Available online at www.sciencedirect.com
SCIENCE DIRECT
Composites: Part B 35 (2004) 323–330
composites Part B: engineering
www.elsevier.com/locate/compositesb

Development of carbon/epoxy structural components for a high performance vehicle

Paolo Feraboli[a,*], Attilio Masini[b]

[a]Department of Mechanical Engineering, University of California, Santa Barbara, CA 93106, USA
[b]R&D Advanced Composites Materials, Automobili Lamborghini S.p.A., Sant'Agata Bolognese 40019, Italy

Received 20 February 2003; accepted 1 November 2003

Abstract

Development of the carbon/epoxy body panels and structural components of the Lamborghini Murcièlago is discussed, while use of aerospace grade technology and materials is justified for this particular application. The influence of fiber architecture on the strength of a composite panel for the same fiber/resin system is discussed, with a focus on the two failure modes usually considered the most critical in designing with polymer composites, delamination and flexural failure. Investigation covers four prepreg tapes and two fabrics, and the use of woven laminates over directional tape is motivated. Resin impregnated carbon fiber components can offer a great deal of weight saving with respect to their predecessors in high performance sport cars, high grade steel and aluminum, yet, while decades of research in metal science have produced manufacturing techniques that guarantee perfect surface finish, alloys that can withstand weathering agents during the vehicle lifetime, 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. Engineering solutions for tooling operations in order to achieve class A surface certification are summarized. Design for environmental aging as well as accelerated degradation testing methods such as ASTM D2247 Cleveland and weatherometer ASTM G26 are described. Development and implementation of hybrid adhesive bonding as sole method of joining the composite body components to the tubular steel chassis is reviewed.

Keywords: Fiber architectures; B. Delamination

1. Introduction

1.1. Background

Composites have been a long-time acquaintance for the automotive industry. They offer great deal of weight saving with respect to monolithic structural materials, but more importantly, if properly designed they represent the ideal engineering material for the wide variety of tasks they can be tailored to perform.

Composites are currently employed on both ends of the spectrum of automotive applications: at the lower end of the scale, the high volume (200,000 exemplars per year) commercial vehicles, which make use of randomly oriented glass fibers as sheet molding compounds (SMCs) or preforms embedded in rapid-curing polyester resins for RTM-type processes [1,2]. At the higher end, the low volume racing vehicles of Formula 1 or Indy championships (1–30 exemplars per year) which employ fighter-jet technologies such as vacuum-bag, autoclave high modulus and high strength carbon/epoxy prepregs [3]. In between find their collocation, closer to the lower end, the relatively high volume and relatively high end sport vehicles (5000–20,000 per year) [4,5], that adopt fiberglass mats with selective unidirectional reinforcements in thermoplastic or lower grade thermoset resins for semi-automated processes; and closer to the high end, lower volume and higher end (50–500 per year) sport-luxury vehicles, as in the case of the Lamborghini Murcièlago [6], which are currently turning to continuous fiber, high grade epoxy composite materials derived from the aerospace industry for their high performance requirements.

The Murcièlago (Fig. 1), presents an entire carbon/epoxy body (bumpers, fenders, hood, etc.) except for the doors and roof structure. Use of composites for this application allows for a weight saving of 75 lb or 34 kg

* Corresponding author. Tel.: +1-805-407-1123; fax: +1-805-893-8651.
E-mail address: pmc@engineering.ucsb.edu (P. Feraboli).

1359-8368/$ - see front matter
doi:10.1016/j.compositesb.2003.11.010

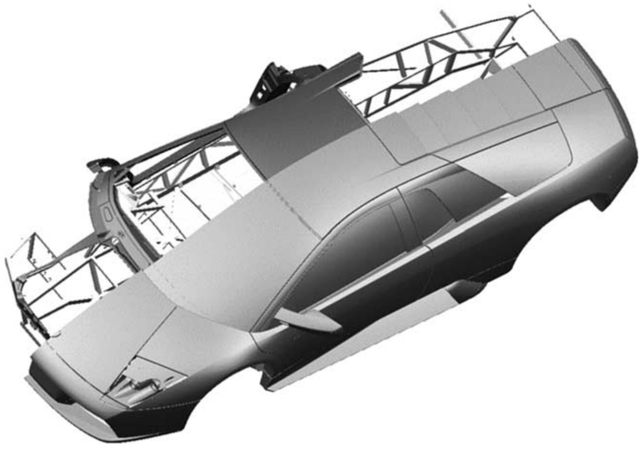


Fig. 1. The composite body of the Murcièlago is shown over its tubular steel frame and steel roof structure.

(about 40%) over its predecessor, the Diablo, which presents an all-aluminum body. Other solutions that employ carbon/epoxy composites include highly stressed structural components such as the transmission tunnel, floor pans and rocker panels (Fig. 2). Such an expensive process as the hand lay-up, vacuum bag, autoclave curing of prepreg carbon/epoxy composites is justified not just by the exclusive niche of auto market these vehicles belong, yet by the specific technical advantages that these materials can be engineered to offer. Particularly, the high torsional and bending rigidity required for better handling and performance; the inherent light weight which can be further optimized with detailed design and analysis; the high strength that is required for improved safety and crashworthiness; the ability of these materials to be readily recycled conforming to newer and more severe regulations; the ability to be quickly shaped for rapid prototyping and product modifications; the inherently higher material and process costs are attenuated by the lower tooling costs necessary for limited annual production; the higher geometric tolerance and surface finish that can be achieved due to the absence of machining; the enormous advantage given by part consolidation, which reduces the number of joints thus increasing structural performance (weight, integrity, vibrations, etc.) and limiting the occasions for failure origination; the increased durability typical of thermoset polymeric materials which offers resistance to environmental and chemical corrosion.

