
Advanced composites for the body and chassis of a production high performance car

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Abstract: Carbon fibre composites can offer a great deal of weight saving and manufacturing flexibility in the design of a high performance vehicle, while decades of research in metal science have produced manufacturing techniques that guarantee perfect surface finish, alloys that can withstand weathering agents during the lifetime of a vehicle and very reliable joining methods, these relatively new materials require constant evaluation in automotive applications to ensure equal if not greater performance than their metallic counterpart. This paper highlights the fundamental contributions of advanced composites in the production of the body panels and integrated chassis components for the Murcièlago and Murcièlago Roadster.

Keywords: composites; carbon fibre; manufacturing methods; class A surface; environmental effects; adhesive bonding.

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Biographical notes: Paolo Feraboli joined the Department of Aeronautics and Astronautics at the University of Washington in the summer of 2005, as Assistant Professor in Aerospace Structures and Materials. He was previously a Visiting Researcher at NASA Langley Research Center in the Mechanics and Durability Branch. He earned his PhD from the University of California at Santa Barbara and holds a degree in Mechanical Engineering from the University of Bologna, Italy. His major areas of interests are composite structures design for damage resistance and tolerance and vehicle safety certification. He is chairman of the MIL-HDBK-17 Working Group on

Crashworthiness and an active member of AIAA, SAMPE and ASC. Prior to moving to the States he worked for Automobili Lamborghini S.p.A. in Sant'Agata Bolognese, where he was involved with the development of an all-carbon-composite door for crash certification for the Murcièlago lineup.

Attilio Masini joined Automobili Lamborghini S.p.A. in 1985 and was assigned to the newly formed Experimental Composites Department. With the introduction of glass fibre reinforced composites in the production components of the Countach Quattro Valvole and 25th Anniversary (1986–1988) and the Diablo (1990), Attilio became supervisor of the Composites Production Division. In 1998, he became the head of a newly formed Advanced Composites R&D Division, which develops experimental components and prototypes for future vehicles, including the Diablo GT (1998). From initial design (1998) to introduction on the market (2001) of the Murcièlago, Attilio supervised every project involving carbon fibre reinforced composites within the company. In 2003 he became a Team Leader for the Murcièlago Roadster Technology Integration. He is currently promoting the insertion of advanced composite materials into primary crashworthy structures for the next generation of high performance vehicles.

Andrea Bonfatti joined Automobili Lamborghini S.p.A. Engineering Division in 1992, with the task to design the engine and gearbox for the Formula 1 racecar and in 1994 was assigned to the Body and Frame R&D Department of the production vehicles. In 1998 he became Technical Head of the space-frame design group, thanks to his prior experiences at Bugatti and BMW and since 2000 he has been the Managing Director of the Body and Frame R&D Department. Within such Department, comprising over 50 engineers, falls the Advanced Composites Division, led by Attilio Masini, with whom Andrea has been actively involved for the development of CFRP components for the Diablo MY2000, GT and GTR, as well as Murcièlago and Murcièlago Roadster. She is currently pursuing the introduction of new processing technologies and material forms in the area of advanced composites, in order to broaden their application in the future supercars of the factory of Sant'Agata Bolognese.

1 Introduction

The Murcièlago (Figure 1) presents an entire carbon/epoxy body (bumpers, fenders, etc.) except for the doors and the roof/pillars structure. Use of composites for this application allows for a weight saving of 34 kg (about 40%) over its predecessor, the Diablo, which presents an all-aluminium body. Carbon/epoxy composites structural components for the integrated chassis (Figure 2) include the transmission tunnel, floor pans and wheel housing panels, see Feraboli and Masini (2004) and in the Murcièlago Roadster (Figures 3 and 4) the doorsill stiffeners and the engine bay subframe, see Feraboli et al. (2006). The expensive process of the hand lay-up and autoclave curing of prepreg carbon/epoxy composites is justified by the specific technical advantages that these materials can be engineered to offer. Particularly, the high specific stiffness required for better handling and performance; the high specific strength required for improved safety and crashworthiness; their aptitude to be recycled in order to conform to newer and more severe regulations; the ability to be quickly shaped for rapid prototyping and product modifications; the lower tooling costs necessary for limited annual production, which

compensate for the higher material and process costs; the higher geometric tolerance and surface finish that they offer as-moulded (net shape moulding); their aptitude to be formed in complex, low part-count components (part consolidation), and their increased durability typical of thermoset polymeric materials which offers resistance to environmental and chemical corrosion.

