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A CONCRETE AND VIABLE EXAMPLE OF MULTIMATERIAL BODY: The EVolution project main outcomes

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Abstract

Funded by the EC FP7 Programme, EVolution project demonstrated that it is possible to consistently reduce the vehicle weight through the wide use of new materials and process technologies, mainly by developing a multi-material Body-in-White. This paper focuses on three of the five structural body demonstrators, the main objective of the framework, strongly hybridized with aluminum and thermoplastic composite materials, specifically developed and manufactured through innovative technologies. Directing in particular the analysis on medium production volumes (> 30,000 units/year), the industrial viability is evaluated in terms of TAKT time, lightweighting costs, weight reduction and structural performances achieved.

Keywords: automotive; Body in White; composites; lightweight; electric vehicle;

1. Introduction

Lightweight is one of the major challenges for car manufacturers since it has a direct impact on energy consumption and CO_2 emissions. The European Commission sets targets for average new car CO_2 emissions of 95 g/km by 2020, and the forecast for 2030 is to reduce emission down to 75 g/km, so CO_2 reduction and resource efficiency became a priority across several industrial sectors.

Lightweight is important both for ICEV (Internal Combustion Vehicle) and EV market, where the increasing demand for safety and connectivity features may move in the opposite direction. For EV, whose diffusion is crucial for CO_2 reduction, it is clear that lightweighting stand-alone is not enough to achieve such targets: currently the traction battery cost and the range of autonomy are among the most limiting factors to EVs spreading, but thanks to lightweighting the battery can be downsized (maintaining the same autonomy), reducing the vehicle cost or, in alternative, keeping the same battery the vehicle autonomy can be increased.

The key of success for CO_2 reduction relies on the conception of a multimaterial body archetype characterized by extreme lightweight strategies, balancing the cost due to lightweighting with the downsizing of the traction battery.

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In this scenario, the EVolution project proposes an intriguing solution of hybrid body with an extreme weight reduction (-30% with respect to starting solution full in Aluminium). This consistent weight reduction is achieved by:

- an extensive employment of advanced forming aluminium technologies which allows to integrate parts, reduce and optimize thickness distribution, especially in the Body-in-White
- a smart usage of optimized composite materials to obtain hybrid or fully composite parts with impressive weight saving and performance comparable or, in same case, improved with respect to "old" metal components.

2. The project

EVolution stands for "The Electric Vehicle revOLUTION enabled by advanced materials highly hybridized into lightweight components for easy integration and dismantling providing a reduced life cycle cost logic".

Funded by the EC FP7 Program, EVolution started in November 2012 and involved 24 partners from 11 different EU countries, with the goal to demonstrate the sustainable production of a full electric 600 kg vehicle (FEV). The project ended in October 2016.

EVolution project was principally based on Pininfarina Nido concept, on part of the outcomes of the FP7 project, E-light [1], based on Nido structure, and on the internal Pininfarina research project Safety Car, developed around the first Nido archetype, winner of the "Compasso d'Oro" award in 2008.

The A-segment Nido EV concept was not derived from an ICE vehicle, but conceived directly as an EV. The BiW (Body in White) fully in Aluminium was composed by commercial extruded profiles and casted parts, carrying cold-formed panels. Main body sections were obtained by assembling different profiles, with a consequent weight increasing even where it is not necessary, as the principal focus of this concept was to save cost, not mass. Hence BiW weight of this solution was 160 kg, while current estimated full vehicle weight was about 850 kg.

Starting from this baseline, the focus of EVolution was on some specific body areas, called demonstrators, mainly part of the BiW: namely the underbody, the side door, the front crossbeam, the structural node (shotgun system) and the front mechanical subframe.

The full body, and in particular these demonstrators, were redesigned in order to achieve the target weight through an innovative mix of design strategies, new materials and processing technologies. In particular, each demonstrator was requested to be 50% lightweighted respect to an equivalent steel solution. To minimize materials costs and supply chain complexity associated with such a large number of potentially suitable materials, EVolution was addressed on a minimum number of them, identified among the existing ones in terms of use, potential for further development, cost effectiveness and environmental impact.

In the following sections a deep insight on the crossbeam, the underbody and the subframe demonstrators is given.

3. The crossbeam

The Front Crossmember has the function to absorb energy in the case of frontal collision, cooperating with the front shotgun in the case of high speed impact. These two elements together represent the front crash management system of a car.