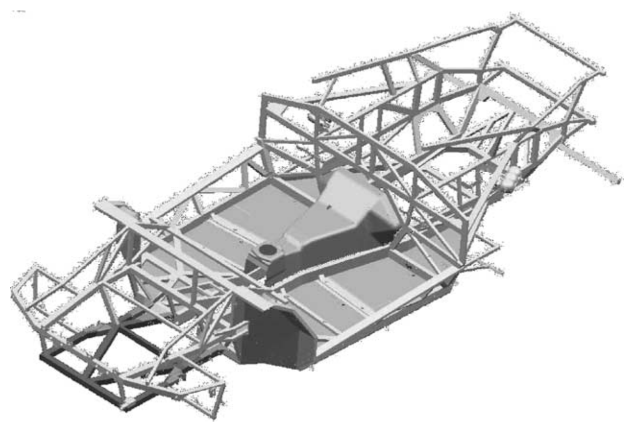


Fig. 2. Flexural test results.

1.2. Purpose of the paper

A testing program was initiated to examine the influence of fiber architecture and stacking sequence on the relative strength of a polymer composite laminate, like the one used in the development of the Murcièlago Elastic properties for the unidirectional lamina of this carbon/epoxy system are reported in Table 1. The flexural strength of a material, as determined with ASTM standard D790 [7], is a fundamental parameter in the design of reinforced plastic structures. The interlaminar shear (ILS) strength is a peculiar property of laminated structures, such as polymer composites, because they exhibit inherently weak matrix dominated properties. ILS stresses originate because of a mismatch in the mechanical properties between individual laminae within the laminate and develop at the free edge and at local discontinuities such as notches, ply-drops, bonded and bolted joints. These stresses need to be evaluated for structural applications and many authors feel that delamination is the fundamental issue in the evaluation of laminated composite systems for durability and damage tolerance. Three-point bend test ASTM D2344 [8], also known as short beam shear test, is often used to measure the apparent ILS strength of composite laminates. Since concerns arise around three-point bend tests because of the strong localized damage occurring underneath the loading roller, a modified version of the test, the four point bending test, is frequently used, as in the present work.

While material systems with the highest mechanical properties are very desirable, such materials might not meet other fundamental engineering requirements such as the need for reliable pseudo-isotropic behavior, ease of manufacturing (drape-ability) and joining, resistance to environmental degradation, and surface finish, hence designers are forced to perform constant trade-offs. Class A surface certification means that a surface has to meet certain criteria for inclusions, voids, roughness and tolerances. Such certification is a system of procedures that not only affects the final product, but the mathematical model as well as the materials and molding tools. Environmental degradation refers to resistance to moisture and UV radiation, and is a function of

Table 1
Elastic properties for the unidirectional tape

$E_x = 18$ Msi (124.1 GPa)	$E_y = 1.5$ Msi (10.3 GPa)	$E_z = 1.5$ Msi (10.3 GPa)
$G_{xy} = 0.8$ Msi (55.2 GPa)	$G_{xz} = 0.8$ Msi (55.2 GPa)	$G_{yz} = 0.6$ Msi (4.1 GPa)
$\nu_{xy} = 0.3$	$\nu_{xz} = 0.3$	$\nu_{yz} = 0.35$

the composite material and process parameters. Metal to composite (hybrid) adhesive bonding as sole joining method of body panels to the steel frame of the Murcièlago, allows for considerable weight savings and part consolidation but requires extensive experimental investigation to limit processing variables and ensure reliable performance.

2. Results and discussion

2.1. Flexural and interlaminar shear performance

The laminates tested are unidirectional $[0]_s$, multidirectional with a balanced and symmetric stacking sequence, cross-ply $[0/90]_s$ and quasi-isotropic $[0/\pm 45/90]_s$ lay-ups of carbon/epoxy impregnated tape. Three fabric laminates are also tested, 2×2 twill in the 3k and 12k fiber tow size, and the eight harness satin.

Flexural specimens present an average geometry of 4.000 in. (101.6 mm) length, 1.000 in. (25.4 mm) width, 0.165 in. (4.2 mm) thickness; ILS coupons are 1.300 in. (33 mm) long, 0.300 in. (7.6 mm) wide, 0.165 in. (4.2 mm) thick for the prepreg tape laminates. Coupons are placed in a sliding roller four point-bending fixture with an inner and outer span of 0.5 and 1.25 in. (12.7 and 31.7 mm), respectively, for the ILS testing and of 1.5 and 3.75 in. (38.1 and 95.2 mm), respectively, for the flexural. The samples are tested to failure on an Instron 1123 test frame under displacement control.

As for flexural results, two separate discussions should be made for tapes and fabrics. In the case of tape laminates, failure occurs suddenly and in the majority of coupons it manifests on the compressive side. Some of the specimens present an evident zone of delamination, i.e. laminate splitting through the thickness around the midplane, while other specimens fail first in tension. Failure of woven laminates failure is less sudden, since the approaching of critical strength is announced by laminate cracking, yet more catastrophic, often resulting in splitting of the coupon in two halves. Average flexural strength results are reported in Fig. 3. The effect of lower fiber tow number is to reduce the displacement to failure, due to the tighter weave that is developed. The flexural strength for the different architectures is substantially different as expected, due to its intrinsically fiber-dominated behavior.

