cycle time reduction with respect to the baseline forged aluminum construction.

Key words: discontinuous fibers, automotive applications, analysis and testing.

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1. INTRODUCTION

The Lamborghini *Murcielago*, in production from 2001 to 2010, used approximately 31% by structural weight of carbon fiber/ epoxy prepreg [1-3]. Carbon fiber/ epoxy prepreg was used for all outer body panels as well internal structural parts, which were bonded to a steel spaceframe. However, the factor limiting a larger utilization of carbon fiber for was the high cost associated to the ply collation and, in part, to the lengthy autoclave cure of the prepreg. This process offers offer minimal opportunities for high volume production of complex structural parts, but was adequate for the *Murcielago*, whose production rate was approximately 400 units per year. In order for carbon fiber to penetrate deeper into the product line of Lamborghini, including the aluminum-intensive Gallardo line-up that sells 2,000 units per year, it becomes fundamental to increase production rate and decrease cost. Out-of-autoclave technologies, including liquid resin infusion in all its variants, reinforced thermoplastics, and advanced compression molding constitute the majority of Lamborghini's current and future efforts. The *Murcielago* successor, called *Aventador*, was unveiled in March 2011 at the Geneva Autoshow, and it features an all-composite monocoque design with 50% structural weight of carbon fiber. This design dramatically increases the performance (torsional stiffness) and safety (crash behavior) of the new vehicle over the *Murcielago*. The monocoque of the *Aventador*, now in production of approximately 800 parts per year, is manufactured mostly utilizing liquid resin technologies such as VaRTM and RTM. While these technologies are very efficient for the volumes considered, for higher volumes it is necessary to consider even more dramatic technologies.

Airframe manufacturers have been proposing the use of high-performance discontinuous systems that are suitable for compression molding of primary structures. The Boeing 787 Dreamliner for example makes use of AS4/ 8552 HexMC® for the window frames, as well as other primary and secondary structural elements [4, 5]. Although the raw material cost associated with these discontinuous systems is typically as high as prepreg, their suitability to be molded in complex geometries with lower processing costs and higher rates can justify their adoption to reduce overall part acquisition costs. Discontinuous carbon fiber systems for advanced compression molding [6-10] have shown highly desirable mechanical properties, particularly with regards to stiffness, since the average modulus reported is identical to that of the quasi-isotropic (QI) continuous prepreg laminate used as the reference. Results also show that the distribution of the reinforcement is indeed random, yielding in-plane quasi-isotropic elastic and strength properties. Furthermore, this material form is much less affected by the presence of defects, holes, notches and impact damage than the reference QI laminate. Open-hole and filled-hole strength is virtually identical to unnotched strength, thereby making it very useful for manufacturing structures with fastener and lightening holes. The material is also more impervious to moisture absorption, and therefore its elevated temperature wet properties are less affected than the laminated equivalent. There are drawbacks to these material forms, in particular average unnotched strengths are lower than the QI, particularly in tension and, to a lesser extent, in compression, shear and flexure. Tension strength is indeed lower than compression strength, unlike continuous fiber composites. The variation observed in strength is also significantly higher compared to the baseline continuous QI laminate. Furthermore, the use of these new discontinuous material forms poses new challenges for the design, analysis and testing of primary structural components manufactured with such materials. The authors have identified three rather unique characteristics, which dramatically set them apart from traditional laminated tapes and fabrics [6-10]. These are notch-insensitive behavior, apparent modulus variability, and low sensitivity to defects. In order to account for these behaviors, new analysis methods based on stochastic approaches need to be developed, opening the way to new certification methodologies.

The technology demonstrator vehicle shown in September 2010 at the Paris Autoshow, called *Sesto Elemento*, was conceived to show the capabilities of advanced compression molding for the manufacturing of primary structural parts. Forged Composite® technology, as it was registered by Lamborghini in conjunction with Callaway Golf, enables dramatic reductions in production cycles and the realization of complex three-dimensional geometries that are not typically feasible with continuous fiber laminates. Forged Composite® technology introduced in the *Sesto Elemento* was utilized for the construction of the one-piece monocoque as well as the all-composite suspension control arms.

This paper focuses on the development of the Forged Composite® suspension arms, whose preliminary design, FEA modeling, and testing was performed at the ACSL/ UW. Detailed CAD design of the arms, as well as mold design and machining were performed by ICE. The manufacturing of the arms was performed jointly by the ACSL/ UW and ICE. Requirements, monitoring and assembly onto the vehicle were performed by the ACRC/ Lamborghini.

Figure 1. The 2010 Lamborghini *Sesto Elemento*, carbon fiber composite technology demonstrator.

