CARBON/EPOXY COMPOSITES FOR THE LAMBORGHINI MURCIELAGO

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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. Laminate design and stacking sequence is reviewed, and the use of woven fabrics over directional tape is motivated. Engineering solutions for tooling operations in order to achieve class A surface certification are analyzed. Design for environmental aging as well as accelerated degradation tests are described. Hybrid adhesive bonding as sole method of joining the composite body components to the tubular steel chassis is reviewed.

Background

A testing program was initiated to examine the influence of fiber architecture and stacking sequence on the relative strengths of a polymer composite laminate, like the one used in the development of the Lamborghini Murcièlago. Elastic properties for the unidirectional lamina of this carbon/epoxy system are reported in Table I. The flexural strength of a material, as determined with ASTM standard D790 [1], 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. Interlaminar shear 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 [2], also known as short beam shear test, is often used to measure the apparent interlaminar shear strength of composite laminates. Since concerns arise around this test 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 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 constantly 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 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.

Discussion

Flexural and Interlaminar Shear tests

The laminates tested were unidirectional $[0]_s$, multidirectional with a balanced and symmetric stacking sequence, cross-ply $[0/90]_s$ and quasi-isotropic $[0/\pm45/90]_s$ lay-ups of carbon fiber reinforced epoxy impregnated tape. Two fabric laminates were also tested, the 2x2 twill and the 8 Harness Satin weave.

Flexural specimens presented 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; interlaminar shear coupons were 1.300 in. (33 mm) length, 0.300 in. (7.6 mm) width, 0.165 in. (4.2 mm) thickness for the prepreg tape laminates. Coupons were placed in a sliding roller four point-bending fixture with an inner and outer span of 0.5 and 1.25 inches (12.7 and 31.7 mm) respectively for the interlaminar shear testing and of 1.5 and 3.75 inches (38.1 and 95.2 mm) respectively for the flexural. The samples were 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 occurred suddenly and in the majority of coupons it manifests on the compressive side. Some of the specimens presented an evident zone of delamination, i.e. laminate splitting through the thickness around the midplane, while other specimens failed first in tension. For woven laminates failure was less sudden, the approaching of critical strength being announced by laminate cracking, yet more catastrophic, often resulting in splitting of the coupon in two halves. Average flexural strength results are reported in [10]. The flexural strength for the different architectures was substantially different, due to their intrinsically fiber-dominated behavior.

As for interlaminar shear, failure manifested as a single crack propagating from a region located about one thickness away from the support, usually at the midplane. 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 and in some cases but will not reach the pristine value. 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 factors do, i.e. fiber volume, void content and curing process parameters.

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 don't 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 component performance is not critical. For the surfaces that are exposed to external agents, such as moisture and impacts, either manufacturing or service related (low velocity impacts such as toolbox drop or door slamming, and high velocity impact such as hail ice) tapes behave worse than fabrics. Lastly, thermal delamination that might occur upon curing is more prone to happen in tapes rather than fabrics.

Body Panels

The Murcièlago (Fig.1), presents an entire carbon/epoxy prepreg body (bumpers, fenders, hood, etc…) except for the roof structure. Use of composites for this application allowed for a weight saving of 75 lbs (34 kg) over its predecessor, the Diablo, which presented an all-aluminum body.

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 2x2 twill in the 0/90 orientation at the surface and in the thickness of 0.008 in. (0.2 mm), a 5 harness satin in the 0.016 in. (0.4 mm) thickness with a 0/90 orientation and again a 2x2 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 FAW (fiber areal weight) from the exterior ply inward (again prevents laminate distortion).

A micrographic picture of a body panel cross section is shown in [10]; the final laminate (from the surface inwards): calls for the paint layer, a polyurethane primer for better paint absorption, an epoxy primer for mold adhesion, the charged epoxy film which is also used for surface preparation and prevents the exposure of the nude fibers, the 3 fabric layers, an insulating layer for moisture resistance. In areas where the body is adhesively joined to the steel chassis, a film epoxy of 2 mm thickness is used and another layer of charged 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. Places 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.