As for ILS, failure manifests as a single crack propagating from a region located at the midplane, about one thickness away from the support. A sharp drop in the load–displacement curves and an audible cracking sound accompany catastrophic delamination. After the first inter-ply failure, load picks up again but will not reach the pristine value. Average ILS strength results are also reported in Fig. 3. Laminate stacking sequence does not affect the ILS strength because of its matrix-dominated nature, for the tested configuration and ply thickness, as much as other

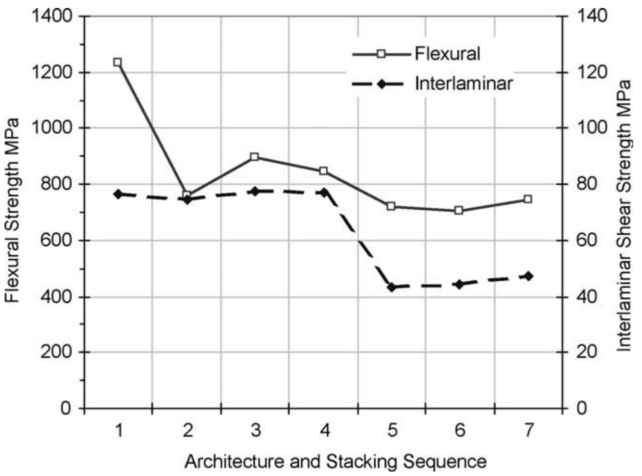


Fig. 3. Interlaminar shear test results.

factors do, i.e. fiber volume, void content and curing process parameters [14–16].

From a mechanical property standpoint, ideal would be to make use of the tape laminates, which offer higher performances, in particular either the cross-ply or the quasi-isotropic since they do not present a high degree of anisotropy. In the case of Lamborghini however, the use of a less performing fabric is justified by the need for the plies to tightly adhere to the complex shape of the molds in the all-manual processes of lay-up and vacuum bagging. Also, while unidirectional tape laminates facilitate the formation of voids—because of their tight fiber arrangement which creates a barrier that keeps gas and air bubbles enclosed—a more loosely arranged fabric allows for better evacuation. Moreover, the quasi-isotropic behavior of the twill facilitates the design of both structural and non-structural components in those cases where the direction of loading is not known a priori. For surfaces exposed to external agents and foreign object impact damage (FOD), either manufacturing or service related (low velocity impacts such as toolbox drop or door slamming, and high velocity impacts such as hail ice or small stones) tapes behave worse than fabrics, exhibiting a much higher damage area. Lastly, thermal delamination that might occur upon curing is more prone to happen in tapes rather than fabrics.

2.2. Body panels

The average body panel laminate thickness is 0.055 in. (1.4 mm), except for panels which require additional stiffness and a Nomex (aramidic) honeycomb core is employed, in the thickness of 0.118, 0.236, 0.394 in. (3, 6, 10 mm). The sandwich structure also allows for excellent vibration damping. The solution adopted involves a 3-ply laminate, which is balanced but unsymmetric. The stacking sequence calls for a 2×2 twill in the 0/90 orientation at the surface and in the thickness of 0.008 in. (0.2 mm), a five harness satin in the 0.016 in. (0.4 mm) thickness with a 0/90 orientation and again a 2 × 2 twill in the 0.028 in. (0.7 mm) thickness in the 0/90 orientation. Use of twill in the most exterior ply is justified by the need to obtain the best surface finish for Class A certification. Use of plain weaves for outer painted surfaces is not recommended because it exposes fiber interweaving, which produces a roughness effect that is not esthetically appealing. This unsymmetric laminate would curve upon cooling if it were not for the complex shape of the molds in which the hand lay-up and vacuum bagging occur (the sharp corners and intricate internal geometry prevent it from relaxing and flexing) and an increasing ply thickness and fiber areal weight from the exterior ply inward (again prevents laminate distortion).

A micrographic picture of a body panel cross-section is shown in Fig. 4: the laminate (from the surface inwards) calls for the paint layer, a polyurethane primer for better paint absorption, an epoxy primer for mold adhesion, the toughened epoxy layer which is also used for surface preparation and prevents the exposure of the nude fibers, the three fabric layers, an insulating layer for moisture resistance.

In areas where the body is adhesively joined to the steel chassis, a 2 mm thick epoxy film adhesive is used and another layer of toughened epoxy prevents the development of a galvanic cell effect between metal and carbon fibers. In places like the variable geometry air intakes where maintenance and accessibility are required, the use of threaded stainless steel inserts and fasteners is required. Locations where intimate contact between the metal structure and the composite body is to be ensured—like in the variable geometry rear spoiler—a double shell technique is adopted, which allows the enclosing of a portion of the metallic component within the composite skins.