2. BASELINE ALUMINUM SUSPENSIONS

The goal of the project was to replace the aluminum wishbone control arms of the suspensions, which are utilized in the 2010 Lamborghini Gallardo LP570-4 Superleggera, and to achieve a weight reduction of 30%, while maintaining equal or better final part acquisition cost. There are 8 control arms on the vehicle, two for each wheel assembly. The left side arms are exact mirrors of the right side arms, thus reducing the complexity of the design to four arms. Of the four, there are two front arms (upper and lower) and two rear arms (upper and lower). The front upper and lower arms are depicted in Figures 2 and 3. Each arm has a unique design, due to geometric packaging and interference, as well as different load requirements. The front upper for example, has to connect to the aluminum frame, the wheel, and to support the shock absorber. However, the front lower arm, Figure 3 (right), is the one that is most critical in terms of requirements, and for that reason the discussion will focus on the development of this arm.

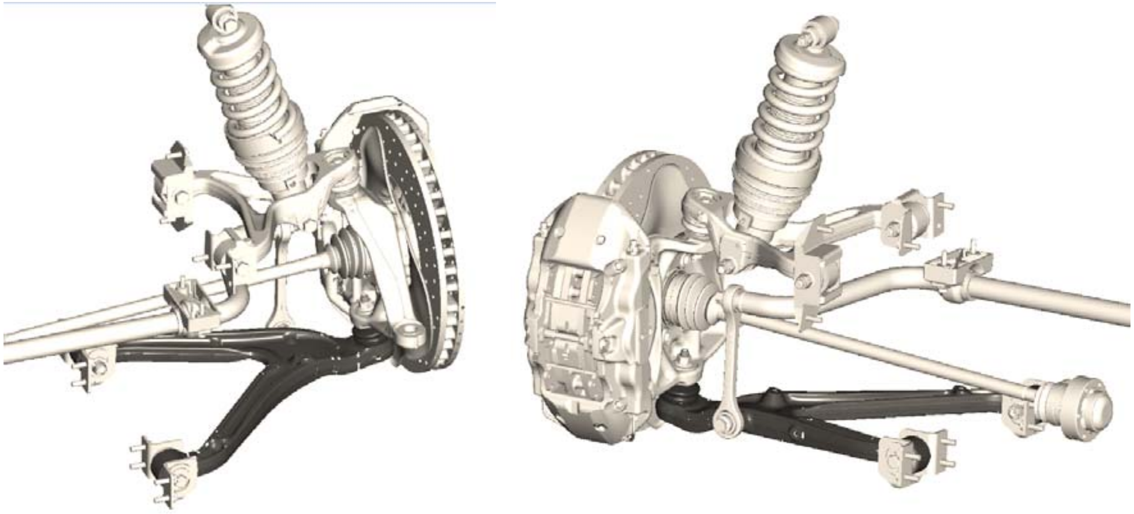


Figure 2. Two views of the wheel assembly showing front lower and upper control arms.

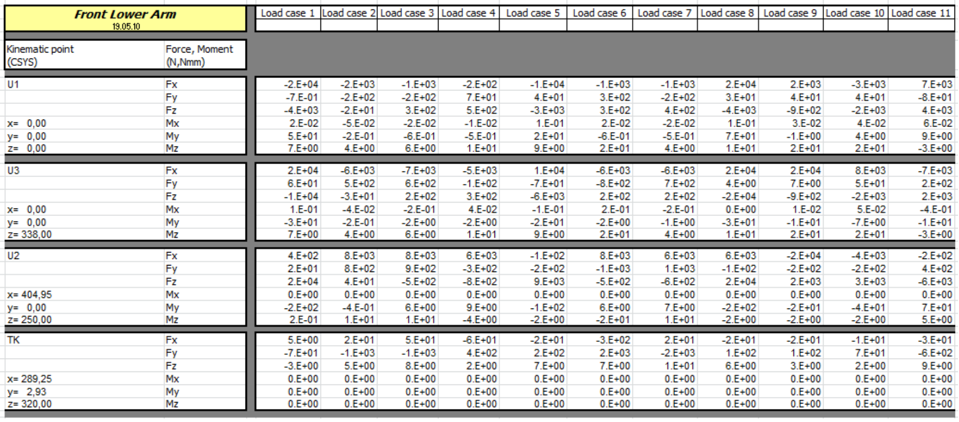
The arm is forged using a 6xxx series aluminum alloy with Magnesium and Silicon, with minimum yield strength of 260 MPa and minimum ultimate strength of 310 MPa. The design of the front lower arm is characterized by 9 different operational load cases, Figure 4, which include curb strike, braking, and cornering. The aluminum part weighs 2.2 kg, excluding the steel ball joint and the two bushings, and 2.9 kg with the ball joint and bushings. The part is designed for a life of 200,000 cycles. Both stiffness and strength criteria are critical for this component.