The behaviour of front crash management system is strongly influenced by the materials properties selected to design and manufacture it. The EVolution challenge is to propose and manufacture a fully composite front crossmember for medium-high production volume competitive in terms of weight, costs and performance to the traditional metallic solution.

In general, the redesign of a metal crossmember into a fully non-metallic one is an engineering challenge consisting in the search for a solution which results to be lightweighted and more efficient in terms of impact energy absorption, keeping into account the different modalities of collapsing of the two families of materials.

The EVolution concept is derived from the outcomes of a previous FP7 project named Nanotough [2], characterized by a high toughness, but with a stiffness not fulfilling the high-speed impact requirements.

Based on the AZT protocol and the ECE94 Full Front Crash simulations, Pininfarina and FPK have analysed different designs and raw materials in order to obtain a component which fulfils all the requirements in terms of performances as well as in weight saving.

After many iterations, the final design (Fig. 1) consists of a beam composed by a front and rear shell members, where the front one is derived from the previous mentioned project, to preserve the mould (saving project costs), and a specific crashbox. Both crashbox and selected beam sections are filled by a core of specific rigid polyurethane (PU) foam to improve crash performances.

Fig. 1. Evolution front crossbeam demonstrator

Final weight of the component is 2.81kg, with a weight reduction of more than 50% respect to the Nanotough steel baseline, whilst the low and high speed impact performances are assured.

3.1. Materials and manufacturing processes

It is remarkable to underline the special features characterizing the manufacturing process of this demonstrator. The main highlight is the opportunity to perform all the process operations into a unique production site, the FPK's one.

Injection Moulding Compound (IMC) technology, used to obtain both rear shell member and crash boxes, is a combination in a single stage of the continuous process of extrusion with the discontinuous operation of injection moulding, linking a twin-screw compounding extruder to an injection process.

The manufacture of the front shell member is a technique combining in one step press moulding of continuous fibre reinforced thermoplastic (polypropylene, PP-based) and injection moulding, using long glass fibre (LGF) reinforced thermoplastic.

Keeping into account these process peculiarities, the main parts of the Front Crossmember are developed in a new material conceived by ICECHIM with the support of AAU. Starting from the background knowledge of Nanotough project, this material is a combination of two key solutions from nanotechnology and advanced materials field [3], specially tailored with the advanced material used by FPK (PP with 30-50% LGF) in which a special nanosilicate is added. The nanosilicate is uniformly embedded into a thermoplastic elastomer matrix to obtain a smart masterbatch, directly usable in the IMC process of FPK products. This masterbatch uniformly disperses in PP with 20-40% LGF based composites.

Thanks to a synergistically effect between the components, an increase of 300% of the impact resistance without decreasing strength and stiffness, respect to virgin PP it is obtained. These properties are better than those obtained within the Nanotough project (Fig. 2).

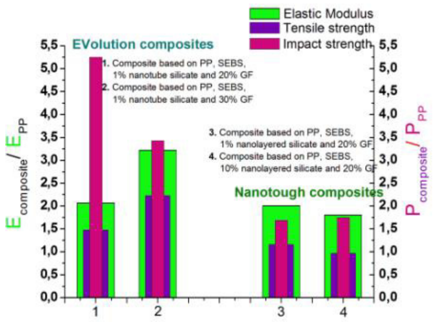

Fig. 2. Nanotough concept (left) and Evolution front crossbeam demonstrator (right)

The solution is covered by a national patent application “Masterbatch for improving the impact strength of polypropylene with glass fibre and process for obtaining it” [4].

A rigid PU foam based on recycled resources is developed by IWC and up-scaled by RITOLS in the range of densities 50-600 kg/m^3.

The main innovation is related to the fact that by using sustainable polyols obtained from recycled polyethylene terephthalate (PET) waste it is possible to replace raw materials from petrochemical origin. It has been demonstrated that the mechanical properties of the rigid PU foams based on polyols from recycled PET do not exhibit worse mechanical properties as their petrochemical counterpart. More in details, the formulation is based on aromatic polyester polyols obtained from recycled PET; the sustainable raw material content reached up to 25 % of PU foam mass [5]. The mechanical properties at high strain rates were tested to select the material with the best combination of weight reduction and energy absorption.

Obtained stress strain curves and other data were used in finite element modelling which identified rigid PU foams with density 70 kg/m^3 and 100 kg/m^3 as the optimal ones to fill the cores of crossbeam and crash boxes respectively.