Large mass-low velocity impact tests are performed with a non-instrumented drop tower apparatus on composite targets as part of the integrated product development (IPD) approach [17]. Flat plates are built and tested in the early design stages to compare material system and stacking sequence performance: damage resistance is performed by impacting the target up to the onset of barely visible impact damage (BVID) from increasing values of impact energy. Failure evaluation beyond visual inspection is performed by ultrasonic C-scans and micrograph analyses: materials with higher incident kinetic energy threshold for the onset of noticeable indentation are selected. Large-scale components are tested to simulate the performance of the component in a real-life configuration, and tests are performed at impact energy values corresponding to typical in-service damage sources to verify structural and surface integrity. High velocity impact tests are also performed in a fashion similar to the stone-chipping test on painted specimens (see surface certification) to assess foreign object damage FOD resistance.

2.3. Chassis components

The transmission tunnel, which has to exhibit a high torsional stiffness, a $[\pm 45]_s$ oriented 2 × 2 twill laminate solution for a total thickness of 0.157 in. (4 mm) is adopted. The orientation is justified by its high torsional properties; the use of twill instead of an angle ply tape laminate is necessary because fabrics adhere better to the shape of the intricate molding tools. Joining is realized with epoxy film adhesive exclusively.

The floor and rocker panels, which have to exhibit high torsional as well as bending stiffness, are comprised of a 6-ply symmetric and balanced laminate for an overall thickness of 0.197 in. (5 mm), exception made again for those areas where a Nomex honeycomb core is employed. Film adhesive is used to ensure a firm joining between the carbon skins and the core in the sandwich structure. Ideal would be to use the same $[\pm 45]_s$ oriented fabric as in the transmission tunnel cover, but its dimensions preclude from the possibility of cutting the shape from one single sheet of prepreg, hence the discontinuity surfaces that originate present a high stress concentration factor after curing. It is

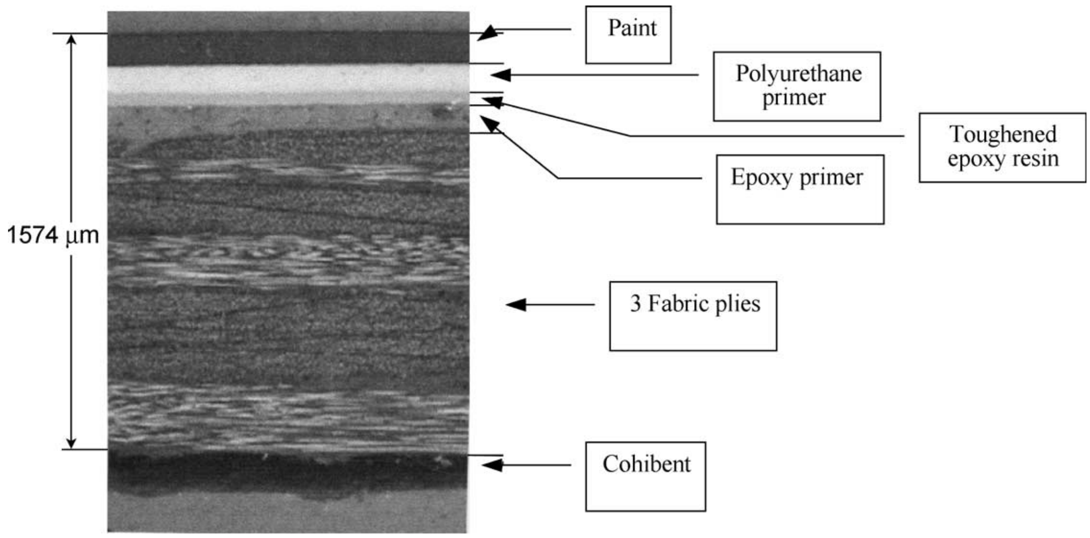


Fig. 4. Micrographic cross-section of body panel.

therefore necessary to adopt a similar solution—yet substantially different—to the one used in the development of the body. The now symmetric lay-up calls for an outer layer of plain weave in the 0/90 orientation, a 5 h satin in the 0/90 and a 2×2 twill with a ± 45 orientation at the symmetry axis. The inner layer is the joined adhesively and mechanically to the chassis, by means of so-called 'chicken' rivets, which provide an extra degree of reliability.

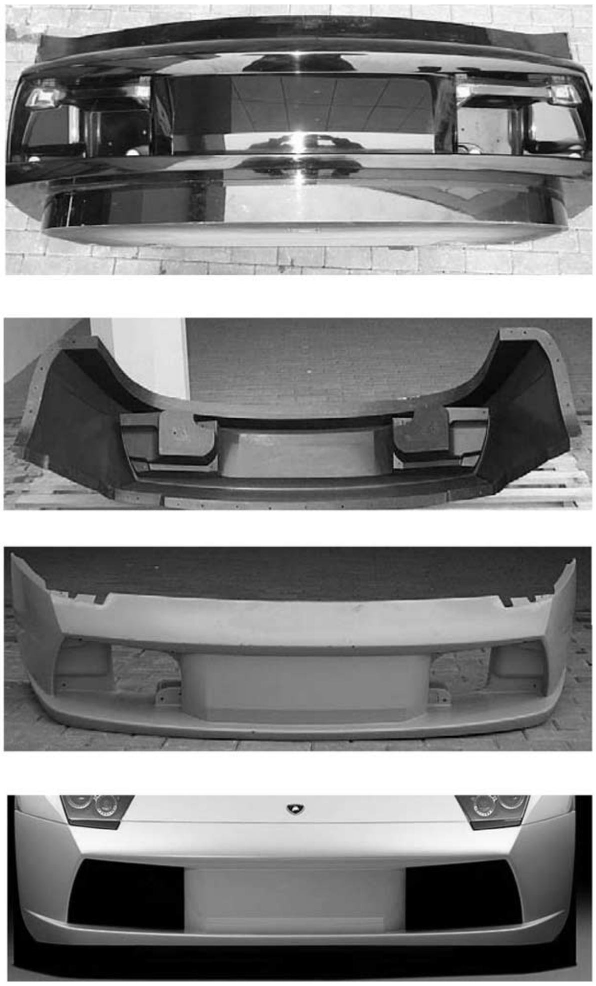
Like other production vehicle, the Murcièlago has to meet US Federal Motor Vehicle Safety Standards (FMVSS) and European New Car Assessment Program (Euro-NCAP) regulations, and due to its high performance nature company policy has been to far exceed in safety requirements, yet crashworthiness is a vast and delicate topic that needs to be the focus of a future publication.

