RECENT RESEARCH RESULTS IN COMPOSITE MATERIALS AND ADHESIVE APPLICATIONS FOR VEHICLE LIGHTWEIGHT

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INTRODUCTION

Automobile production has increased in the last 20 years, reaching the total amount of about 58 million units (excluding commercial vehicles) in 2000. According to the estimations made by the Organization for Economic Cooperation and Development (OECD), the total number of vehicles in OECD countries is expected to grow further by 32% from 1997 to 2020 [1]. The already evident consequences of high energy consumption for transportation of passengers and goods and this sharp forecasted increase in the number of circulating vehicles create concern in the society, as vehicles impact the environment in several ways throughout their life cycle. On one hand, the main energy source for automobile motion is the direct combustion of fossil fuels and this results in a large contribution to the global CO2 emissions. One must consider that burning 1 kg of petrol, diesel, kerosene and the like in a vehicle engine leads to approximately 3.15 kg of CO2 emissions. Among the circulating road transport means, emissions from the ‘‘light duty vehicles’’, i.e. passenger cars and vans, are responsible for approximately half of CO2 emissions [2]. On the other hand, currently, only about 75% of each vehicle, mainly its metallic components, is truly recycled at its end-of-life in the European Union, avoiding to further fill landfills and to waste precious resources. Therefore, the rest (~25%) of the vehicle material is wasted and generally is burnt or is sent to landfills contributing to make the landfill situation more and more critical. This generates between 8 and 9 million tons of waste every years in the European Union [3].

The transportation sector is responsible of nearly one-third of global energy demand and consequently is one of the major source of pollution and greenhouse gas emissions in urban areas. This stimulates a wide expectation for energy saving opportunities and for clean technology adoption. The environmental sustainability represents one of the major driving forces for the innovation considering European Commission’s regulation for CO2 emissions which sets stringent values for fuel economy depending on the average fleet weight as reported in figure 1. The EU directive No. 443/2009 [4], established in 2009, is prescribing that for the average fleet, in 2020 a target of 95 gCO2/km and in 2025 a target of 75 gCO2/km which represents a great challenge for vehicle development. Additional regulations for light commercial vehicles, introduced in 2011, require that they must not exceed emissions of 175g CO2 /km by 2017, and 147g CO2 by 2020The adoption of new materials and technologies can help greatly in this perspective. While in case of insufficient improvement, automotive OEM will have to pay a bill of 91€ for every gram of CO2 emitted above the threshold which may mean up to more than 3000€ per car. This represents a strong driving force to new lightweight materials in order to help in decreasing CO2 emission. Based on preliminary calculations, every 10% of weight saving will bring to a 3-

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5% of fuel economy and CO2 emission decrement, which can be translated into a cost acceptable increment in the range of 3-5 € per kg saved.

In additions, European Parliament and Council Directive 2000/53/EC on vehicle end-of-life set out specific measures to be actuated by Member States in relation to the collection, storage, dismantling, reuse and recycling of materials and components at vehicle end-of-life. As per this Directive, each Member State is required to achieve a recovery and recycle target of 95% (with a minimum of 85% material recycle) by 1 January 2015 and to ensure that all end-of-life vehicles are dismantled, treated and recovered by industry at no cost for the final owner of that vehicle and in a manner that does not cause environmental pollution [5].

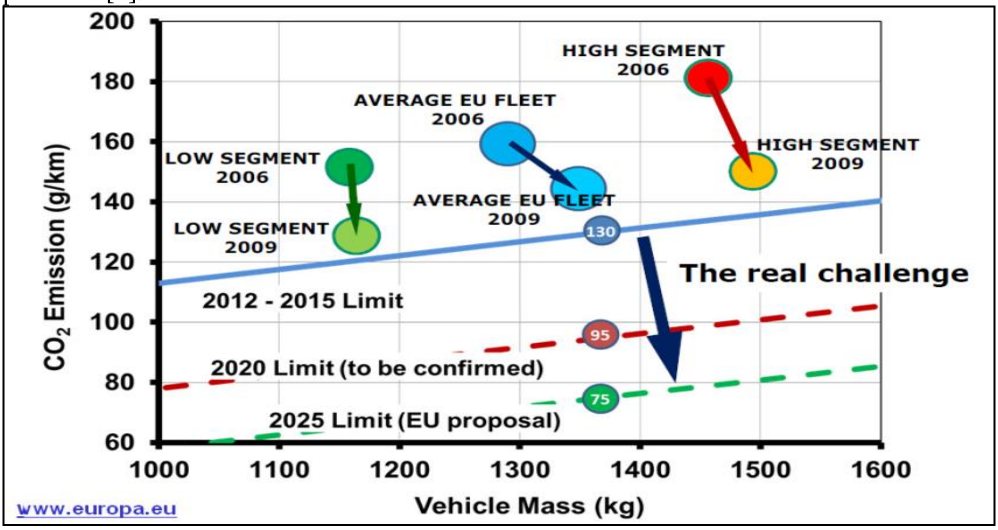

Figure 1 – Evolution of the CO2 emission limits in the EU for the next years

One of the most promising way to enhance operating efficiency is the use of lighter structural and semi-structural materials including advanced metals (high-strength steel, aluminum) and polymeric materials as glass fibers and carbon fibers reinforced plastic (GFRP, CFRP).