The component has prescribed tolerances in all locations where it is mated to other mechanical components, as well as strict geometric requirements due to interference and proper operation. After forging, the arm undergoes secondary machining to accommodate two bushings, which are the fixing location on the front aluminum spaceframe. On the wheel side, the arm has to accommodate a ball joint, which moves together with the wheel and its rotor, Figure 3. The bushings are inserted by press-fit with small interference, while the ball joint is torqued to a predefined amount on to a threaded seat. Both operation are quite critical and constitute two additional load cases, bringing the total number of stress checks for each part to 11.

The component is designed through FEA, and sized based on maximum Von Mises stresses for each load case. The maximum stress is compared to an allowable strength, which is approximately 30% lower than the nominal yield strength of 260 MPa to account for fatigue life. The NASTRAN FEA model uses 3 mm tetrahedron elements, Figure 4, top. The loads are introduced through Rigid Beam Elements at Multi Point Constraints in the bushing and ball joint locations. From the FEA, the most stress-critical load cases are associated to the braking operation, and lead to a peak stress at the inner radius of 207 MPa, Figure 4, center. On the other hand, the most deflection-critical load is a lateral load of 10,000 N associated to braking and cornering, and amounts to 24 mm. Every other load case imparts a deflection that is an order of magnitude lower, including the vertical direction.

Figure 3. Front upper and lower aluminum arms (left) and CAD detail of front lower arm (right).

Table I. Summary of load cases used for the sizing of the front lower arm, including 9 operational loads and 2 installation loads.



Front Lower Arm 19.05.10		Load case 1	Load case 2	Load case 3	Load case 4	Load case 5	Load case 6	Load case 7	Load case 8	Load case 9	Load case 10	Load case 11
Kinematic point (CSYS)	Force, Moment (N,Nmm)											
U1	Fx	-2.E+04	-2.E+03	-1.E+03	-2.E+02	-1.E+04	-1.E+03	-1.E+03	2.E+04	2.E+03	-3.E+03	7.E+03
	Fy	-7.E-01	-2.E+02	-2.E+02	7.E+01	4.E+01	3.E+02	-2.E+02	3.E+01	4.E+01	4.E+01	-8.E+01
	Fz	-4.E+03	-2.E+01	3.E+02	5.E+02	-3.E+03	3.E+02	4.E+02	-4.E+03	-9.E+02	-2.E+03	4.E+03
x= 0,00	Mx	2.E-02	-5.E-02	-2.E-02	-1.E-02	1.E-01	2.E-02	-2.E-02	1.E-01	3.E-02	4.E-02	6.E-02
y= 0,00	My	5.E+01	-2.E-01	-6.E-01	-5.E-01	2.E+01	-6.E-01	-5.E-01	7.E+01	-1.E+00	4.E+00	9.E+00
z= 0,00	Mz	7.E+00	4.E+00	6.E+00	1.E+01	9.E+00	2.E+01	4.E+00	1.E+01	2.E+01	2.E+01	-3.E+00
U3	Fx	2.E+04	-6.E+03	-7.E+03	-5.E+03	1.E+04	-6.E+03	-6.E+03	2.E+04	2.E+04	8.E+03	-7.E+03
	Fy	6.E+01	5.E+02	6.E+02	-1.E+02	-7.E+01	-8.E+02	7.E+02	4.E+00	7.E+00	5.E+01	2.E+02
	Fz	-1.E+04	-3.E+01	2.E+02	3.E+02	-6.E+03	2.E+02	2.E+02	-2.E+04	-9.E+02	-2.E+03	2.E+03
x= 0,00	Mx	1.E-01	-4.E-02	-2.E-01	4.E-02	-1.E-01	2.E-01	-2.E-01	0.E+00	1.E-02	5.E-02	-4.E-01
y= 0,00	My	-3.E+01	-2.E-01	-2.E+00	-2.E+00	-2.E+01	-2.E+00	-1.E+00	-3.E+01	-1.E+01	-7.E+00	-1.E+01
z= 338,00	Mz	7.E+00	4.E+00	6.E+00	1.E+01	9.E+00	2.E+01	4.E+00	1.E+01	2.E+01	2.E+01	-3.E+00
U2	Fx	4.E+02	8.E+03	8.E+03	6.E+03	-1.E+02	8.E+03	6.E+03	6.E+03	-2.E+04	-4.E+03	-2.E+02
	Fy	2.E+01	8.E+02	9.E+02	-3.E+02	-2.E+02	-1.E+03	1.E+03	-1.E+02	-2.E+02	-2.E+02	4.E+02
	Fz	2.E+04	4.E+01	-5.E+02	-8.E+02	9.E+03	-5.E+02	-6.E+02	2.E+04	2.E+03	3.E+03	-6.E+03
x= 404,95	Mx	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00
y= 0,00	My	-2.E+02	-4.E-01	6.E+00	9.E+00	-1.E+02	6.E+00	7.E+00	-2.E+02	-2.E+01	-4.E+01	7.E+01
z= 250,00	Mz	2.E-01	1.E+01	1.E+01	-4.E+00	-2.E+00	-2.E+01	1.E+01	-2.E+00	-2.E+00	-2.E+00	5.E+00
TK	Fx	5.E+00	2.E+01	5.E+01	-6.E+01	-2.E+01	-3.E+02	2.E+01	-2.E+01	-2.E+01	-1.E+01	-3.E+01
	Fy	-7.E+01	-1.E+03	-1.E+03	4.E+02	2.E+02	2.E+03	-2.E+03	1.E+02	1.E+02	7.E+01	-6.E+02
	Fz	-3.E+00	5.E+00	8.E+00	2.E+00	7.E+00	7.E+00	1.E+01	6.E+00	3.E+00	2.E+00	9.E+00
x= 289,25	Mx	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00
y= 2,93	My	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00
z= 320,00	Mz	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00