2.4. Class a surface certification

Requirements on surface finish for the Murcièlago are particularly restrictive, since they require for the fabric weave not to show through the paint by means of marks or imprints. The specific procedure adopted in order to achieve class A surface certification involves the entire manufacturing process and the guidelines are here summarized.

Patterns. Models or patterns are milled with CNC machinery from epoxy resin blocks according to the mathematics supplied by the Technical Development team. Design tolerances are accounted for, and usually the model has a maximum ± 0.5 mm (0.02 in.) dimensional allowable. After the milling operation, the model is in a matte condition and visual inspection of the surface is difficult: it is therefore polished with a layer of translucent black epoxy, which facilitates inspection. Before the mold is created form the model, a release coating layer is laid on the model and cured in the oven.

Molding tool. Special mold epoxy resins are used, and ad hoc systems are researched in order to give the best curing parameters (Fig. 5B). Polymerization temperature and time are kept the lowest admissible, 45 °C (113 F), in order to reduce deformations and strains. Since the temperature increase in the mold is proportional to its mass hence volume, this is kept the smallest possible by fabricating the mold with a concave shape, which is internally empty. Thus temperature gradient is higher and temperature distribution more uniform. Optimum thickness along the tool is found to be around 100 mm (3.94 in.) 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; long and integer plies are cut, a practice that differs from the non-esthetically focused aerospace one, which calls for patch-like patterns on the wing skin. Geometrical considerations are also important in order to offer an operator-friendly ply lay-up. Six layers of wax are applied, which at such low curing temperatures act both as a release agent and as a filler for micro-porosities, thus avoiding the need for fillers. Post-curing of the mold is



A B C D

Fig. 5. (A) Epoxy model for the front bumper: visible is the black epoxy finish for surface inspection; (B) Graphite/epoxy mold obtained from the previous model; (C) Component after extraction from the mold: visible is the green epoxy primer for better paint absorption and sanding; (D) Final component after painting and assembly.

necessary in order to increase its T_g up to processing temperature of 130–180 °C (250–350 F). At the end of the process a polishing operation with abrasive paste is performed, which ensures better release properties, followed by 12 layers of release coating, which is cured in the autoclave prior to the first tooling operation.

Molding procedure. First, a fresh, thinner layer of release agent is applied then cured: this operation will be repeated for each forming cycle (Fig. 5C). Then, an epoxy primer is applied for a dual purpose, first to facilitate the sanding operation which precedes the painting procedure, without exposing the fibers, then to increase surface smoothness, by almost 30%. These layers are pre-cured before prepreg lay up and the final component curing process. As mentioned in the previous section, body panels are laminated with carbon/epoxy fabrics, mostly a 2×2 twill 3k, since use of thicker or heavier fabrics increases surface roughness and markings on the paint.

Paint. 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 process that is similar to the mechanical abrasion that precedes adhesive bonding operations (Fig. 5D). A polyurethane primer is used to increase luminosity and finally the polyurethane paint is sprayed on the panel. In the case of varnished (unpainted) components which allow for carbon fiber weave exposure, the matte epoxy primer cannot be employed, therefore application of the release coat is followed by a hand-brushed layer of the monolithic epoxy resin used for the prepregs, now toughened for UV resistance, thus avoiding the need for gel coats. A transparent polyurethane varnish is then applied. Relatively low-pressure curing and fine fiber weaves are necessary in order to avoid porosity and roughness that would not be esthetically acceptable.

Certification. Finally, components are ready for inspection by Quality Assurance, which ensures the product to be absent of inclusions, burns, blisters, surface tensioning, holes and the paint tone, tint and hardness to be uniform.

2.5. Environmental effects

Four tests are used to validate the resin systems, namely water resistance at 100% humidity, water immersion, operating light exposure and DSG. The first three are performed in a sequence, which means that only resins that survive a test stage advance to the next, while the last is independent of the others.

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. Test parameters according to ASTM D2247 Cleveland (45 °C for 240 h at 100% relative humidity) are the most stringent available of this kind [9]. The specimens that passed the test are immerged in water for 48 h at 40 °C (104 F). This test is prescribed as ASTM D870 [10], but even though it provides another means for composite system selection, it yields a scarce representation of real life situation. The weatherometer test ASTM G26 [11] simulates all environmental degradation effects, UV radiation, heat and humidity and is therefore considered the most significant test for this kind of investigation. Test period is imposed to be 800 h.