Figure 1 The CFRP body components of the murcièlago include the four fenders, the front and rear bumpers, the large rocker panels, the variable geometry air intakes, the front hood and the rear engine bonnet



Figure 2 Tubular chassis of the Murcièlago. CFRP structural components comprise the floor pans, the wheel housing and the transmission tunnel

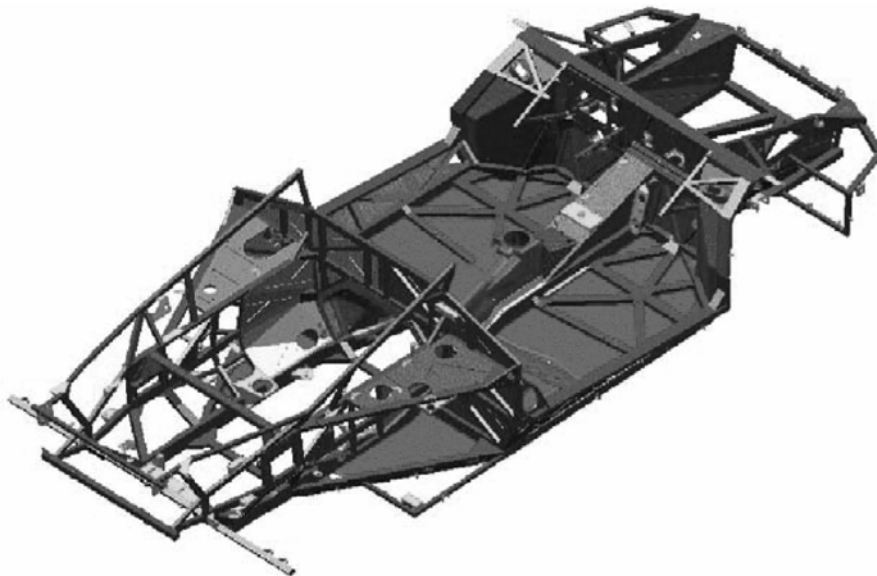


Figure 3 Three-quarter view and cutaway of the 2005 Murciàlago Roadster highlights the all CFRP body panels, which are adhesively bonded to the hybrid CFRP/tubular steel chassis

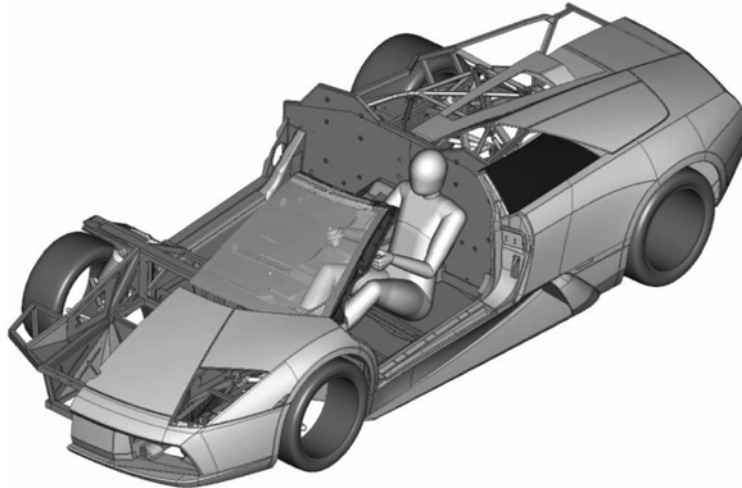
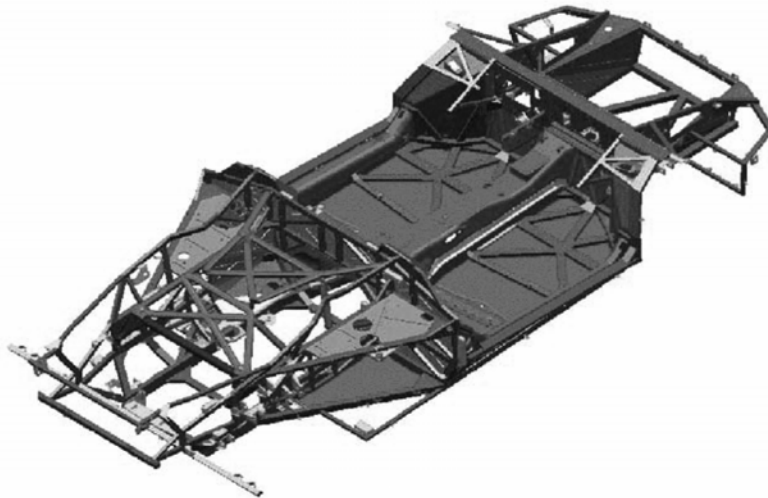