Chassis Components

Other solutions that employ carbon/epoxy composites in the new Lamborghini vehicle include highly stressed structural components such as the transmission tunnel, floor pans and rocker panels.

As for the transmission tunnel, which has to exhibit a high torsional stiffness, a $[\pm 45]_s$ oriented 2x2 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. Joints are realized with epoxy film adhesive and steel rivets.

The floor and rocker panels, which have also to exhibit high torsional stiffness, see a 6-ply symmetric and balanced laminate solution 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 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 5hs again in the 0/90 and a 2x2 twill with a ±45 orientation at the symmetry axis. The inner layer is the joined adhesively and mechanically to the chassis.

Class A surfaces

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

Model. Models (fig. 2A) are milled with CNC machinery on the mathematics supplied by the designers out of epoxy resin blocks. 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 creating the mold, a release coating 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. 2B). Polymerization temperature and time are kept the lowest admissible, 45 deg 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 laid 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 necessary in order to increase its Tg up to processing temperature of 130-180 deg 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, another layer of release agent is applied then cured: this operation will be repeated for each forming cycle (fig. 2C). Then, an epoxy primer is laid for two separate tasks, first to facilitate the sanding operation which precedes the painting, without exposing the fibers, then to increase surface smoothness (by almost 30%). These layers are precured before prepreg lay up and final curing process. The body panels are laminated with carbon/epoxy fabrics, in particular a 2x2 twill 3K for a ply thickness of 0.4 mm (0.016 in.). 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. 2D). A polyurethane primer is used to increase luminosity and finally the polyurethane paint is sprayed on the panel. In the case of varnished components which allow for carbon fiber weave exposure, the matte epoxy primer cannot be used, therefore the release coating is followed by another layer of the same epoxy resin as the prepregs but transparent. No gel coat is required. 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 the Quality Assurance Group, which ensures the product to be absent of inclusions, burns, blisters, surface tensioning, holes and the paint tone, tint and hardness to be uniform.

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 deg C for 240 hrs at 100% relative humidity) are the most stringent available of this kind. The specimens that passed the test are immerged in water for 48 hrs. at 40 deg. C (104 F). This test is prescribed as ASTM D870, 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 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 hrs.

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. A different investigation is performed via the Differential Scanning Calorimeter, to determine the Tg 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.

Hybrid Adhesive Bonding

Epoxy and polyurethane (PU) adhesives have been previously considered for this particular task, since they already find application on the vehicle body in composite-to-composite joints. Methacrylate (MA) 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 PU paste adhesive, because of its compliant behavior is used where elasticity requirements prevail, for example where vibration damping or shock absorption is necessary. The MA paste adhesive exhibited a balanced trade-off between the characteristics of epoxy and PU adhesives.

A testing program with conventional ASTM D1002 [16] 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, which is superficially treated by Electro-Phoresis Coating (EPC). The composite adherents are two fabrics, fiberglass and carbon fiber in the 2x2 Twill architecture pre-impregnated with the same epoxy resin [10,11].

Various parameters are varied in order to determine the most performing configuration. For the fiberglass:

- 2 different bond line thickness, namely 1 and 4 mm (0.039-0.158 in.);
- 2 different aging treatments are performed to simulate the effects of processing as well as environmental conditions on the stability and performance of the joint, in particular a post curing (120 deg C for 45 mins., treatment 1) and a conditioning cycle (-30 deg C for 4hrs and +50deg C for 4 hrs. at relative humidity of 100% followed by 16 hrs. at 22 deg C, this procedure repeated 8 times consecutively,

treatment 2);

Supported by the results obtained with fiberglass, testing of the carbon fiber focuses on:

- Bond thickness of 1, 2 and 3 mm (0.04 – 0.12 in.), see fig. 4;
- Laminate thickness of 1.3, 1.5 and 1.7 mm (0.05 – 0.07 in) are also tested to determine the influence of the parameter on the bond failure mode (see fig. 5);
- The joint was tested both in natural (treatment 0) and in the post cured (treatment 1) configurations, since the fiberglass coupons satisfactorily passed the cycling conditioning (see fig. 6).