The resin systems that are selected for the final application on the Murcièlago are the ones that presented no imperfections after accelerated environmental degradation. These imperfections include blistering, laminate distortion, paint changes, loss of adhesion, softening, embrittlement, crazing, cracking, flaking, chemical separation and fiber exposure. Final paint and resin adhesion is verified after the three consecutive tests with a tape test such as ASTM D3359 [12], which consists in the application of an adhesive strip to an isolated area. A different investigation is performed via the Differential Scanning Calorimeter, to determine the glass transition temperature (T_g) of a resin or prepreg and their working temperature range. Its use is fundamental to determine the composite systems most suitable for employment in temperature critical areas, such as the engine bay or the exhaust nozzles.

2.6. Hybrid (dissimilar materials) adhesive bonding

Epoxy and polyurethane adhesives have been previously considered for this particular task, since they already find application on the vehicle body in composite-to-composite joints. Methacrylate adhesives are more suitable because of their intermediate mechanical properties. Epoxy film adhesive guarantees the stiffest bond and is therefore used for load carrying members, as well as in those areas where aesthetical constraints impose perfect joint stability. The polyurethane paste adhesive, because of its compliant behavior is used where elasticity requirements prevail, for example, where vibration damping or shock absorption is necessary. The methacrylate paste adhesive exhibited a balanced trade-off between the characteristics of epoxy and PU adhesives.

A testing program with conventional ASTM D1002 [13] single lap shear joint configuration is initiated to characterize the shear strength of MA adhesives in steel-to-composite joints under different geometrical and environmental conditions, in order to determine design and processing allowables. The metallic adherent is conventional construction steel, while the composite adherents are two fabrics, fiberglass and carbon fiber in the 2×2 twill architecture pre-impregnated with the same epoxy resin [6].

Various parameters are varied in order to determine the most performing configuration. For the fiberglass, two different bond line thickness, namely 1 and 4 mm (0.039–0.158 in.); and two different preconditioning treatments are performed to simulate the effects of processing as well as environmental conditions on the stability and performance of the joint. Conditioning 0 refers to no conditioning, conditioning 1 is a post-curing (120 °C for 45 min) and conditioning 2 is a hygro-thermal cycle (−30 °C for 4 h and +50 °C for 4 h. at relative humidity of 100% followed by 16 h at 22 °C, this procedure repeated eight times consecutively).

Since bond-line thickness of 1 and 4 mm have chosen as extremes to account for processing inaccuracies, it is discovered that 4 mm thick bond yields an unacceptable performance. Supported by these results obtained, testing of the carbon fiber focuses on a bond-line thickness of 1, 2 and 3 mm (0.04–0.12 in.). Furthermore, since composite adherent thickness varies locally according to geometric constraints as well as manufacturing requirements or imperfections, three laminate thickness are also tested, namely 1.3, 1.5 and 1.7 mm (0.05–0.07 in.).

Carbon fiber adherent joints are also tested both in natural (conditioning 0) and in post-cured (conditioning 1) configurations, since fiberglass coupons have shown that conditioning 2 has little effect on average bond strength.

Both composites are polished with methyl–ethyl ketone (MEK) before application of the adhesive, while the steel, which is superficially treated by electro-phoresis coating

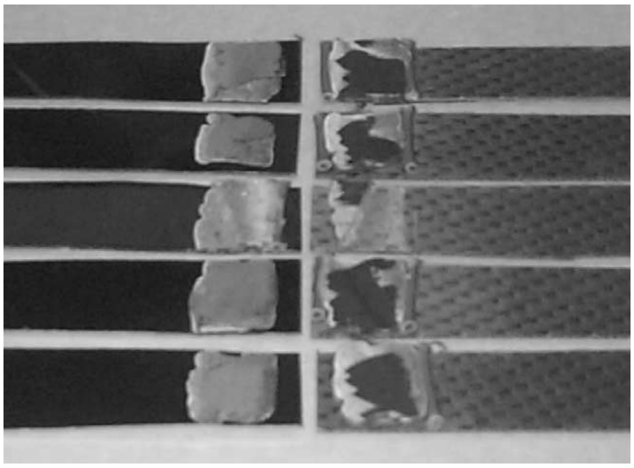


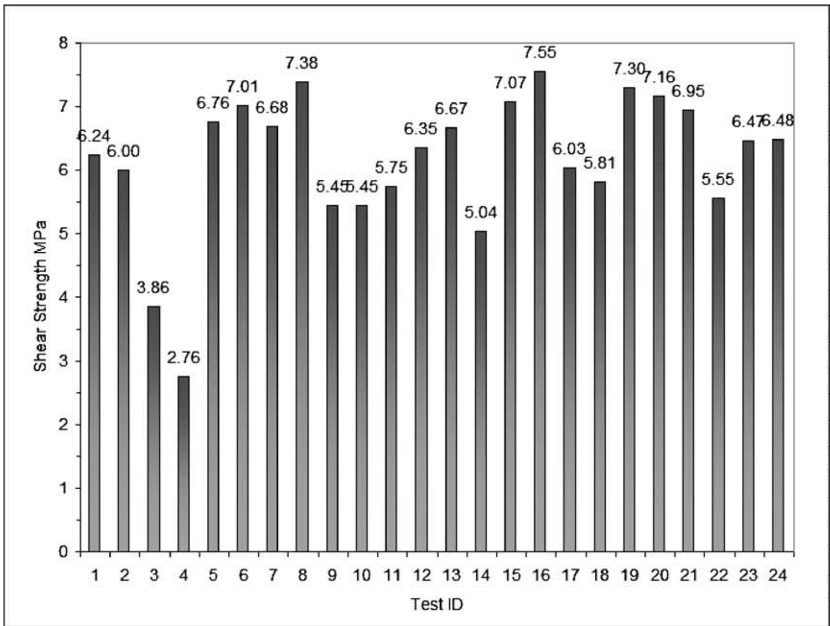
Fig. 6. Single lap shear test coupons: EPC steel adherent on the left and carbon fiber on the right. Visible are also the blue paste of the methacrylate adhesive and the red spacing wires. All three failure modes are visible.