Material selection for component construction depends on the performance requirements of the component itself, on its location and functional role in the automobile. Thus components can generally be categorized according to the following three main groups that have peculiar characteristics: body and exterior, interior, and powertrain. In the short term, vehicle lightening can be achieved by replacing heavy steel components with components made by materials such as high-strength steel, aluminum, or fiber-reinforced polymer composites. The mechanical properties and manufacturing of these materials are well established. In the longer term, even greater lightening is possible (50%–75% weight reduction for some components) through use of carbon-fiber-reinforced composites as shown in figure 2a by means of a comparison between steel and different type of composites.

Composite materials are gradually increasing their employment on vehicles. For some special vehicle they are already used for the manufacturing of structural components such as for the Alfa Romeo 4C monocoque (see figure 2b) that debuted at the 81st Geneva International Motor Show in March 2011 (commercially available in 2013). The Alfa Romeo 4C is small lightweight rear wheel drive sports car using carbon fiber tub, front rear crash box and hybrid rear frame to keep its weight below 1000 kg.

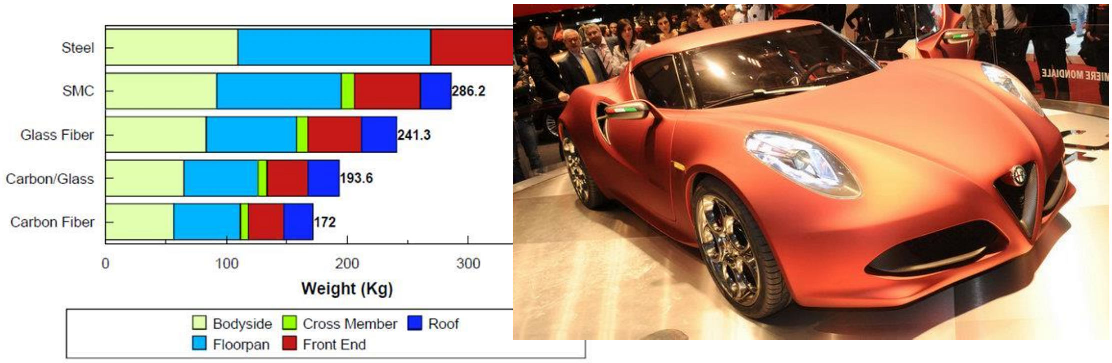

Figure 2 – a) Comparison between steel and composites for different car parts; b) Alfa Romeo 4C

The present work, that summarizes some of the recent results that has been obtained through the research cooperation between researchers of Politecnico di Torino and of FIAT, is dedicated to discuss the design capability of alternative novel materials for a couple of automotive components, a bumper beam and a engine subframe, that can contribute to significant improvements toward the solution of the above stated problems.

Bumper is an important structural component of automobiles to prevent or reduce physical damage to the front and rear ends of vehicles during low-speed collisions. In modern passenger car it has to satisfy two main structural requirements. On one hand, it needs to be deformable enough to absorb as much impact energy as possible to reduce the risk of injury for pedestrians or damage to other vehicles during low velocity collisions and on the other hand it needs to be stiff enough to protect nearby expensive-to-repair vehicle components such as fenders, hood, light groups, water cooler and intercooler. Therefore the material selection has to address both the above issues.

Random long glass fiber reinforced polypropylene Glass Mat Thermoplastic (GMT) is already widely used by the automotive industry for numerous applications. Current production applications include a number of noise shields and front end structures, as well as the Mercedes A Class rear hatch and double floor structure, the Volvo 850 rear seat structure and Volvo truck dashboards [6]. Kumar and Johnston [7] studied and compared the performance of C- and I-section bumper beams made of GMT composite using a variety of compression-molds. Gilliard et al [8] developed the I-section beam with 40% (mass fraction) of chopped fiber glass GMT. They found that the I-section bumper design has improved static strength and dynamic impact performance by means of the use of lower cost mineral filled/chopped fiber glass GMT. Belingardi and co-workers [9] have developed a specific study for the design of the bumper beam made by GMT as a possible solution for the front bumper in alternative to the present steel solution. The GMT solution, being based on thermoplastic matrix composite material, essentially polypropylene (PP), has better recycling performance with respect to other possible solutions made with composite materials based on thermosetting matrix such as epoxy resin [10].