Both composites are polished with Methyl-Ethyl Ketone (MEK) before application of the adhesive, while the EPC steel 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 allows for all three different failure modes to be observed, namely adhesive, cohesive and substrate (EPC, fiberglass or carbon fiber delamination [11]. Both glass and carbon fiber results show that: environmental cycling deteriorated the joint strength very slightly; increasing the bond thickness causes its strength to drop (the 1 mm bond-line proved to give the highest results, but 2 mm was still very performing); a noticeable oscillation in the results can be observed on the basis of the laminate thickness and environmental treatment; average strength values for carbon fiber are substantially greater than for glass fiber.

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 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 [11], 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 mins.) and then kept in place for the necessary 2 hrs. curing time at room temperature.

Conclusions

Even though strength considerations would suggest the use of tapes, in the case of the Murcièlago manufacturing solutions and engineering approaches justify the use of the less performing fabrics. The procedure used to obtain class A surface certification has been described, and it involves not just the design and manufacturing solutions adopted for the component itself, but of its model and mold. Accelerated environmental degradation methods used to validate laminate solutions have been described and criteria for composite system selection reviewed. Methacrylate adhesive was used for the hybrid joining of the body panels to the frame of a vehicle, because of the good compromise between strength, stiffness, vibration damping, sealing behavior and curing time.

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Tables & Figures

Table I. Elastic properties for the unidirectional tape:

Ex = 18 Msi (124.1 Gpa)	Ey = 1.5 Msi (10.3 Gpa)	Ez = 1.5 Msi (10.3 Gpa)
Gxy = 0.8 Msi (55.2 Gpa)	Gxz = 0.8 Msi (55.2 Gpa)	Gyz = 0.6 Msi (4.1 Gpa)
νxy = 0.3	νxz = 0.3	νyz = 0.35

Figure 1. The composite body (orange, except for the windows) of the Murcièlago is shown over its tubular steel frame (yellow): the steel roof and posts are visible in gray.

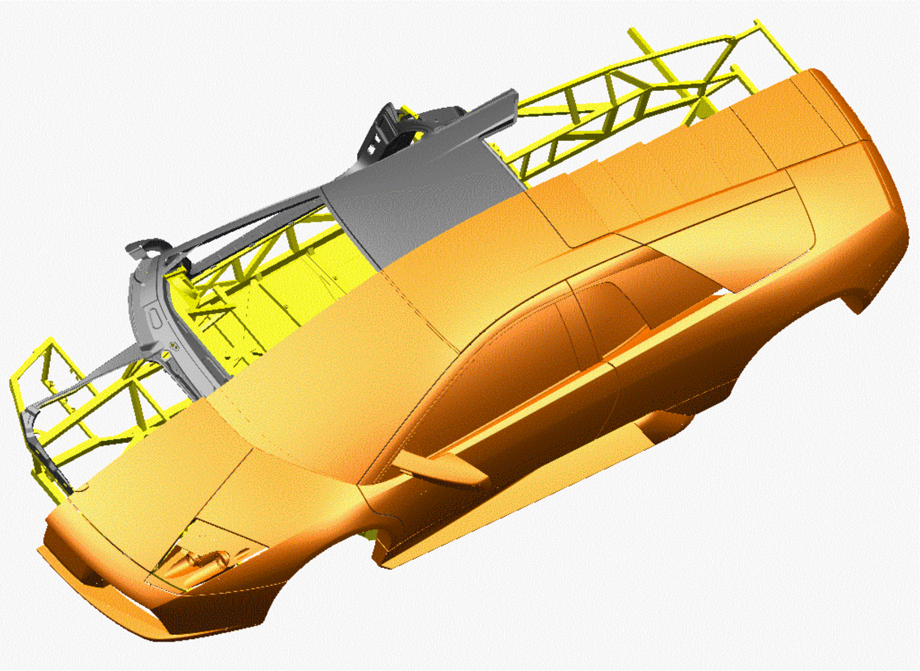


Figure 2. A) Epoxy model for the front bumper: visible is the black epoxy finish for surface inspection; B) Graphite/epoxy mold obtained from the previous model; C) Component after extraction from the mold: visible is the green epoxy primer for better paint absorption and sanding; D) Final component after painting and assembly.