Figure 4 Chassis of the 2005 Murciàlago Roadster. CFRP members now include an elongated and reinforced transmission tunnel, the doorsill stiffeners, the reinforced wheel housing panels, and the engine compartment subframe



The chassis of a car is the framework that provides the mounting points for the suspensions, as well as the support for the steering mechanism, the power train, the fuel tank and the seats for the occupants and every additional electrical cable and fluid line fundamental for the operation of the vehicle. While fulfilling these functions, it has to provide sufficient rigidity for accurate handling, absorb crash energy for the safety of the occupants and resist operational static and cyclic loads due to the interaction with the road. Lastly, it needs to be light enough to increase fuel economy and speed and to reduce inertia, thereby increasing performance, as we learn from Campbell (1955).

A chassis is typically designed for stiffness rather than strength. It has to be stiff enough not to influence the dynamical behaviour of the vehicle and to resist large deformations, which can deteriorate the mechanical properties of joints and components. The concept of torsional stiffness is fundamental from the handling perspective, since it allows the lateral (i.e. cornering) loads to be distributed from front to rear, proportionally to the suspension roll stiffness. It is therefore an indication of the ability of the vehicle to closely follow the road surface, see Saccone (2004). From the early days of automotive design, the appearance of the chassis has changed dramatically: large-volume passenger cars are currently built with a unibody approach, whereby the classical box frame has disappeared and each body panel is a load-carrying member, see Jambor and Beyer (1997), Bruderick et al. (2002) and Voss et al. (2003). On the other hand, low-volume, high-performance, super-luxury cars are built with either a complex spaceframe approach or a monocoque design, while body panels are not significantly stressed. A typical spaceframe is comprised of transverse members or bulkheads, which provide the majority of strength and stiffness, interconnected by longitudinal and diagonal hollow tubular sections. The integral design of a monocoque chassis has instead the advantage of providing the highest stiffness to weight ratio, particularly if built employing lightweight materials such as Carbon Fibre Reinforced Polymers (CFRP). However, while the fixed costs associated with the use of CFRP materials are sensibly lower, the variable costs remain higher due to the inherent cost of the raw material and the highly labour-intensive process (hand lay-up, vacuum bag and autoclave cure), therefore the vehicles employing a composite monocoque approach for the entire passenger compartment are usually very limited production vehicles.

A common measure of torsional stiffness is the twist produced under torsion, see Feraboli et al. (2006), having units of N m/deg, which is obtained by measuring the maximum deflection of the vehicle that occurs under a prescribed load applied at the front axis, with the remaining one clamped. While modern passenger cars exhibit average torsional stiffness values of 10,000 N m/deg, high performance vehicles need to exhibit much higher values, in the range 15,000–30,000 N m/deg. In this context, the original Lamborghini Murcièlago Coupe exhibits a total of 21,000 N m/deg for the chassis-body assembly while the Lamborghini Gallardo Coupe achieves 28,000 N-m/deg thanks to its aluminium monocoque construction and its smaller dimensions. This paper summarises the contribution of advanced composites to the development of the body panels and chassis components of the Lamborghini Murcièlago and Murcièlago Roadster.