Engine sub-frame is used to support the engine into the engine compartment and to connect through the engine mounts the engine to the body structure. Strength and stiffness are main targets for the frame design as well as its vibration response as it is directly submitted to the vibration excitation applied by the motor engine during its operation. The reference engine sub-frame basically consists of two longitudinal and two cross beams, these parts are made of steel. The two longitudinal beams and the rear cross beam are made of two half-shells that, after deep-drawing, are joined together by spot welding, while the front cross beam is made with extruded profile. Both the engine and vehicle front suspension systems are assembled on the rear cross beam and rear parts of longitudinal beam, respectively. To get robust stiff assembled engine sub-frame, two vertical links are generally introduced at the middle of longitudinal beams to connect with BIW. In order to support the cooling system, additional horizontal cross links are incorporated on the frontal cross beam of sub-frame.

Composite material solution has been developed by choosing a CFS003/LTM25 Carbon/Epoxy fabric prepreg, i.e. a material with high structural performance. Stacking sequence has been optimized in order to get the best results both in terms of frame bending stiffness and in terms of strength. Further, appropriate increment in the wall thickness and structural reinforcements has been designed in order to solve the structural problems in the most stressed zones.

In relation to the use of composite material, especially in the case of multi-material solutions, adhesive joining is considered as the main joining technology even if, in order to join plastic components, also mechanical fastening and welding [11,12, 13] can be considered.

Traditional mechanical joining involves the use of fasteners such as metallic and polymeric screws. This technique has the advantage of a rapid and effective disassembling process both for inspection and part substitution. Unfortunately, this type of mechanical joining is associated with an increase of the final weight and, very often, with an increase of the manufacturing time and costs. In welding, the plastic materials are fused together by the proper combination of heat and pressure; heat is applied to melt the polymeric material on the joint surfaces, to enable polymer intermolecular diffusion across the interface and chain entanglements to give the joint strength, and surfaces are pressed together for polymer solidification and consolidation.

Adhesive joining is a process whereby an adhesive is placed between the parts (adherends) where it serves as the material that joins the substrate and transmits the load through the joint. The principal benefits deriving from the use of adhesive joining involve: low cost, design flexibility, improved stiffness of the joint, ability to damp noise and vibrations, uniform distribution of stresses over the assembled areas, possibility to join dissimilar materials and no direct contact between parts. Having in mind the end-of-life recycle problems, the use of thermo-plastic adhesive could be of particular interest.

Adhesives and induction welding could be combined to achieve special benefits and obtain unique joining combination by means of the use of an electromagnetically nano-activated adhesive; this choice is relevant for reversible assembling/disassembling technologies.

This innovative technology is based on the embedding of electromagnetically active susceptors in an adhesive matrix. Suitable choices are iron particles, iron oxide, stainless steel, ceramic, ferrite or graphite [14, 15]. Once an alternating electromagnetic field is applied, the magnetic particles within the adhesive activate and rapidly heat: the amount of the generated heat depends on the nature, the quantity and the morphology of the particles.

The increasing temperature is thus able to melt the thermoplastic adhesive matrix and the assembling process of polymer-made automotive components is possible. Once the joint is created, it can also be quickly and effectively disassembled by simply use of the same apparatus and conditions.

VEHICLE WEIGHT REDUCTION

This topic has already been considered in a previous paper [16] presented at the MVM 2012 Conference. The interested reader can make reference to that paper. However some further elements can be brought to underline the evolution of the vehicle weight in the years. Figure 3 gives a rough information, for sake of exemplification, for medium size FIAT cars.

Figure 3 – Evolution of the vehicle weight for a FIAT medium size car

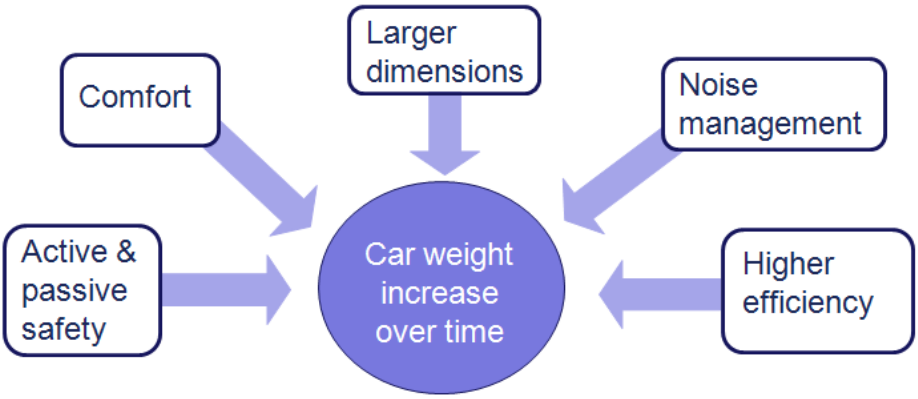

Figure 4 – Main contributions to weight increment for European cars.