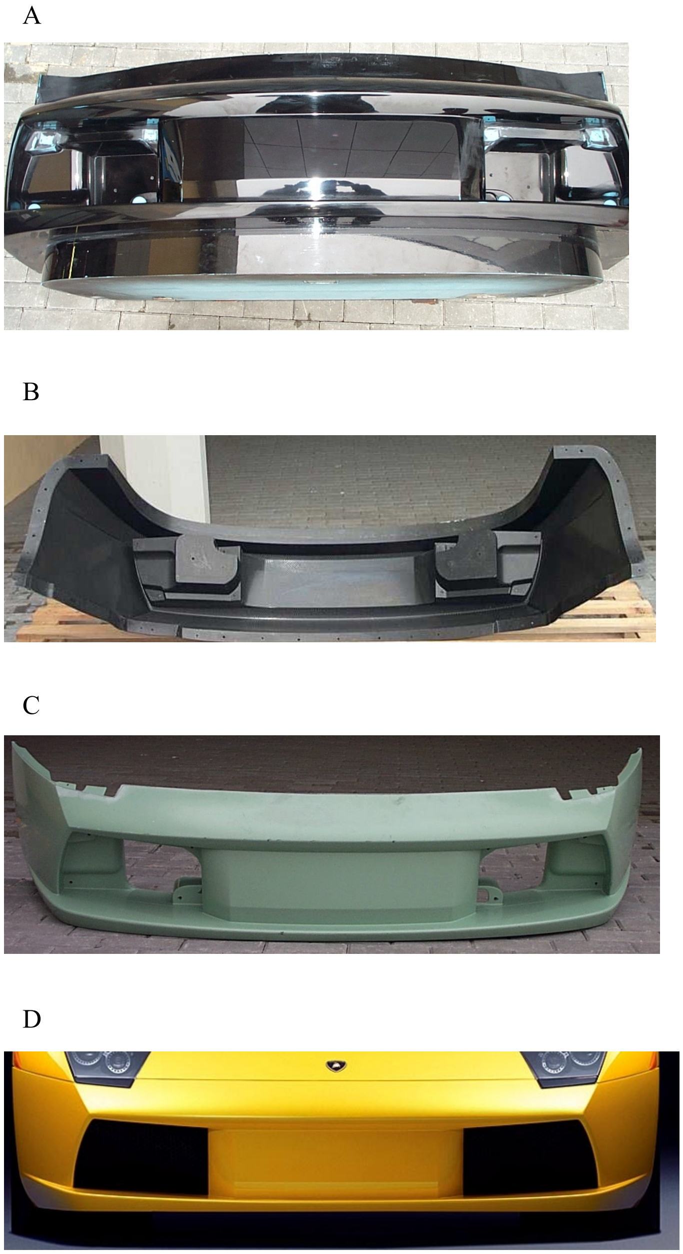
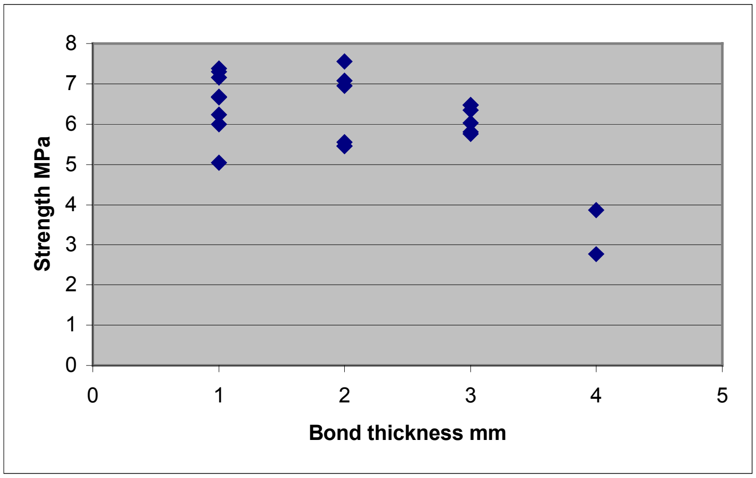
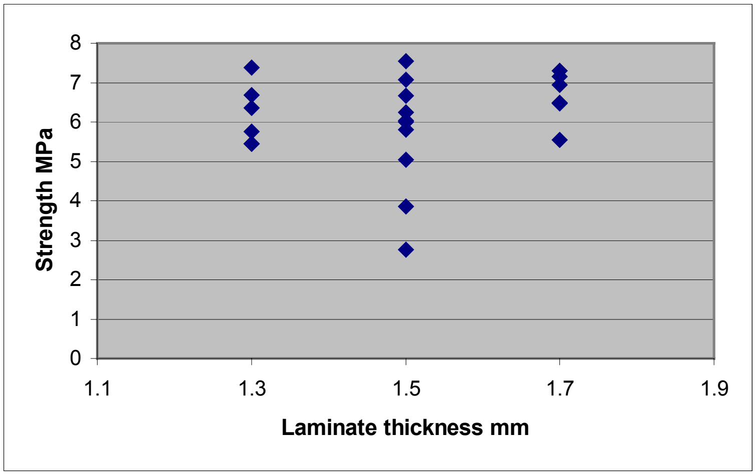