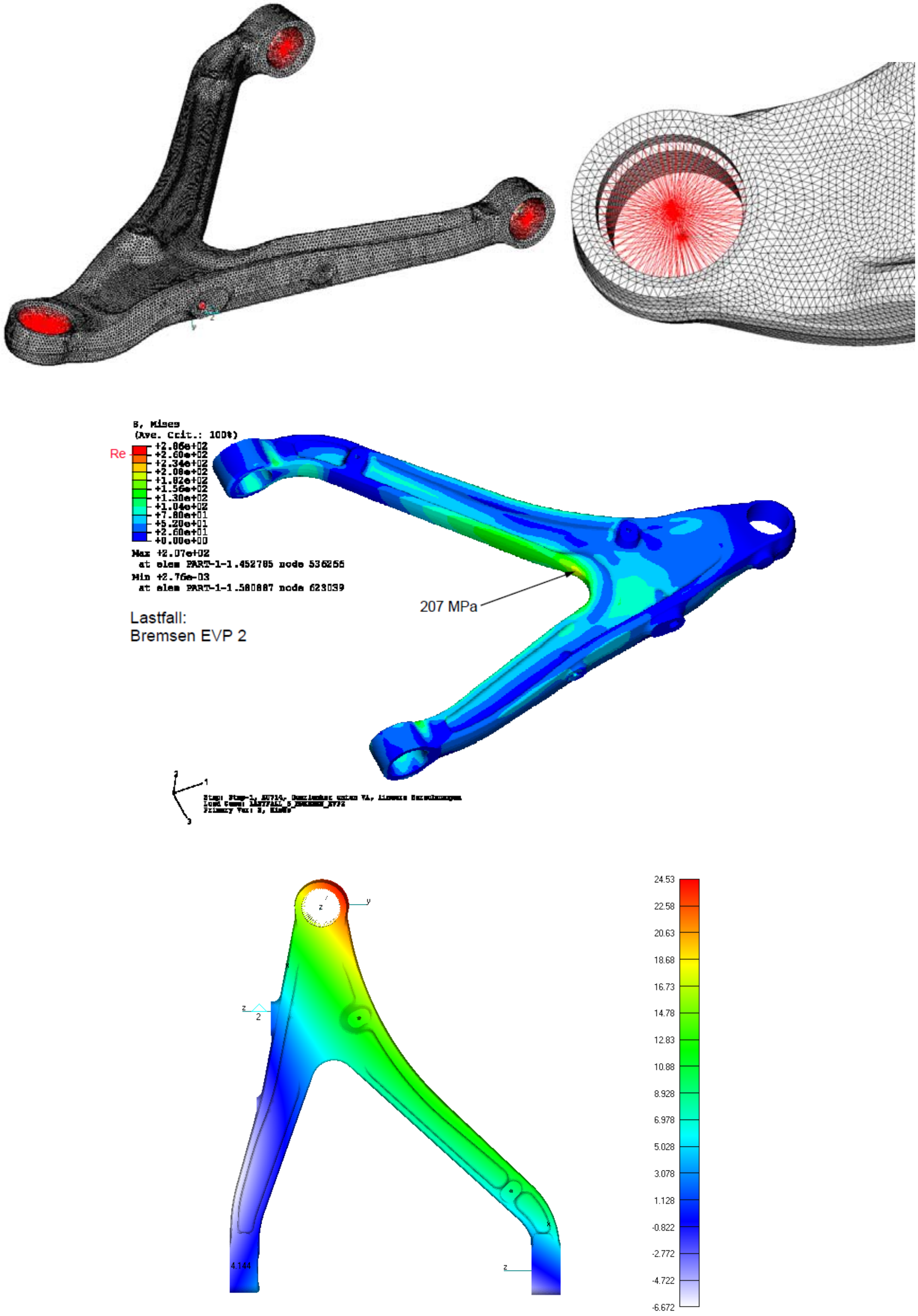


Figure 4. Nastran FEA model (top), maximum Von Mises stress in the worst load condition (center), and maximum deflection in the worst load condition (bottom).

3. DESIGN OF “FORGED COMPOSITE®” SUSPENSION ARMS

MATERIAL SELECTION

The Carbon Fiber Sheet Molding Compound (CFSMC) material is supplied by Quantum Composites. It is comprised of 25.4 mm long carbon fiber tows, randomly distributed into a mat, sandwiched between two layers of vinylester resin. The stack is compacted between rollers into sheet form, and spooled into rolls similar to standard prepreg. The carbon fiber content is 53% by weight. The material