Naturally this dramatic change in weight can be explained, as shown in figure 4, by the growth of the requirements both in term of costumer satisfaction (riding comfort, noise reduction, internal climatisation, info-mobility and so on) and in term of regulation requirements (reduction of noxious gas emissions, improvement in safety, driving assistance and so on). But this increment in the vehicle performance has not been accompanied by appropriated changes in the architecture and in the mix of the used materials. Car makers tend to go on with soundly experienced structural solutions that give high guarantee of good quality in the vehicle overall manufacturing.

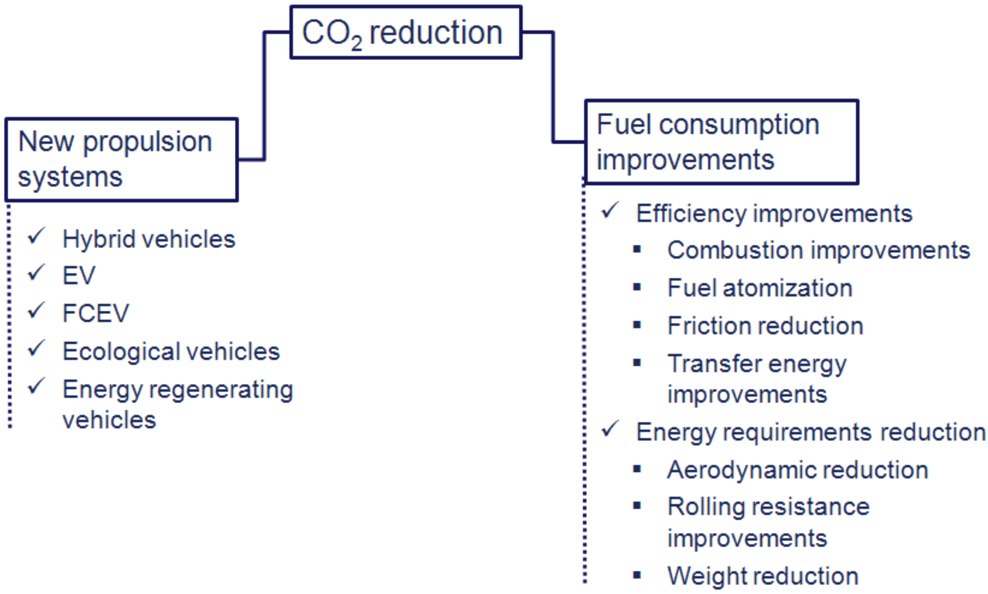

Figure 5 – Main strategies toward reduction of CO2 emission

Figure 5 is giving a general view of the main strategies that a car manufacturer can pursue toward the relevant reduction of the CO2 emission required by the EU regulations.

On the left side of the diagram it is visible the evolution in the propulsion system, from the presently adopted Internal Combustion Engines (ICE), with different possible types of energy sources such as methane, natural gas, GPL, Hydrogen and so on, toward Hybrid Vehicles (HV) and purely Electric Vehicles (EV).

On the right side of the diagram the two main choices (that are not mutually exclusive but could be synergic) that can be pursued are listed: an increment in the vehicle efficiency and a decrement of the amount of energy required for the vehicle ride. The first choice is related to the engine, that can be further optimised with respect to its thermo-fluido-dynamic performance, but also to the transmission line. A huge amount of energy is wasted as a consequence of the friction loss inside the engine itself, in the gearbox (teeth mating), in the differential box (gear geometry and teeth mating) and finally into the transmission joints. The second choice is related to the vehicle and finalised to reduce all the terms that contribute to the power required to ride the car [16] and in particular the aerodynamic drag, the rolling resistance for the tires but, as main contribution, the vehicle weight.

Table 1 is giving some order of magnitude in the advantage that can be obtained by means of a performance improvements of the above mentioned factors. While reading the results shown in the table one must take into account that the hypothesized improvements has been set equal to 10% for all the factors, despite the possibility of really achieving this improvements.

For what concern the improvements for the engine a lot of work has already been done and a very valuable reduction of the fuel consumption (that is strictly linked to the CO2 emission amount) has already been achieved, as shown in table 2, but this improvement has been accompanied by a big increment in the vehicle weight.

Table 1 – Main factors toward reduction of fuel consumption and CO2 emission and effect estimation.