3.2. Main highlights from virtual and physical tests

A tests campaign on body subsystems integrating the front crossmember demonstrator was performed. These tests, based on Allianz Protocol (AZT) and calibration procedures (basically, rigid wall impact tests at medium speeds) confirmed the virtual forecast and allowed the model correlation and consequently further optimizations of the part.

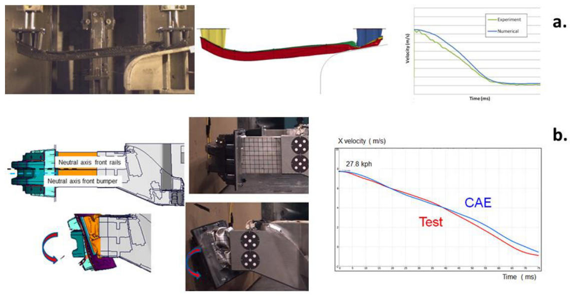

Fig. 3. AZT test/CAE (a) and calibration test/CAE (b)

Thanks to that, it is remarkable to see that in the ECE R94 full front crash for European homologation, the EVolution crossmember is capable to absorb a 30% surplus of energy more than Nido component with a similar weight in the first 20·10^{-3} sec (the range in which commonly a crossmember works in the abovementioned mission). These already impressive results could be improved removing the constraint to derive the concept from Nanotough project.

Basing to these outcomes, and to the synergistically design of the structural node demonstrator (the front shotgun system, out of scope of the present paper) and of the underbody, the whole EVolution structure is ready to obtain good biomechanical values through an appropriate development of the restraint system and interior trim (which were out of scope of the project), which can be synthetized as follows:

- the energy was absorbed gradually without no peaks that could affect the dummies biomechanics;
- the steering wheel intrusion in the three directions X-Y-Z are very low and showed that the structure has a sufficient stiffness to avoid high movement of the steering wheel;
- the body structure undergoes low deformations

4. The mechanical subframe

A mechanical subframe is a structural module designed to carry front vehicle suspensions; it concurs in filtering on BiW the road loads transmitted by vehicle suspensions. The EVolution challenge, as for thefront crossmember, is to propose and manufacture a fully composite subframe for medium-high production volume competitive in terms of weight, costs and performance to the traditional metallic solution.

The Nido solution is made of two welded steel sheels with welded steel brackets. The strategy of redesign is mainly driven by strength and durability performances and geometry definition for low rate cost/lightening composites.

The final EVolution design is a solid component without hollows and with variable thickness developed by FPK (Fig. 4).

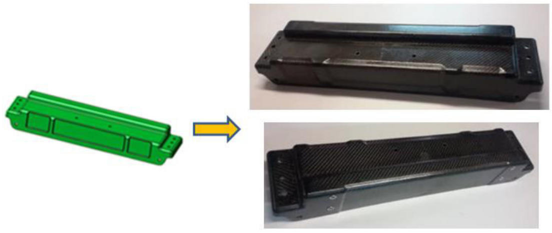

Fig. 4. Evolution subframe final demonstrator

The final release of the subframe demonstrator fulfills the performances and the weight requirement (3.48 kg as final weight versus 6.8 kg as metal baseline weight).

4.1. *Materials and manufacturing processes*

Fatigue behaviour and strength are the main mechanical characteristics to be assured by a proper design and material development into the subframe demonstrator.

The fatigue behaviour of any composite is influenced by the toughness of the resin. In this project, polyamide (PA) is considered for the polymeric matrix due to its toughness and low cost. The reinforcement selected is Carbon Fibre (CF), superior to Glass Fibre (GF) in fatigue as well as specific strength, chemically redesigned to be compatible with PA, as the CF commercial fibres are all compatible with epoxy resin only.

The main goal to obtain a composite thermoplastic material with high mechanical properties consists of achieving a good chemical anchorage between the fibres and the matrix.

To achieve this purpose, TEC develops a specific PA-CF based material optimized for its patented manufacturing process named CAPROCAST.

The CAPROCAST technology of TEC is based on the casting or in-situ polymerization of APA6 (Anionic PolyAmide), and through a fast RTM process enables the manufacture of continuous fibre reinforced PA6 structural components, with the added benefit of a low initial level of investment for both moulds and equipment.

With this solution, PA composites are obtained and a step in the manufacturing process is removed. In fact the process starts with the monomers as the raw material, and these are injected into a mould with the shape of the required component, within which the reinforcement has previously been placed in the form of a fabric. After injection, the monomers react with a catalyst to form the corresponding polymer, thereby obtaining the composite, with the required shape and incorporating the reinforcement, in a single operation.