2 Body panels

2.1 Materials

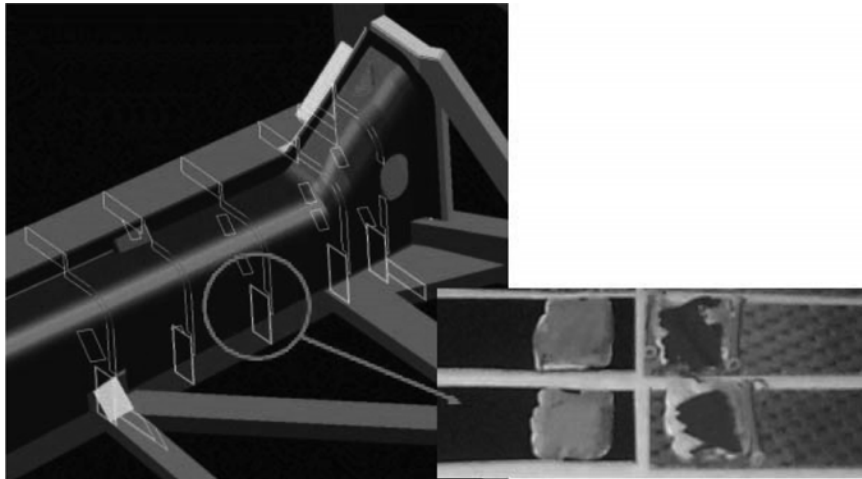
The average body panel laminate thickness is designed to be 1.4 mm thick, except for those areas where additional bending stiffness is required and a Nomex™ (aramid) honeycomb or Rohacell™ (polymethacrylimide) foam core is employed, in the thickness of 3, 6 and 10 mm. The laminate is comprised of three plies oriented in the 0/90 direction, namely a 2 × 2 twill 0.2 mm thick at the surface, followed by a 0.4 mm thick five-harness satin and another 2 × 2 twill 0.7 mm thick. More complex weaves, such as 5- or 8-harness satins, allow for less fibre crimping, hence the 2 × 2 twill is

preferred to the plain weave in the outermost ply in order to achieve the highest degree of surface finish (Class A). The increasing ply thickness, due to the higher Fibre Areal Weight (FAW), as well as the extremely complex contours of the geometry prevent the laminate from distorting after the cure. As mentioned in the introduction, the body panels (e.g. the fenders) are not inherently structural and are not required to meet specific strength requirements. Their design is stiffness-dominated, as they need to maintain the shape under the aerodynamic loads, as well as not bend excessively under their own weight (e.g. engine bonnet) or during operational loads (person leaning against the panel). For moving structures (e.g. the trunk), the strength of the joint, such as a latch, becomes the key to ensure safe operation.

2.2 Joining

The body panels, such as the four fenders, are adhesively bonded to the underlying structural space frame, which is comprised of square tubular steel members, see Feraboli and Masini (2004). Adhesive ductility is an important factor in minimising the adverse effects of shear and peel stress peaks in the bond layer. Because of the single lap joint configuration of the actual structure (Figure 5), it is important to allow for a certain degree of joint flexibility. Therefore, although epoxy adhesives are used, both in film and paste form, for the assembly of CFRP components (e.g. the inner shell and outer skin of the trunk lid), methacrylate adhesive is chosen for this application because of its intermediate mechanical properties. Polyurethane-based adhesives, on the other hand, proved to be too compliant.

Figure 5 Typical structural adhesive joint between a CFRP component (the door sill stiffener in this case) and the tubular steel chassis element. The single-lap joint configuration is visible and justifies the simple test method



The carbon/epoxy adherends (e.g. the skin) are 1.4 mm thick, while the nominal bond line thickness is 2 mm, with a ± 1 mm allowable, see Feraboli and Masini (2004). As previously observed these thickness values are an order of magnitude greater than in the case of high performance aerospace adhesive joints, which are in the range of 0.2 mm thick as reported by MIL-HDBK-17 (2002a,b), but are however very close to the values

used in General Aviation aircraft. Previous research on laboratory-sized specimens by Satoh et al. (1996) used 0.15 mm thick epoxy adhesive for the joining of steel and aluminium automotive structures. However, such tight tolerances are hard to achieve in real automotive structures, because of the need to ensure actual contact between the large, bulky components. While a thinner bond line provides a better the mechanical response, see MIL-HDBK-17 (2002a,b), below a certain adhesive thickness structural integrity might not be ensured, due to the inaccuracies that can manifest during the manufacturing of the adherends or the bonding operation. The components are held in place by means of clamps during the 2 hr room-temperature cure of the adhesive. Prior to the application of the adhesive, the bonding areas on the panel and on the chassis are thoroughly wiped with Methyl Ethyl Ketone (MEK) and Isopropanol Alcohol (IPA), for the composite and the steel adherend, respectively. It has been shown by Phariss et al. (2005), Smith (2005) and Bardis and Kedward (2002) that surface preparation is fundamental in achieving a good joint and that the use of the correct peel ply (release film) and surface cleaning can greatly improve the strength of the joint. On the other hand, grit blasting has shown mixed results in improving lap shear strength, therefore sand blasting is not performed, also because it would not be practical over such a large bonding area.