Factor	Improvement	Impact on fuel consumption
Tires rolling resistance	- 10%	- 1,5%
Aerodynamics (Cx frontal area)	- 10%	- 2,7%
Weight	- 10%	- 3,5%
Powertrain efficiency (engine, gearbox, transmission)	+ 10%	- 10%

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Table 2 – Comparison between the performance of two vehicles of the same class after ten years

	FIAT BRAVO 1.9 Diesel 100hp - 1999	FIAT BRAVO 1.6 Diesel 105hp - 2009	Δ
Fuel consumption - combined cycle (l/100km)	6.3	4.5	- 28.6%
Weight (kg)	1155	1320	+ 14 %

Table 3 – Comparison of the weight reduction and of the cost increment that comes out if components made with the materials listed in the second column are redesigned with the materials listed in the first column

Lightweight material	Material replaced	Mass reduction (%)	Relative cost (Assuming HSS=1)
High strength steel	Mild steel	10 - 25	1
Aluminum	Steel, cast iron	40 - 60	1.3 - 2
Magnesium	Steel or cast iron	60 - 75	1.5 - 2.5
Magnesium	Aluminum	25 - 35	1 - 1.5
Glass FRP composites	Steel	25 - 35	1 - 1.5
Carbon FRP composites	Steel	50 - 60	2 - 10+
Al matrix composites	Steel or cast iron	50 - 65	1.5 - 3+
Titanium	Alloy steel	40 - 55	1.5 - 10+
Stainless steel	Carbon steel	20 - 45	1.2 - 1.7

Table 3 gives a rough estimation of the mass reduction and of the variation (increment) of cost that is coming out if components that in the normal present production are made of the “traditional“ materials listed in column 2 of the table are redesigned with the adoption of the “innovative“ materials listed in column 1. Only in a few situations (see column 4) the cost change is very small, most of the times we have a relevant increment of the cost up to twice and even more. But at the same time (see column 3) a relevant reduction in the component mass can be achieved, in several cases up to 40% and in some cases even up to 60%.

TWO EXAMPLES OF VEHICLE COMPONENTS MADE OF COMPOSITE

The bumper beam

Figure 6 shows the present solution for the front bumper system of the FIAT 500. The main structure consists of a transverse beam made of deep drawn steel, covered by a layer of polypropylene foam and a polypropylene shield (the so called fascia) that has mainly aesthetical and aerodynamic functions. The transverse beam is connected to two longitudinal crash-boxes that have the aim of absorbing energy in case of low velocity impacts, while preserving the other body front structure and the engine compartment components and devices.

Figure 7 shows the solution that has been studied taking advantage from the particular mechanical characteristic of the GMT material in its base configuration and in a modified configuration with some layers of unidirectional or fabric reinforcement. One of the main advantage in using this type of material relays on the manufacturing technology that can be adopted and is based on die-forming procedure. This technology enables the designer not only to obtain an interesting solution for the bumper transverse beam but to integrate in the same part the two crash-boxes, as is shown in figure 7 [9]. The crash-box has a thin-walled prismatic tapered shape. By choosing appropriately the dimensions (length, side width and wall thickness) in relation with the specific material strength, it is possible to obtain a crumpling behaviour, in case of impact, with energy absorption of the expected amount.

It is worth of note that the integration of the two crash-boxes and the bumper transverse beam into one single piece is of the greatest interest because it avoid to manufacture a number of different pieces (more than 10), to handle these pieces along the production lines, to dedicate some working stations for their assemblage operations.

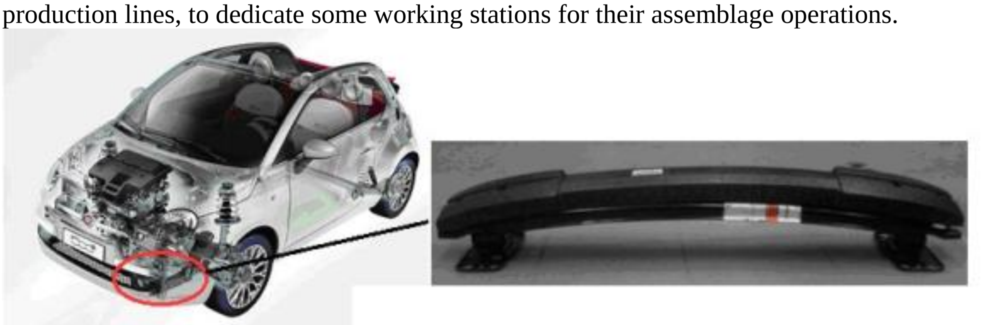


Figure 6 – The present solution for the front bumper system with the bumper beam and the crash boxes made by steel, through the assembly of different parts

The manufacturing process and the tooling result to be largely simplified and a relevant reduction of the production cost can be obtained. This can be a typical example of the need of using a wider view when comparing the costs of two alternative solutions based on the use of different materials: it is needed to account not only the cost of the materials but also the costs of the manufacturing process. Very often the composite material solution allow for integration and thus large simplification of the process.