(EPC), is wiped with iso-propanol alcohol (IPA); no abrasive operation (grit blasting or sanding) is performed. Since the MA is a paste adhesive, constant bond thickness is achieved with the aid of a spacing music wire of desired diameter.

Visual inspection after failure is conducted on the specimens, and all three different failure modes can be observed: adhesive, cohesive and substrate, where the EPC coating or carbon fiber laminates delaminate (Fig. 6). Very few specimens fail cohesively, while failure is almost equally distributed between adhesive and adherent, thus confirming the validity of the adhesive and of the surface prep. To be observed is that the vast majority of the substrate failures are due to EPC coating delamination, while composite adherent delamination occurs only in carbon fiber specimens with thicker laminates.

Both glass and carbon fiber (CF) results show that environmental cycling deteriorates the joint slightly; bond-line thickness has a dramatic effect on joint strength; average strength values for carbon fiber specimens are higher than for glass fiber (GF); a noticeable oscillation in the results can be observed on the basis of the laminate thickness but generally thicker adherents perform better than the thinner ones. Optimal configuration, as can be seen from Fig. 7, is given by CF adherents, with intermediate laminate thickness, subject to a post-curing and having a 1 or 2 mm bond line thickness. The stiffer CF specimens performed better than the GF ones probably due to the fact that the higher modulus reduces the amount of rotation of the specimen with respect to the supports, typically observed in single lap shear testing, therefore limiting the amount of out-of-plane stress components (peeling) acting on the adhesive [18]. Double lap joints could have been tested to eliminate the influence of adherent compliance on the apparent average bond strength, but since final assembly calls for a single lap solution due to geometrical restraints and manufacturing simplicity, this factor is accounted for in the final design process.

Final production accounts for an average carbon/epoxy adherent thickness of 1.4 mm and for a peel ply to be used to provide better adhesion. Optimum bond thickness from design specs is 2 mm (0.08 in.), with a ±1 mm (0.04 in.) allowable: while the thinner adhesive the better the mechanical response, below a certain thickness structural stability is not ensured. Use of sealants is not furthermore required because of the MA spreadability. No abrasion is required, but wiping with MEK is prescribed on the composite adherent and with IPA on the EPC steel rail. EPC treatment on the metal is required, otherwise an epoxy primer is to be applied on the naked steel. Since the MA



1	FG - 1 mm bond - 1.5 mm laminate - precond. 1
2	FG - 1 mm bond - 1.5 mm laminate - precond. 2
3	FG - 4 mm bond - 1.5 mm laminate - precond. 1
4	FG - 4 mm bond - 1.5 mm laminate - precond. 2
5	FG - 2 mm bond - 1.5 mm laminate - precond. 1
6	FG - 2 mm bond - 1.5 mm laminate - precond. 2
7	CF - 1 mm bond - 1.3 mm laminate - precond 0
8	CF - 1 mm bond - 1.3 mm laminate - precond 1
9	CF - 2 mm bond - 1.3 mm laminate - precond 0
10	CF - 2 mm bond - 1.3 mm laminate - precond 1
11	CF - 3 mm bond - 1.3 mm laminate - precond 0
12	CF - 3 mm bond - 1.3 mm laminate - precond 1
13	CF - 1 mm bond - 1.5 mm laminate - precond 0
14	CF - 1 mm bond - 1.5 mm laminate - precond 1
15	CF - 2 mm bond - 1.5 mm laminate - precond 0
16	CF - 2 mm bond - 1.5 mm laminate - precond 1
17	CF - 3 mm bond - 1.5 mm laminate - precond 0
18	CF - 3 mm bond - 1.5 mm laminate - precond 1
19	CF - 1 mm bond - 1.7 mm laminate - precond 0
20	CF - 1 mm bond - 1.7 mm laminate - precond 1
21	CF - 2 mm bond - 1.7 mm laminate - precond 0
22	CF - 2 mm bond - 1.7 mm laminate - precond 1
23	CF - 3 mm bond - 1.7 mm laminate - precond 0
24	CF - 3 mm bond - 1.7 mm laminate - precond 1

Fig. 7. Bonded joint shear strength for carbon and glass fiber adherents for four values of bond-line thickness; three values of laminate thickness; three types of environmental preconditioning.