2.3 Environmental degradation

Three tests are used sequentially to assess a composite system's resistance to environmental degradation, namely water resistance at 100% humidity, water immersion and operating light exposure, see Feraboli and Masini (2004) and MIL-HDBK-17 (2002c). Only those resin systems that survive a stage advance to the following one, thus the number of candidate systems at the end of the process is usually quite low. In the Q-Fog Cyclic Corrosion Test Chamber, water is evaporated with heat supplied by an electrical resistance and condensed on the painted or varnished coupons. The following test, the water immersion, is performed for the sake of completeness, but has so far been of little additional use. The last test, the weatherometer, is the most stringent because it combines all environmental degradation effects (UV radiation, heat and humidity). The resin and composite systems that are selected for the final application on the Murcièlago are the ones that are free of imperfections after accelerated environmental degradation and these include blistering, laminate distortion, paint tone changes, loss of adhesion (delaminating/debonding), softening, embrittlement, crazing, cracking, flaking, chemical separation and fibre exposure, see Feraboli and Masini (2004). During the design phase of the Roadster, numerous and evident changes were made to the engine bonnet, both for aesthetic purposes and practical considerations. The absence of the roof structure forces changes to the aerodynamics of the vehicle and the way it looks. The bonnet was redesigned to open from the front, thus the hinge was moved from its fore location, where it was on the Coupe, to the aft location on the Roadster. Furthermore, its geometry was radically changed to a streamlined design that follows the headrests and pop-up roll bars. The new geometry is quite complex (Figure 6) and it features a number of sharp corners on the outer class-A surface. These changes led to the occurrence of visible blistering and cracking of the paint, which were solved only after numerous trials and reworks. Among the unsatisfactory trials, the lamination of metallic inserts in the lay-up or the adoption of more gentle corners were identified as the most suitable, while changes in the material system did not yield noticeable improvements. The problem was

solved thanks to the adoption of unidirectional tape, rather than the typical twill, in the proximity of these radii, since the one-dimensional tape allows for better evacuation of air bubbles than the twill architecture, as mentioned by Feraboli and Masini (2004).

Figure 6 Typical blistering and cracking problems that can be observed in the manufacturing of class A components with complex geometries and large surfaces



2.4 Manufacturing

The specific procedure adopted in order to achieve class-A surface certification involves the entire manufacturing process and the guidelines are here summarised.

Pattern: models or patterns are milled with CNC machinery from epoxy resin blocks on the CAD model supplied by the technical development team. Dimensional tolerances are ± 0.5 mm by design. After the milling operation, the surface of the pattern is opaque and visual inspection difficult, hence it is polished with a layer of translucent black epoxy, which facilitates inspection. Finally, a layer of release coat is painted on the pattern and cured in the oven before creating the moulding tool.

Moulding tool: special mould epoxy resins are used and ad hoc systems are researched in order to give the best curing parameters. Polymerisation temperature and time are kept the lowest admissible (around 45°C), in order to reduce deformations and strains. Since the temperature increase in the mould is proportional to its mass, the volume is minimised by employing concave moulds (internally empty). Thus temperature gradient is higher and temperature distribution more uniform. Optimum thickness along the tool is found to be around 100 mm for dimensional stability. Individual plies are placed on the model ensuring that ply pick-ups and drops occur outside of the plane surfaces, in order to avoid marks. Geometrical considerations are also important in order to offer an operator-friendly ply lay-up. Six fresh layers of wax are applied, which at such low curing temperatures act both as a release agent and as a filler for microporosities, thus avoiding the need for fillers. Post-curing of the mould is necessary in order to increase its T_g up to processing temperature of $130\text{--}180^{\circ}\text{C}$. Lastly, the mould is polished with an abrasive paste, which ensures better finish and release properties, then painted with 12 layers of release coating, which is cured in the autoclave prior to the first tooling operation.

Moulding operation: before each moulding cycle, a fresh, thin layer of release agent is applied, then cured. Then, an epoxy primer is applied, which will then be partially sanded off after the cure and before the painting. The use of such primer has increased the quality and smoothness of the surface by 30%. After a brief time in the oven, the mould is finally ready for the prepreg lay-up, vacuum bagging and curing process. Relatively low-pressure curing and fine fibre weaves are necessary in order to avoid unacceptable amounts of porosity and markings on the surface.