is designed for compression molding in a matched metal tool in a heated press. The cure temperature ranges between 270-320ºF (132-160ºC), applied pressure ranges from a 1000-1500 psi (69-103 bars), and cure time ranges from 3 to 5 minutes. The charge has typical mold coverage of 60-70%. The Tg is of the material is 245ºF (120ºC). Minimum part thickness achievable with this material is usually 0.1 in. (2.5 mm).

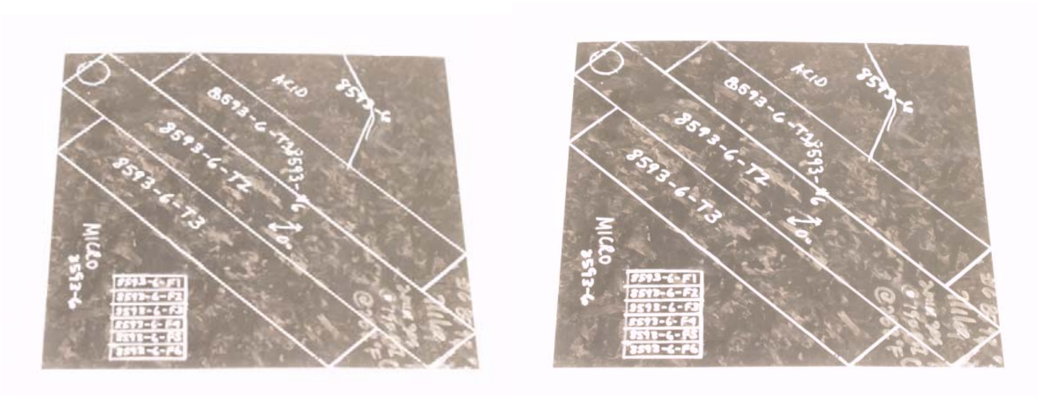


Figure 7. Panel made with Forged composite, before (left) and after sanding (right).

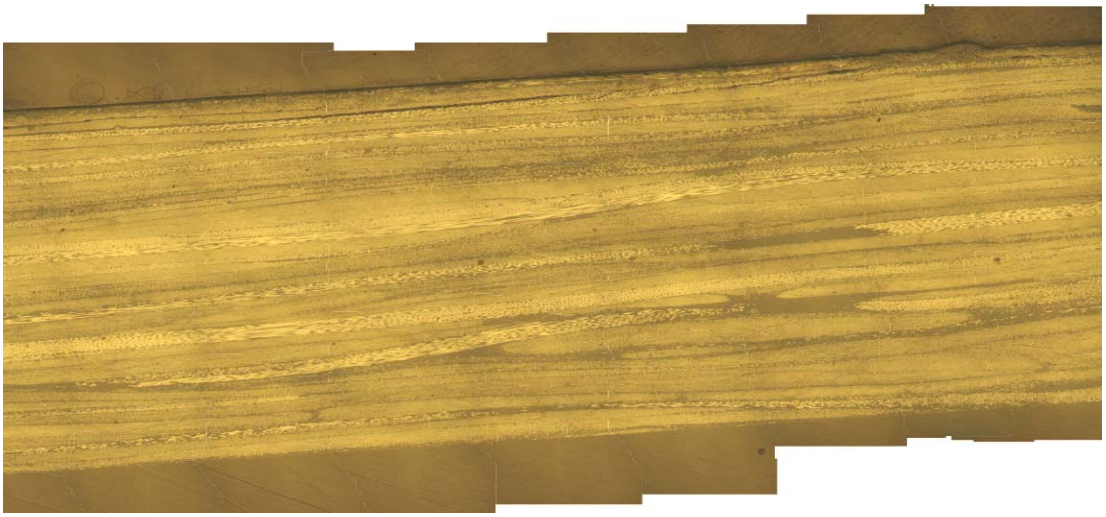


Figure 8. Typical cross section of Forged Composite®, made using CFSMC.