Figure 3. Bonded joint strength for various values of A) Bond-line thickness; B) Adherent thickness; C) Environmental cycling.

A



B



C

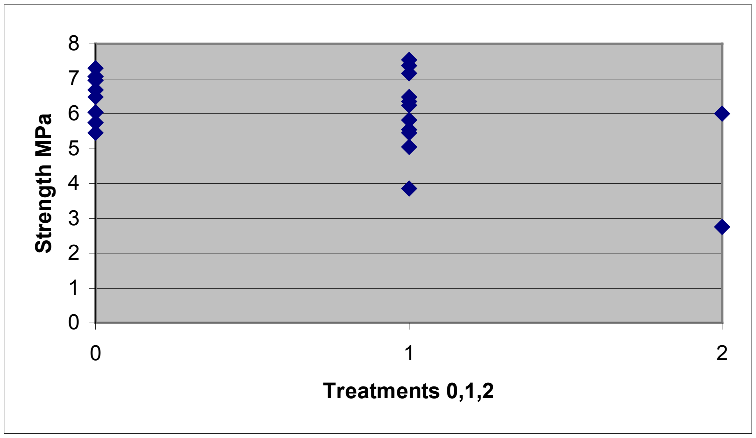


Figure 4. Single lap shear test coupons: EPC steel adherent on the left and carbon fiber on the right. Visible are also the blue paste of the Methacrylate adhesive and the red spacing wires. All three failure modes are visible.

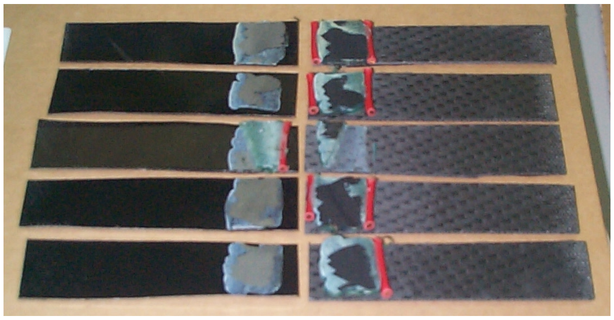


Figure 5. Frame and passenger compartment of the Murcièlago. Light blue indicates the carbon/epoxy floor pans, rocker panels and transmission tunnel. The red lines represent the rails along which body panels are adhesively joined to the frame.