Paint: after extraction from the mould, the components are finished off by removing the excess resin (flash). The epoxy primer outer layer of the component is sanded in order to activate fresh molecules in the lower layers, which offer better adhesion to the paint. A polyurethane primer is applied before the final painting operation with polyurethane spray. In the case of varnished (unpainted) components which allow for carbon fibre weave exposure, the matte epoxy primer cannot be employed, therefore application of the release coat is followed by a hand-brushed layer of the transparent epoxy resin used for the prepregs, thus avoiding the need for gel coats.

3 Chassis components

The Murcièlago transmission tunnel (Figure 2) is a monolithic 2×2 twill laminate of total thickness 4 mm, oriented in the ± 45 direction. The orientation is justified by its high torsional properties, required by the application. The use of the twill instead of the tape is due to the fabric's better drape-ability or ability to closely follow complex shapes. The tunnel is adhesively bonded to the metallic subframe with the same methacrylate adhesive used for bonding the outer skins. In the Coupe the tunnel ends halfway in the passenger compartment (Figure 2), but in the Roadster its length is extended to reach the front firewall (Figure 4), thereby further increasing the overall bending rigidity of the vehicle and providing a more favourable load path. It is furthermore reinforced with the introduction of eleven unidirectional plies, each 0.15 mm thick, oriented longitudinally, thus increasing its thickness to 5.7 mm (Figure 7).

Figure 7 New CFRP structural components on the Roadster include an elongated transmission tunnel and the door sill stiffeners



The floor pans (Figure 2) are CFRP sandwich laminates and are designed to exhibit high bending stiffness. The skins are comprised of two [0/90] and one [± 45] fabric plies face-sheets, the core is a 5 mm-thick aramid honeycomb and epoxy film adhesive is used to bond the core to the skins. The core terminates 40 mm away from the edge of the component, where the facesheets taper down to form a 6-ply form symmetric and balanced peripheral border. In this area, which is 5 mm thick, the CFRP pans are mated to the steel chassis by means of hybrid joint, comprised of methacrylate adhesive and steel rivets, see Feraboli and Masini (2004). The corrosion-resistant rivets do not contribute to the strength of the joint by design, but provide added safety for potential out-of-plane (peel) load conditions that may occur.

During an early offset frontal crash test of the Roadster, the passenger compartment demonstrated a tendency to buckle in the front doorsill area, due to the intrusion wheel/brake/suspension assembly, which in turn prevented the post-crash operation of the door. The portion of the front firewall corresponding to the wheel housing (Figure 4), originally comprising six fabric [0/90] oriented plies, is reinforced with eight unidirectional (tape) plies, equally distributed in the [+45] and [-45] orientations, for a total thickness of 4 mm. In the effort of replenishing the loss of mass and structural integrity due to the absence of the roof structure in the Roadster, new doorsill stiffeners (Figures 4 and 7) are added to provide increased bending stiffness and crash resistance. The stacking sequence is comprised of six [0/90] five-harness satin plies, which constitute 4 mm of the laminate, heavily interleaved by groups of unidirectional plies oriented in the axial direction, which contribute an additional 4.7 mm. In the event of a crash, these members are designed to transfer, together with the transmission tunnel, the kinetic energy from the frontal crush members through the passenger compartment, toward the rear bulkhead, where the majority of the vehicle's mass is contained (the 12-cylinder engine/power train assembly constitutes a large portion of the curb weight of the vehicle). These inner stiffening members are also adhesively joined to the tubular steel chassis by means of methacrylate adhesive and contribute in resisting a large portion of the load coming from the wheel assembly, preventing it from intruding in the passenger compartment. Altogether, the reinforced wheel housing panels, the newly designed doorsill stiffeners and the extended transmission tunnel provided a great deal of improvement to the crash performance of the vehicle, which was successfully certified to both US Federal Motor Vehicle Safety Standard (FMVSS) and European New Car Assessment Program (Euro-NCAP).