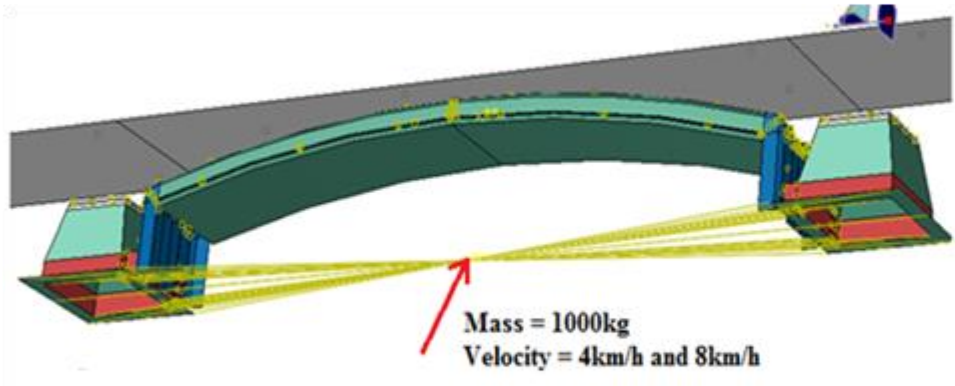


Figure 7 – The proposed solution for the front bumper system with the bumper beam and the crash boxes made by composite (GMT) material, the solution is integrating the different parts into one piece [9].

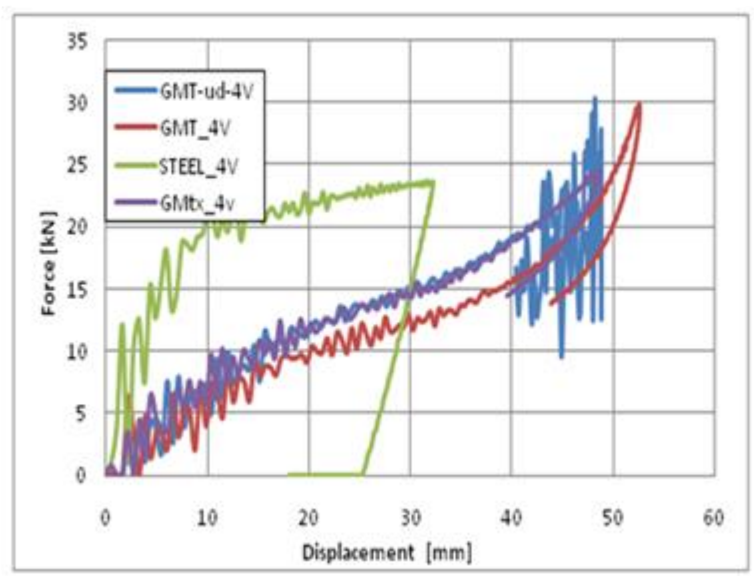


Figure 8 – Comparison of the force-displacement diagrams obtained through numerical simulation of the impact performance of the front bumper. One curve is describing the results related to the NP solution, the other three curves the composite material ones.

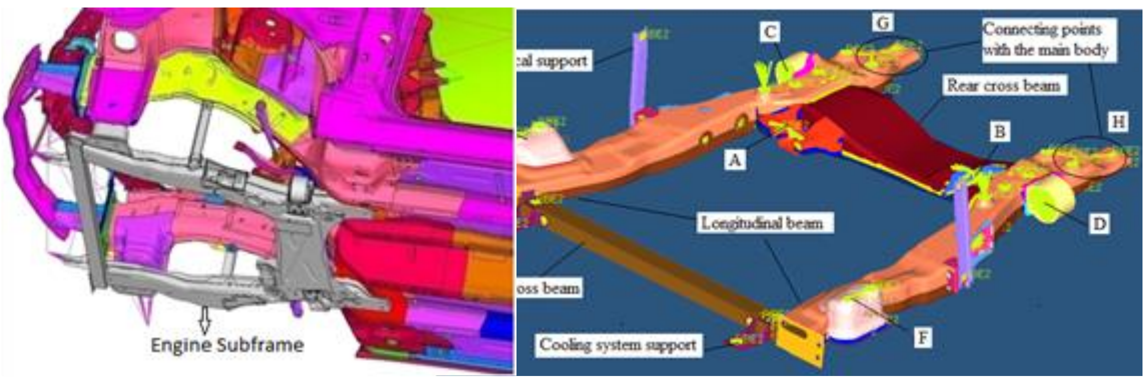
Finally figure 8 shows the comparison of the force-displacement curves for the case of the front bumper impacting at a velocity of 4 km/h against a rigid wall. The vehicle is supposed to have 1000 kg mass. In the figure four curves are superimposed, one is for the bumper beam made with steel (i.e. the NP solution) and the other three are for the composite solution of figure 7, made with different GMT materials: a simple GMT (that is the red curve, as expected, being this the less performing material, the curve is the lower one), a GMT-tex (that is the GMT reinforced with the fabric made of long glass fibers) and a GMT-ud (that is the GMT reinforced with unidirectional long glass fibers). These two latter alternatives result to be equivalent, being the curves nearly superimposed. The maximum displacement for the composite solutions, although larger than the steel one, does not exceed 50 mm and thus the intrusion into the engine compartment is not critical.

The advantage in terms of mass for the composite solutions with respect to the steel one is of the order of magnitude of -52 %, that is about 4 kg.