A brief summary of the tensile mechanical properties of the material is reported in Table II, and compared to the baseline aluminum and typical composite materials of use at Lamborghini. The set of properties listed is limited and insufficient for thorough analysis, but can help the reader understand the challenges associated to the design of the suspension arm. A detailed and extensive testing effort was performed to characterize the material's behavior in tension, compression, shear, flexure, interlaminar shear, open-hole properties, filled-hole properties, bearing, compression-after-impact, and dynamic crushing in order to build a statistically significant database and compare to the existing database for traditional epoxy-based materials in use at Lamborghini such as prepreg tapes, prepreg fabrics, RTM fabrics, and RTM multiaxial stitched non-crimp-fabrics. The detailed results are not discussed here.

Table II. Non-normalized tension properties of aluminum and composite materials: for aluminum the minimum yield strength is reported, while for the composites the typical ultimate strength is reported.

Average Properties	Tension strength ksi (MPa)	Tension modulus Msi (GPa)
6xxx Aluminum	37.7 (260)	10.0 (70.0)
Prepreg 2x2 twill quasi-isotropic	108 (745)	6.0 (41.4)
RTM stitched NCF quasi-isotropic	92 (634)	5.0 (34.5)
Forged Composite®	35.8 (246)	4.9 (33.8)

It should be reminded the reader that for discontinuous CFSMC, tensile properties are by the most critical, while compression and flexure are, in the order, significantly higher [10]. This behavior differs significantly from continuous composite material forms, regardless if tape, fabric, prepreg or RTM, where flexural and compressive strengths are much lower than tensile strengths. Another note is that the 3 composite materials utilize the same T700 fiber, but have different fiber volume contents.

Through extensive R&D, Callaway, UW and Lamborghini were able to improve the material as well as the process in order to be able to manufacture parts with lower minimum thickness (as low as 0.035 in. or 1 mm) as well as reduced variation in strength, thus ensuring higher and more repeatable material properties. This improvement was achieved by selectively and locally hybridizing with unidirectional fibers and utilizing low-flow molding. This type of molding uses a mold coverage area of over 90%, and thus minimizes the chance for alignment of the fibers during flow.