4 The roadster subframe

The single, most complex, CFRP structure found in the Roadster is the rear tubular subframe, which embraces the entire engine bay (Figure 8). It is introduced in the roofless vehicle to increase its torsional rigidity below its beltline. The subframe is required to have high stiffness, resist the (cyclic) loads coming from the rear suspension attachments and removable in order to allow for the servicing of the engine and to be light, not to penalise the overall weight of the vehicle. Most importantly, it has to fit within the existing limited geometric envelope, since rearrangement of the engine mounting points would not be admissible. Advanced composites are particularly appealing for this application, because of their low density and their static and dynamic fibre-dominated (tension and compression) mechanical properties. Aesthetic

considerations are also important for an application such as this one, which is constantly exposed to the customer's view, and the use of a carbon fibre weave for the outer ply becomes particularly attractive. Lastly and perhaps most importantly, these materials allow for greater design versatility, if properly engineered. The use of carbon fibre composites allows the engineers to tailor their design to maximise the stiffness of the subframe within the given envelope. With CFRP it is possible to adopt an elliptical cross section for the cross members, which contributes to achieving a greater moment of inertia for a fixed vertical dimension (shell height).

Figure 8 The engine bay subframe, featuring transparent CFRP struts and titanium-coloured CFRP joints

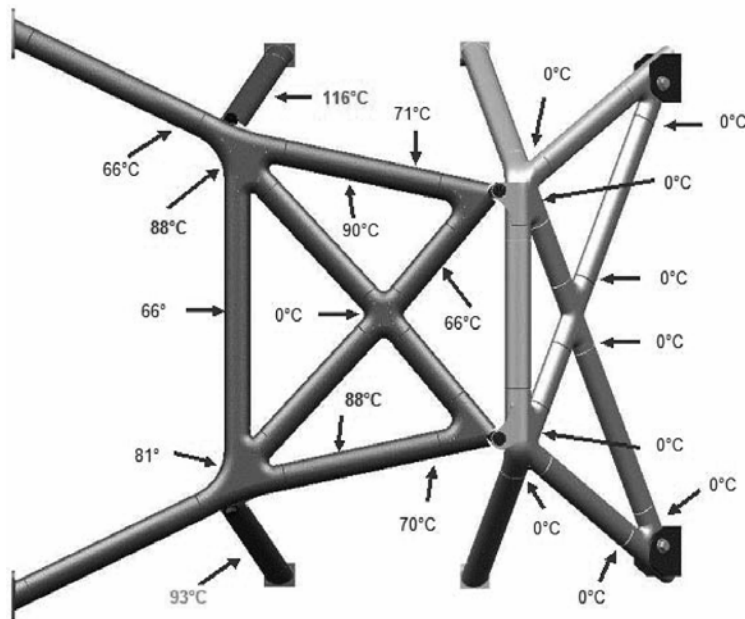


An important consideration in the design of the subframe is the temperature distribution within the engine compartment, which reaches 116°C (Figure 9). Careful selection of the composite system is aimed at ensuring that the glass transition temperature (T_g) of the resin is well above the maximum operating temperature and as a rule of thumb a minimum of 25°C is selected. Therefore resins that cure at or around 120°C are not suitable for this application and resins with a T_g of 149 or 177°C are needed.

From conception to final production four different manufacturing methods are considered for the production of the subframe. The first CFRP subframe is developed by hand lay-up of prepreg tape over an aluminium mandrel, followed by vacuum bagging for autoclave cure. The subframe is comprised of 17 separate struts, of lengths ranging from 100 to 350 mm. Each strut has an elliptical cross section, with axes 39 and 25 mm long. It therefore fits within the 25.4 mm available envelope given by the distance between the outermost engine surface and the lowest point of the engine bonnet. The wall is 3.4 mm thick and the laminate stacking sequence is comprised of both fabric and unidirectional plies, namely $[(0/90)_2/0_2/(\pm 45)/0_2/(\pm 45)/0_2/(\pm 45)/0/90]_T$. Joining of the individual struts is performed with CFRP elements, which are laminated and cured separately. These elements can bring together two to four struts and can exhibit complex three-dimensional geometries. The struts are mated to an internal (pseudo-conical) tapered sleeve by means of tubular lap joint. The clearance between the strut (outer adherend) and the sleeve (inner adherend) ranges from 0.2 to 0.5 mm. A paste epoxy adhesive is employed for this application because of its more forgiving nature,

which allows for compensating inevitable manufacturing inaccuracies. The class-A struts are painted with a transparent polyurethane finish, in order to expose the 'checkerboard' pattern of the plain weave, while the joints are painted with a titanium-coloured polyurethane paint. Although the subframe thus developed successfully meets the stiffness requirements and weighs only 6.85 kg, the hand lay-up over male mandrel process leads only to fair results with regards to surface finish. This is mainly attributable to the extensive amount of post-cure finishing (e.g. sanding) required to clean the outer surface. It also proves excessively time consuming both in the lay-up and bonding operations, thereby leading to unacceptable costs, see Feraboli et al. (2006).

