Lamborghini "Forged Composite" Technology

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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. 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.

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. 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. 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]. 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. The authors have identified three rather unique characteristics, which dramatically set these material forms 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.

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

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. 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 arm is forged using a 6xxx series aluminum alloy. 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.

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, left. 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, right. 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.

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

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

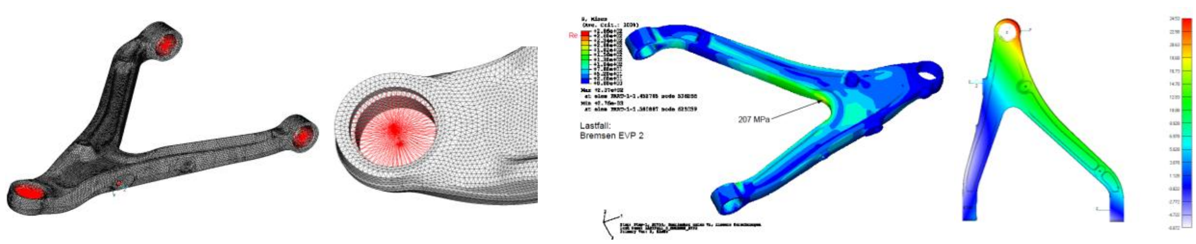

Fig. 4. Nastran FEA model (left), maximum Von Mises stress in the worst load condition and maximum deflection in the worst load condition (right).

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 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%.

Fig.5. Typical cross section of Forged Composite®, made using CFSMC (left). Complex shapes achievable (right).

A brief summary of the tensile mechanical properties of the material is reported in Table I, and compared to the baseline aluminum and typical composite materials of use at Lamborghini. 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.

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].

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.

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)

Table I. Non-normalized tension properties of aluminum and composite materials: for Aluminum the minimum yeld strength is reported, while for the composites the ultimate strength is reported..

Geometry modification

It can be seen from Table I 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. 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. 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. The cure cycle is under four minutes. The part is 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 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.

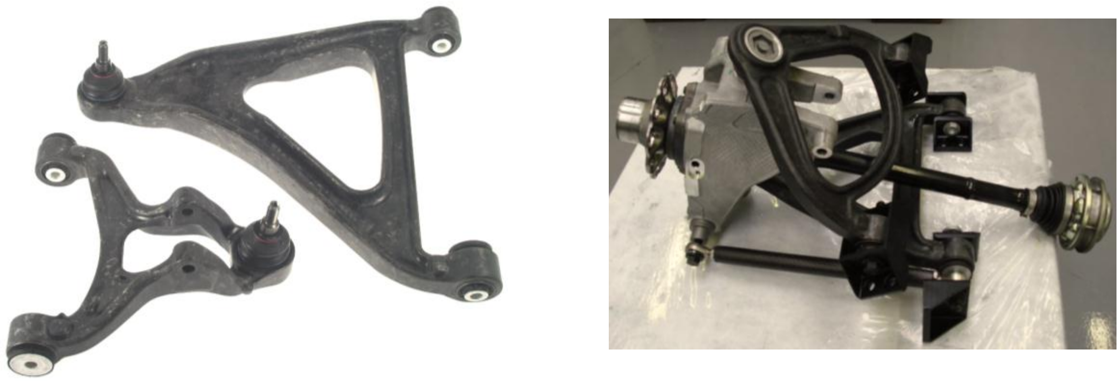

Figure 6. Front upper and lower arms (left) after machining and installation of the bushings and ball joint. upper and lower cotrol arms installed on the wheel assembly

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 baseline aluminum suspension arms). 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.

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.

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