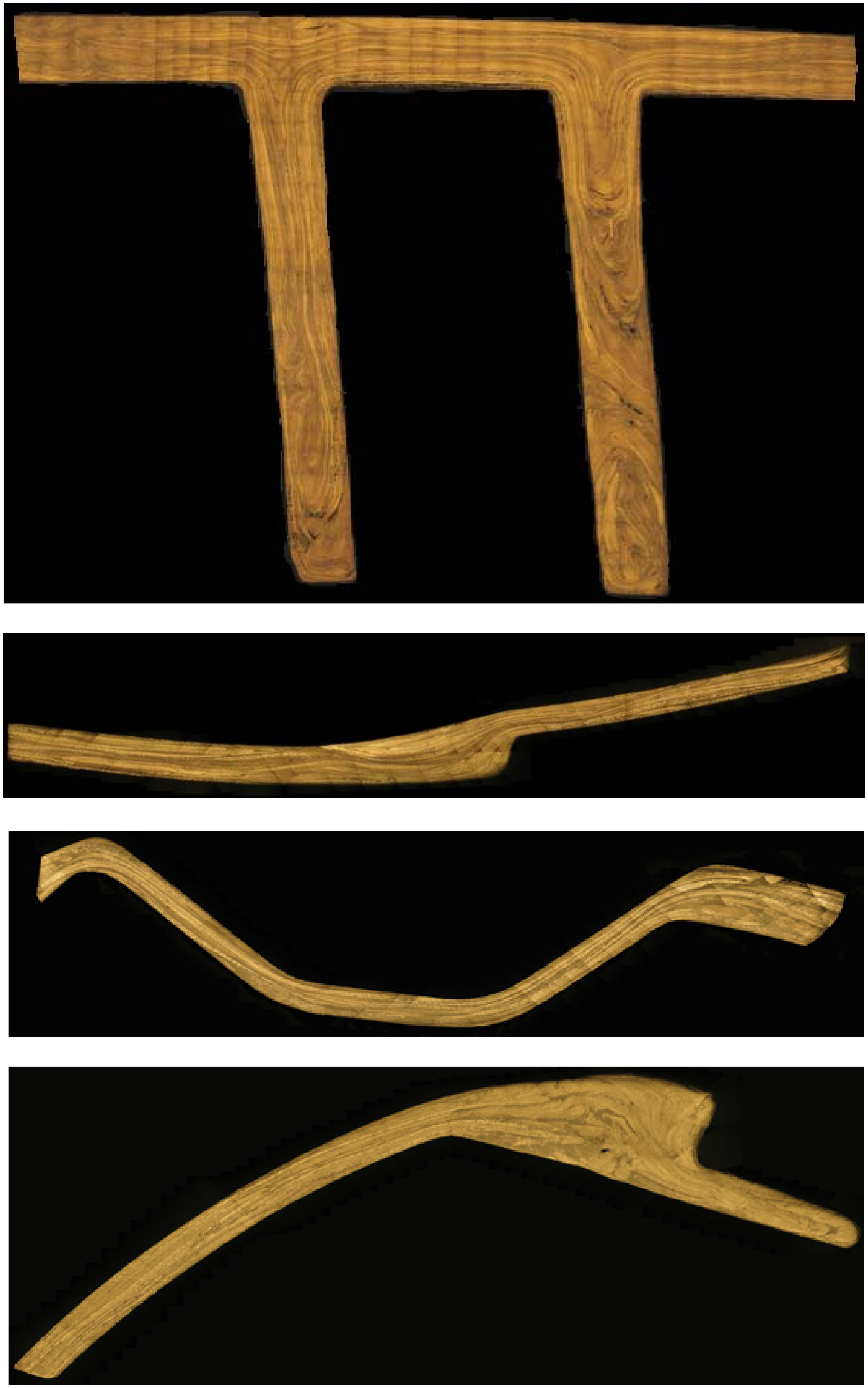


Figure 9 A-D. Complex shapes achievable with Forged Composite® technology.

GEOMETRY MODIFICATION

It can be seen from Table II that the design of the suspension becomes particularly critical in terms of stiffness, since the strength is nearly identical to the aluminum baseline. Direct substitution of the Forged Composite® material with the existing geometry generates a 60 mm deflection in the lateral direction, nearly 2.5 times higher than the aluminum one. While many parameters, such as location and type of attachment points, clearances and outer geometric envelope, could not be modified, it is possible to modify aspects of the inner envelope. The most evident change is the addition of the third cross member, which provides a significant increase in lateral stiffness. Secondly, all webs are thinned in order to allow for the flanges to be increased 20% over the entire surface of the part. Lastly, the seat of the ball joint was made larger in order to accommodate a threaded aluminum insert.

The material is cut into rectangular patterns to form the charge, which is sized based on the nominal weight of the final part. The charge is comprised of a main charge and several secondary charges, which are strategically located. Selective localized unidirectional reinforcements are utilized within the charge. Charge cutting with an automated cutting table takes only seconds, while charge positioning takes 2-3 minutes. Once the charge is ready, the preheated matched aluminum mold is closed and pressure applied. The cure cycle is under four minutes. The part is then extracted from the mold with near net shape, with minor trimming required. The seats (holes) for the bushings are obtained during molding operation with the use of two sliders. The large seat for the ball joint is instead machined after molding using waterjet cutting. The joints used are the same identical ones as for the aluminum suspension. The two steel bushings are inserted by press-fit, while the ball joint is bolted onto a threaded aluminum insert. The insert is surface-coated for corrosion protection and bonded with film adhesive to the composite suspension. The same torque and installation requirements are required and met for the redesigned composite suspension.

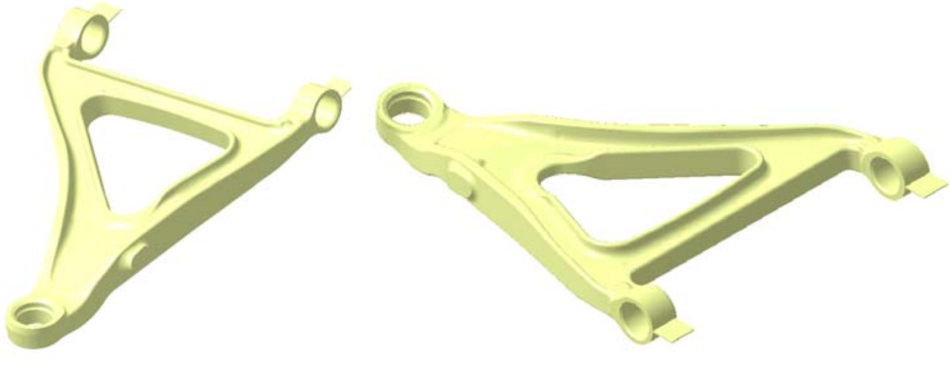


Figure 10. CAD geometry of the redesigned front lower suspension arm.