Figure 9 Maximum temperatures recorded on the CFRP subframe measured during controlled operation of the vehicle



The second manufacturing trial is performed with tube rolling, a technique used extensively for the manufacturing of golf shafts, where the individual plies are rolled over an aluminium mandrel and subsequently wrapped with an external thermo-retractable material (cello-wrap) before being cured in an oven. Although more economical than hand lay-up, this process exhibits numerous disadvantages, mainly the even greater amount of sanding required to remove the imprint of the wrapping material and the non-uniform laminate thickness, which is a direct result of the non-uniform pressure distribution between the sides and the radii. The variable thickness of the resulting laminate (± 0.4 mm) affects the bond-line clearance and delays the bonding operation.

The third solution involves a technique used successfully for the manufacturing of complex commercial applications, such as high performance bike frames. The bladder moulding process consists in an external aluminium tool and in an internally pressurised Nylon™ bladder, which substitutes function of the traditional vacuum-bag. The component is cured in a regular oven, rather than in an autoclave and allows for a near

as-moulded class-A surface finish, see Feraboli and Masini (2004) and Feraboli et al. (2006) since the exterior of the component is on the tool side. This process allows for manufacturing of enclosed parts, such as the terminating subframe members, since the internal bladder can be left inside the component at the end of the cure (Figure 10). The whole subframe can be manufactured in two complex, large components (Figure 11). These components are connected by means of universal ball joints, which are incorporated in the component during the lamination process, in the same fashion as other metallic inserts. The costly and time-consuming practice of adhesively bonding each tubular member to a separately is then avoided altogether and the structural integrity of the component is increased due to the continuity of the one-piece construction. With the bladder moulding process, the cost of the final component is over three times lower than the first two methods, and the total weight is further decreased to 5.2 kg.

Figure 10 Cross section of the production subframe exhibiting the distortion of the laminate at the location of the 'joint', following the bladder moulding process

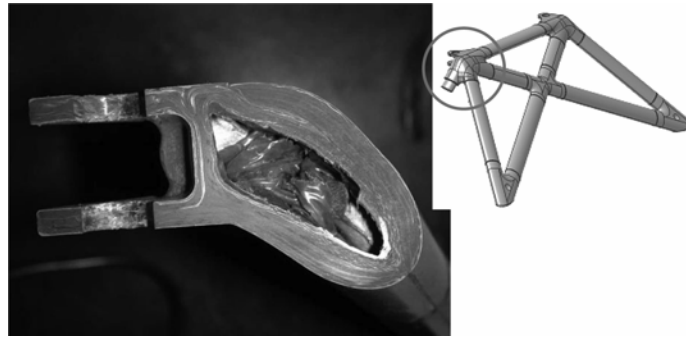
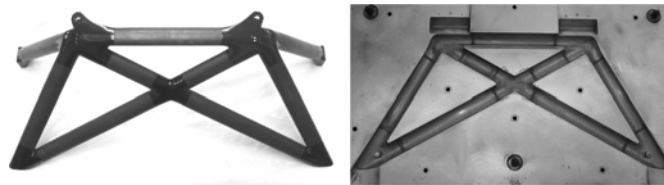


Figure 11 Lower half of the final subframe, obtained as a single component through complex tools for the bladder moulding process



The fourth and last method investigated, which is adopted for the production of the subframe, is a slight modification of the bladder moulding process. The main difference is that rather than laying the plies in the female mould before inserting the pressurised bladder, the plies are wrapped around the pressurised male mandrel and then closed in the female mould. This method facilitates the lay-up procedure and ensures better part quality thanks to the greater control over the fibre orientation.

5 Conclusion

Development of body panels and chassis components for the Murciélago and Murciélago Roadster using advanced carbon fibre composite systems has been discussed. Laminate design, surface quality, accelerated degradation investigations and dissimilar material

adhesive joints were reviewed. Final specification of composite components for exterior (body) and structural (chassis) applications was described and technical and technological requirements summarised. The Roaster features an advanced tubular subframe, first of its kind, whose engineering design and manufacturing was discussed. Several other reinforcing members were introduced below the belt line of the vehicle to increase its dynamic performance and contributed in achieving the desired value of torsional rigidity.

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