This manufacturing solution is protected by three patent applications. The first one (EP2338665) [6] covers the manufacturing process beginning with the monomers, and the two most recent applications (EP2743061 and WO2015/082728) [7, 8] cover the necessary equipment.

The mechanical properties of the composite material obtained through CAPROCAST technology could be compared with the current commercial thermoplastic composite materials named organosheets.

Table 1. Mechanical properties comparison between Caprocast materials and organosheet.

Material		Warp-weft	% Fibre in volume	Modulus (GPa)	Strength (MPa)
PA 6 Fabric Tecnalia	GF.L	80/20	48	31.4	670
	GF.T			11.6	190
	CF.L	50/50	48	48.2	629
	CF.T			48.2	561
PA 6 Organosheet*	GF.L	80/20	47	30.1	605
	GF.T			12	125
PA 66 Organosheet*	CF.L	50/50	47	53	785
	CF.T			51	725

* Source: Bond Laminate

The CAPROCAST process has some advantages over those organosheets:

- only one moulding process from raw material to final parts (T-RTM process) vs two process of the organosheet (sheet obtaining and press-forming step);
- forming of complex 3-D geometries, with very depth shapes and complex angles, always keeping a perfect thickness control and a defined orientation of the fibres;
- design flexibility to obtain the mechanical requirement; i.e. the fibre lay-up and the thickness in each zone of the part can be customized, while the design with the organosheet is subjected to the commercial available materials.

The mechanical subframe design needs the advantages above. Its 160 mm-depth and its variable thickness, as well as the specific fibres orientation are difficultly obtainable with a traditional press process.

Even considering feasible simpler geometries, the thermoforming process is more energy consuming, and due to the high pressure level, the tool is more expensive.

Similar costs and energy consideration can be made for HP-RTM process, whose advantage is to allow complex shapes as CaproCAST, but unfortunately not recyclable and not weldable as the resin is epoxy-based.

It can be concluded that the use of continuous fibre thermoplastic composites based on APA6 in situ polymerization process instead of current metallic material solutions is indeed innovative.

4.2. Main highlights from virtual and physical tests

Apart the static performances and the dynamic stiffness verified through virtual analysis, the EVolution subframe has been experienced through a durability test specifically defined by PIN and CRF (Fig. 5), according to the Stair-Case methodology, for the stand-alone component, as the front suspension has not been available.

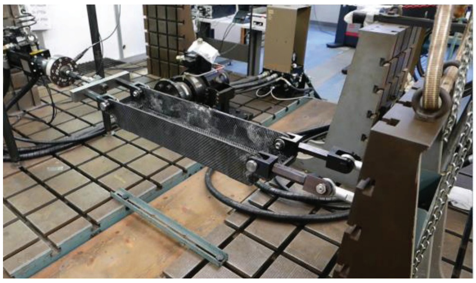

Fig. 5. Durability test set-up of Subframe demonstrator

The whole component has successfully passed 2.200.000 cycles with a maximum fatigue stress equal to 72% of the ultimate strength of the quasi-static bending test, evidencing minor and local damages in some circumscribed areas requiring minimal design modifications.

Keeping into account all these results, it can be concluded that the EVolution subframe is the first component manufactured with thermoplastic composite in the automotive sector with high mechanical requirement, which achieved the weight target and the main structural performances, becoming a valid alternative to traditional steel solution.

5. The underbody

The EVolution underbody is a hybrid system mainly based on advanced forming technologies for high-strength Aluminium alloys (5xxx family). The approach is to merge in few new components as much parts as possible, optimizing each element for its function and reducing the thickness, respecting performance from one side and process constraints from the other. This methodology allows the maximum potential in weight saving with respect to Nido underbody: proposed technologies enables complex geometries with reduced thickness and a consistent part count reduction. As final result, EVolution underbody weight is about 20 kg lightened (-47%) respect to Nido underbody, fully in aluminium and the total part number is reduced down to 1/3.
The main differences between Nido and EVolution are shown in Fig. 6.