The engine subframe

Figure 9 shows the present solution for an engine sub-frame. It consists of two longitudinal and two cross beams, all these parts are made of steel. The two longitudinal beams and the rear cross beam are made of two half-shells that, after deep-drawing, are joined together by spot welding, while the front cross beam is made with extruded profile. In figure 9b the points E,F,G and H are the connection points of the frame with the body structure, points C and D are the connection points with the oscillating arms (left and right) of the front suspension system, finally points A and B are the connection points with the engine mounting and suspension system. In figure 8b also the water cooling system supports are visible.

This frame is a quite complex structure with multiple functions. In some solutions the longitudinal beams are extended toward the front of the vehicle to constitute a further load path very useful in case of frontal impact.



a) b)

Figure 9. Engine subsystem: a) Assembly of engine sub-frame with Body-In-White; b) Detail view of engine sub-frame.

Figure 10 shows the solution that has been studied taking advantage from the particular mechanical characteristic of a CFS003/LTM25 Carbon/Epoxy fabric prepreg, i.e. a material with high structural performance. By means of repeated virtual simulations the stacking sequence has been optimized in order to get the best results both in terms of frame bending stiffness and in terms of strength. Further, appropriate increment in the wall thickness and structural reinforcements has been designed in order to solve the structural problems in the most stressed zones.

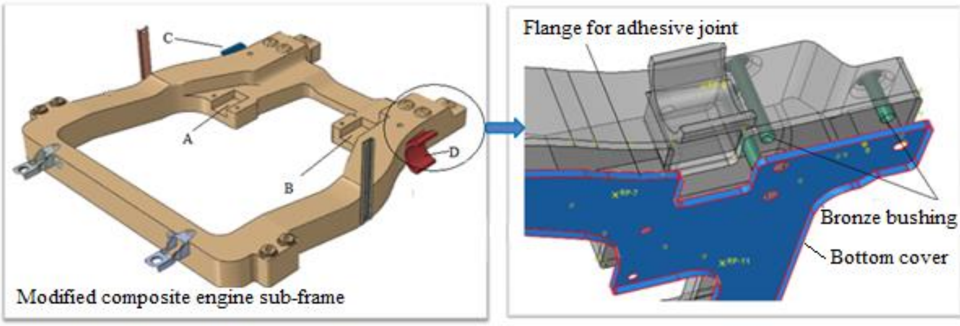


Figure 10. Conceptual design of the composite engine sub-frame [17]

By a comparison of the composite solution depicted in figure 10 and the NP solution depicted in figure 9, it is coming out with evidence that the composite solution is structurally simpler as it integrates into one single part a number of different parts that constitutes the steel solution. Some local reinforcements (for example the bronze bushings needed for the connection of the sub-frame with the vehicle structure, as shown in figure 10b) can be co-stamped and co-cured while the composite structure is manufactured.

Figure 11 is showing the distribution of the maximum principal stresses in the composite material, for the load case of the maximum torque given by the ICE. The calculated values for the stress are fully compatible with the strength of the adopted material.

Figure 11. Maximum principal stress distribution on engine sub-frame with reinforcements [17]

The advantage in terms of mass reduction for the composite solutions (that have a mass of less than 6 kg) with respect to the steel one (that has a mass of about 16 kg) is of the order of magnitude of 10 kg that is about - 62 %.

ONE EXAMPLE OF INNOVATIVE ADHESIVE JOINING

As mentioned in the introduction, in this paragraph we want to present some results obtained during a particular research activity about the use of adhesive for structural joints. The main concerns that has stimulated this type of research are to make experience with a thermo-plastic adhesive, to use nano-particles sensitive to the electro-magnetic field for reduce the polymerization time (and thus the duration of the production cycle), to use the same physical principle used for a selective melting of the adhesive for dismounting purposes (i.e. for separating the parts that has been joined both for easier repair and for easier end-of-life recycling).

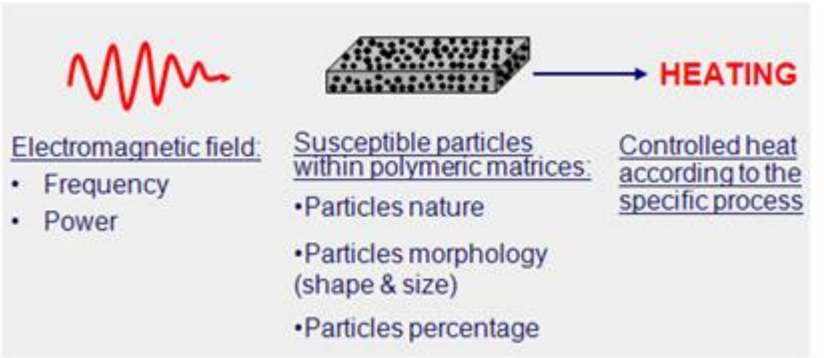


Figure 12. Physical principles of the electromagnetic activation of the nano-modified adhesive and design variants.