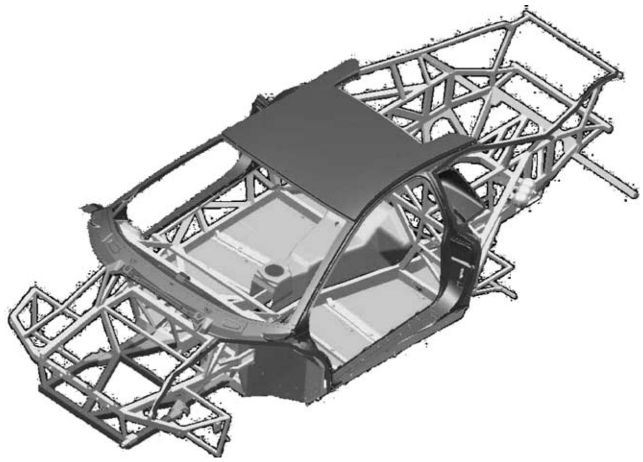


Fig. 8. Tubular chassis and passenger compartment of the Murcièlago. Light blue indicates the carbon/epoxy floor pans, rocker panels and transmission tunnel. The red lines represent the rails along which body panels are adhesively joined to the frame.

adhesive is a two part green–blue paste in a 1:1 mixing ratio, homogeneity in the bond line is required, but assessment of sufficient mixing is determined by visual inspection, simply making sure that the color is uniform. Bonding of the composite body components to the welded tubular steel frame is performed along rails (Fig. 8), which can be removed and replaced with new ones, thus simplifying the maintenance and repair procedures. Components are to be firmly tightened during the bonding process (work time 30 min) and then kept in place for the necessary 2 h curing time at room temperature.

3. Conclusions

Development of body panels and chassis components using carbon/epoxy prepregs systems for hand lay-up, autoclave cure for a luxury high performance car has been discussed. While design for strength and stiffness suggests the use of multidirectional tape materials, manufacturing solutions and engineering approaches in the case of the Murcièlago impose the use of woven fabrics, in particular durability, environmental resistance, and esthetical considerations. Accelerated degradation test methods were reviewed, including the simultaneous exposure to high temperatures, high humidity and UV light, and the test sequence used to validate application-specific composite systems. Body panels are adhesively bonded to the tubular steel chassis by solely means of methacrylate adhesive, which exhibited the best compromise between strength, stiffness, vibration damping, sealing behavior and processing needs among other candidate adhesives, such as epoxy (film and paste) and polyurethane. Single lap shear testing was performed to determine the influence of bond-line thickness, composite adherent thickness, fiber type, processing- and environmental-related degradation. Final specification of composite components for exterior (body) and structural (chassis) applications was accurately described, and technical and technological requirements for such applications have been reviewed.

Acknowledgements

The authors would like to thank the entire *Area Tecnica* and *Ufficio Risorse Umane* of *Automobili Lamborghini S.p.A.* for realizing this wonderful product, in particular *Dr. Ing. M. Ceccarani* (Technical Director) for leading the company toward greater achievements; *Mr. M. Reggiani* (Head of Technical Development) and *Mr. A. Bonfatti* (Head of the Body-Frame Division) for guiding the R&D program of the Murcièlago; *Dr. C. Galli* and *Dr. C. Scaramelli* for the continuous effort of improving the staff of the Technical Team. Paolo would also like to acknowledge the help of *Dr. K. T. Kedward*, UC Santa Barbara, for being a terrific professor, a careful mentor, a generous friend and the person who introduced him to composites.

References

[1] Karkkainen RL, Caliskan AG. Energy absorption in glass and carbon fiber composite sandwich structures in lateral loading. 18th A.S.C. Technical Conference; 2003.
[2] Browne AL, Johnson NL. Dynamic axial crush of automotive rail-sized composite tubes. Part 5. Effects of test conditions. 18th A.S.C. Technical Conference; 2003.
[3] Saccone M. Composite design procedures for racing cars. Third S.P.E. Automotive Composites Conference; 2003.
[4] Bruderick M, Denton D, Shinedling M, Kiesel M. Applications of carbon/fiber SMC for the 2003 Dodge Viper. Second S.P.E. Automotive Composites Conference; 2002.
[5] Voss M, Remy J, Pottish N. Development of the class A carbon fiber hood for the 2004 Chevrolet Corvette Z06. Third S.P.E. Automotive Composites Conference; 2003.
[6] Masini A, Feraboli P. Carbon/epoxy composites for the Lamborghini Murcièlago. Third S.P.E. Automotive Composites Conference; 2003.
[7] ASTM D790. Flexural properties of unreinforced and reinforced plastics.
[8] ASTM D2344. Apparent interlaminar shear strength of unidirectional parallel fiber composites by short beam method.
[9] ASTM D2247. Testing water resistance of coatings in 100% relative humidity.
[10] ASTM D870. Testing water resistance of coatings using water immersion.
[11] ASTM G26 (G155). Operating xenon arc light apparatus for exposure of non-metallic materials.
[12] ASTM D3359. Test methods for measuring adhesion by tape test.
[13] ASTM D1002. Apparent shear strength of single lap joint adhesively bonded metal specimens by tension loading.
[14] Feraboli P, Kedward K. Four-point bend interlaminar shear testing of uni- and multi-directional carbon/epoxy composite systems. Composites, Part A 2003;34:12–12.
[15] Daniel IM, Ishai O. Engineering mechanics of composite materials. Oxford: Oxford University Press; 1994.
[16] Engineered Materials Handbook. Composites, vol. 1. ASM International; 1989.
[17] Feraboli PJ, Ireland DR, Kedward KT. On the use of force, energy and stiffness in low velocity impact events. 18th A.S.C. Technical Conference; 2003.
[18] Lamborghini Diablo 6.0 R&D internal protocol for composite body panels.