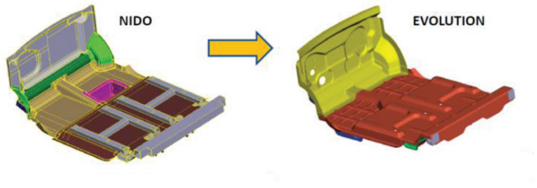

Fig. 6. Nido underbody concept (left) and Evolution underbody demonstrator (right)

The underbody demonstrator is hybridized with a rear reinforcement conceived in a specifically developed thermoplastic PA-based material reinforced with GF and manufactured through the above mentioned CAPROCAST process. The final solution is shown in Fig.7.

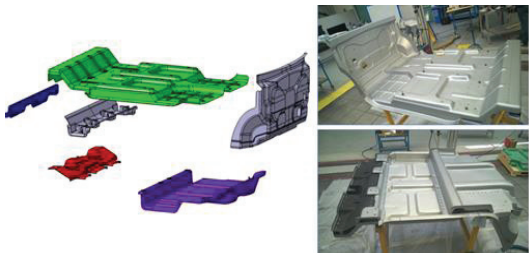

Fig. 7. Evolution underbody demonstrator

5.1. Main highlights from virtual and physical tests

In a complete car the underbody contributes to the overall static and dynamic stiffness of the body structure and plays an important role in the durability. Standard tests on the underbody requires the presence of a number of additional body elements which are out of scope of the EVolution project, so only static tests on selected components are possible. In particular, torsion and bending tests are performed on the underbody composite rear reinforcement to improve CAE models correlation (Fig. 8).

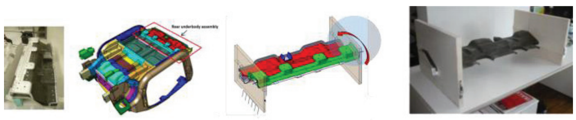

Fig. 8. Underbody composite reinforcement torsion test

Thanks to this activity it is confirmed the consistent contribution of the reinforcement to the torsional stiffness performance (more than 20%).

Besides, with the support of CRF, it is experimentally demonstrated the rear reinforcement material surviving to the e-coating process, giving to engineers the freedom to choose if to treat this part as a BiW element or not in the assembly stage.

6. Viability of the EVolution solution and conclusions

The industrial viability is assessed both from a technical point of view, by means of scalability study of the considered technologies and physical tests as described in the previous sections, and from the point of view of costs and production time.

Today there is a general consensus among the Automotive Industry that the increment of cost due to lightweighting is acceptable if below 6 €, considering a production of 50,000 cars/year (value close to EVolution 30,000):

$$\text{cost per kg saved} = \frac{\text{Evolution part cost} - \text{Reference part cost}}{\text{Weight of the reference part} - \text{weight of the EVolution part}} \quad (1)$$

The relative production time (TAKT[1] time) for 30,000 units/year it is equal to 5.7 min[2].

The new technologies proposed on the five demonstrators are in line with the TAKT time and the cost-per-kg-saved requested for medium production volumes (30,000 units/year). Further improvement can be achieved imagining applying extensively these technologies in all the BiW parts.

Table 2. Costs-per-kg-saved and TAKT time for the 3 analysed demonstrators

Demonstrator	Δcost-per-kg-saved		TAKT time	
Crossbeam	0,55 €/kg saved	☺	<1 min	☺
Subframe	2,62 €/kg saved	☺	4-5 min	☺
Underbody	1,50 €/kg saved	☺	6 min[3]	☺

The multi-material BiW, focused on the five demonstrators, is in line with the weigh target (at level of BiW and of demonstrators) and performances-compliant; in particular the new structure achieves the crashworthiness level requested in Europe for homologation. Only small design adjustments are requested for optimization, thanks to the outcomes of physical tests.

At full vehicle level, weight saving increases range with existing battery or maintain range with smaller battery. Due to the fact that the EV cost is directly related to battery size, being fixed the rate €/kWh and the range, the lightweighting design will be a balance between weight and cost.

The overall purpose of the EVolution project (to demonstrate the sustainable production of a Full Electric Vehicle (FEV) of 600 kg, taking as starting point the FEV concept Pininfarina Nido), is almost achieved with the final weight of 606 kg.

Acknowledgements

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[1] TAKT time is intended as the average time between the start of production of one unit and the start of production of the next unit; it is the rate at which a finished product needs to be completed in order to meet customer demand

[2] Assuming production volumes of 30,000 cars per year and 220 working days per year and considering a standard inefficiency around 15%, 2 shifts and 7.5 hours per shift.

[3] The TAKT time for the underbody is referred to a low-automation scenario, thus there is room for improvements.