Figure 12 is recalling the physical principle for the activation of the adhesive nano-modified by means of susceptible particles dispersed into the polymeric resin [15]. The electromagnetic field acts as source of energy for the polymer heating. Both the parameters of the electromagnetic field (power and frequency) and the nano-particles (material type, particle shape and size, particle percentage) are design variables for the manufacturing process.

At the moment this process can be applied for joining components made of plastic materials. After having performed a number of laboratory tests in order to assess the methodology and to analyse the effects of the main design variables [15], the case of tail gate of the Lancia Musa was chosen for performing a real part application.

Figure 13 shows some detail of the application. The tail gate external trim consist of two shells made of polypropylene that have to be joined in order to obtain the lower trim of the rear door.

Figure 13. The Lancia Musa tail gate as chosen vehicular application.

Figure 14 shows the special tooling that has been prepared to join the two shells and produce the tail gate trim adopting the described innovative technology. A copper circuit has been laid along the joining area to act as electromagnetic inductor, activated by an alternate electric current with the selected values of power and frequency.

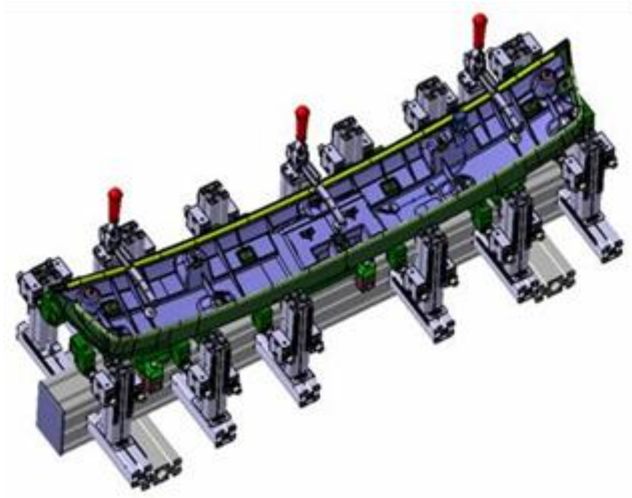


Figure 14. Scheme of the tooling for the manufacture of the innovative adhesive joints applied to the Lancia Musa tail gate [18].

Figure 15 – Disassembled low tail gate [18]

Finally figure 15 is showing the tail gate that has previously manufactured by joining with the described tooling and procedure, and then submitted to similar heating procedure for the dismounting. The supplied power raises the adhesive temperature, because of the reaction of the metallic nano-particles, and, when the appropriate temperature is reached, near the polymer melting threshold, the shells detachment is easily obtained.

CONCLUSIONS

The paper has addressed the present concern in the automotive engineering related to the environmental problems, with particular reference to the fuel consumption and to the noxious and GH gas emissions. Transportation is recognized as one of the main source of the carbon bioxide CO2, that is considered the main GH gas and consequently cause of the current, evident climate change.

The international European legislation is forcing the reduction, on the basis of the average fleet performance, of the fuel consumption reduction. For the CO2 emissions a progressive decrease is targeted, with relevant penalties for the car manufacturer in case of exceed.

The car makers have different possible strategies to develop their products in order to match these normative limits. These strategies can be developed in a concurrent way. One of the strategic line is the lightweight of the vehicles. Some options are at disposal of the designer, the most promising is the substitution of the traditional material (generally low-carbon steel) with more performing metallic materials or with fiber reinforced plastics, as it is widely done in the aeronautical industry sector.

It is the authors' opinion that the first step toward lightweight will consist in the use of more performing metallic materials, but the most important results will be obtained by the extended use of fiber reinforced plastics. This second step is requiring some more research activities in order to extend the already relevant knowledge of the behaviour of this class of materials, with particular reference to the mechanical characteristics (fatigue and impact response), the manufacturing technologies, the reparability, the recycling possibility at the vehicle end of life.

The cost of production is always of concern. In the evaluation of the costs one has to take into account not only the greater cost of the base material (typically fiber reinforced composites have larger costs with respect to metallic materials) but also the generally lower cost in the tooling, the cost reduction that can be obtained by structural integration of the several (very often tenths) metallic pieces, assembled together to construct one single component, into even single piece that can be obtained by plastic die manufacturing.

The paper has presented and discussed two particular examples that have been developed within the fame of the research cooperation between FIAT and Politecnico di Torino.

Further some results have been presented about an innovative adhesive joining technology, based on the use of an adhesive nonmodified by means of the dispersion of metallic particles that are sensitive to the electro-magnetic field. The proper application of the electro-magnetic field is resulting in the polymer heating and this can be used both to accelerate and control the adhesive polymerization during the joining procedure as well as to make possible and easy the disassembly of the joint, in case of repair or dismount. Preliminary results in the application to the Lancia Musa rear door low tail gate have been shown.

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