Figure 11. Two views of the as-molded front lower control arm.

Figure 12. Front lower control arm after machining and installation of the bushings and ball joint.

Figure 13. Front upper and lower arms (left), and rear upper and lower (right) control arms.

The final front lower control arm weighs 1.25 kg for the carbon fiber alone, and 1.4 kg with the bonded aluminum insert. With the addition of the two bushings and the ball joint, the final part weight increases to 2.1 kg, compared to the 2.9 kg of the aluminum construction. A total of 8 arms and 8 different matched-mold sets were manufactured. The final weight saving for the set of 8 control arms, complete of bushings and ball joints, is 4.92 kg (or 27% with respect to the), which is slightly lower than the desired 30%. The weight savings varies among the various control arms, from a high of 32% for the front upper arm, to a low of 22% for the rear upper. The final part cost is highly competitive with the forged aluminum construction, as the total cycle time is just under one hour, from raw material to complete part with bushings and ball joint.

Figure 14. Rea upper and lower cotrol arms installed on the wheel assembly.

4. CONCLUSIONS

Forged Composite® technology, developed as collaboration between Callaway Golf, Automobili Lamborghini and the University of Washington, has enabled the realization of the first carbon fiber suspension control arms that meet the same static and durability requirements of the forged aluminum ones they replace. The technology employs a CFSMC discontinuous carbon fiber reinforced vinylester supplied by Quantum Composites. All eight suspension control arms for the *Sesto Elemento* composite technology demonstrator car, presented at the 2010 Paris Autoshow, have been supplied by the University of Washington to Automobili Lamborghini as finished and certified parts. The paper reviewed the design approach for the lower front suspension arm, which is the most critical of the set. The most critical loading case, associated to braking and cornering operations, imposes high lateral loads, which require the control arms to be redesigned to meet the maximum deflection criteria of the aluminum suspension. The redesigned suspension arms achieve an average weight saving of 27% with respect to the baseline aluminum arms, and employ only 6 minutes from raw material to finished part. Additional time is required to perform the machining of the large center hole, bonding of the insert, and installation of bushings and ball joint.

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References

1. P. Feraboli, A. Masini, A. Bonfatti, "Advanced composites for the body and chassis of a production high performance car", International Journal of Vehicle Design, 44/ 3-4, 2007, pp. 1-14
2. P. Feraboli, A. Masini, L. Taraborrelli, A. Pivetti, "Integrated Development of CFRP Structures for a Topless High Performance Vehicle", Composite Structures, 78/ 4, 2007, pp. 495-506.
3. P. Feraboli, A. Masini, "Development of carbon/epoxy structural components for a high performance vehicle", Composites (Part B), 35/4, 2004, pp. 323-330.
4. Miller, A.G., "The Boeing 787 Dreamliner", Keynote Address, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Waikiki, HI, 2007.
5. "Boeing 787 features composite window frames", Reinforced plastics, Application News, Vol. 51, Issue 3, March 2007, page 4.
6. P. Feraboli, T. Cleveland, M. Ciccu, P. Stickler, L. DeOto, "Defect and damage analysis of advanced discontinuous carbon/epoxy composite materials", Composites (Part A), 41/7, 2010, pp. 888-901.
7. P. Feraboli, T. Cleveland, P. Stickler, J. Halpin, "Stochastic laminate analogy for simulating the variability in Modulus of discontinuous composite materials", Composites (Part A), 41/4, 2010, pp. 557-570.
8. P. Feraboli, E. Peitso, T. Cleveland, P. Stickler, "Modulus measurement of prepreg-based discontinuous carbon fiber/ epoxy systems", Journal of Composite Materials, 43/19, 2009, pp. 1947-1965.
9. P. Feraboli, E. Peitso, T. Cleveland, P. Stickler, J. Halpin, "Notched behavior of prepreg-based discontinuous carbon fiber/ epoxy systems, Composites (Part A), 40/3, 2009, pp. 289-299.
10. P. Feraboli, E. Peitso, F. Deleo, T. Cleveland, P. Stickler, "Characterization of prepreg-based discontinuous carbon fiber/ epoxy systems", Journal of Reinforced Plastics and Composites, 28/10, 2009, pp. 1191-1214.