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# Design and manufacturing issues in the development of lightweight solution for a vehicle frontal bumper

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**Abstract**

Automobile bumper subsystem is the frontal and rear structure of the vehicle that has the purpose of energy absorption during low velocity impact. The main component of this subsystem is the transverse bumper beam, generally made by steel. Design of vehicle subsystem for lightweight and for safety seems to lead the designer toward opposite directions. Quite interesting solutions can be obtained with the use of composite materials. This paper is analysing some possible alternative solutions for the particular case of the front and rear bumper.

## 1. Introduction

Automobile bumper subsystem is the frontal and rear structure of the vehicle that has the purpose of energy absorption during low velocity impact. Usually, bumper subsystem consists of bumper transverse beam, stays, impact-absorbing materials (such as foam or honeycomb) connected to the structural components (generally the bumper beam) and a cover, that has both aesthetic and protection purposes. Among those elements, the bumper beam is the main structural component; it is expected to be deformable enough to absorb the impact energy, in order to reduce the risks of injury for pedestrians and other vulnerable road users, but, at the same time, it should also have sufficient strength and stiffness to give place to small intrusion of the engine compartment and, therefore, to protect the nearby vehicle components.

Composite materials are characterised by high specific strength, both in static and impact loading conditions, and high specific stiffness; they could be an interesting candidate material for this type of component, posing as targets the lightweight together with the maintenance of at least the same level of safety performance in comparison with the present steel solution.

When designing with composite material, it is always needed not only to chose the appropriate material but to think composite (i.e. to not simply replace the metallic material with the new one, but to redesign the part) and to select the type of production technology that will be used in manufacturing, as this choice will affect deeply both the structural performance, the cost and the production rate [1]. Therefore material, design and manufacturing technology are strictly linked each other and should be considered all together.

From the point of view of manufacturing technology we have taken into consideration two different of manufacturing processes: pultrusion and die forming.

Pultrusion is a rapidly growing, cost-effective and fully automated manufacturing process for producing constant cross-section composite profiles. FRP pultruded products are often stronger then a similar product manufactured by hand-layup, vacuum bag infusion, and other composite processing methods. This is due to the fact that, during the pultrusion process, the many fiber bundles are pulled downstream using hydraulic or caterpillar grippers'. Due to this pulling, the fiber filaments are in tension when curing in the heated die. When in tension, the fibers have higher strength values and are better aligned allowing good compaction, with more fibers fitting into a given volume.

Die forming manufacturing technology is also rapidly growing technology able to produce composite shells with the desired shape. Die forming has a capability of producing structurally integrated crash box and beam as a single component. This is an extremely interesting feature of this technology because it leads to remarkable improvements both manufacturing and assembly rate and for reduction of the number of different components that should be produced and assembled to construct the front end structure. Besides, since joining is one of the critical issue in using composite part in automotive structures (as structures often have their weak points where their parts are joined together), The die forming technology is suitable for producing an integrated bumper beam and crash box structure thus eliminating the need of joints in between.

To assess the structural performance and the energy absorbing capability for the bumper beam made from composite material with the above mentioned manufacturing technology, six different materials were considered:

- E Glass/epoxy pultruded bumper beam solution compared with a bidirectional fabric E Glass/epoxy and reference steel material. The detailed mechanical properties of the three material are documented in [2].
- die formed integrated crash box- bumper beam made by a classic glass-mat-reinforced thermoplastics (GMT) compared with GMTex, i.e. a chopped fiber glass mat reinforced PP laminate with randomly oriented glass fibers and additionally reinforced with a fabric inside, GMT-UD, i.e. a chopped fiber glass mat reinforced PP laminate with randomly oriented glass fibers and additionally reinforced with unidirectional glass fiber layers and with reference steel solution . The detailed mechanical properties of the three material are documented in [3]

The impact responses and damage mechanisms for the whole group of composite materials are more complex than conventional metallic materials and depend on a number of different parameters including fibre and matrix type, section shape and dimensions, impact velocity, impact angle, shape of striker, target geometry and target material. A composite tube is capable of absorbing significant impact energy by material fragmentation and large changes in the tubes cross-sectional geometry when the tube undergoes large flexural deformation [4, 5, 6, 7, 8, 9, 10, 11].

## 2. Bumper beam design

As indicated in the introductive paragraph, two different types of manufacturing technology, namely pultrusion and die forming, have been considered to manufacture the beam with the desired shape.
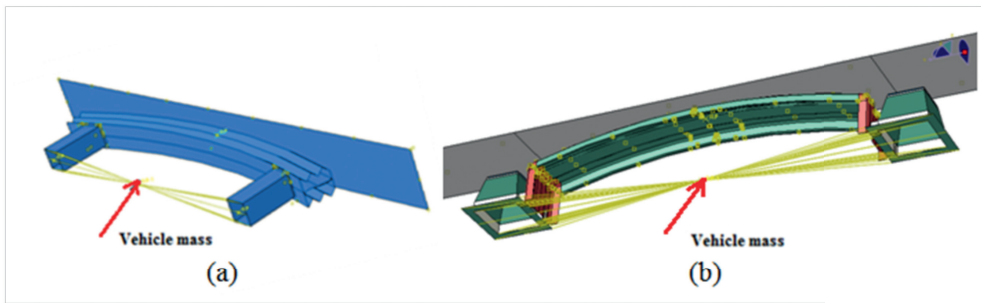
Fig. 1. Simplified FEM bumper models: a – pultruded beam solution, b – die forming integrated beam – crash box solution

For both proposed manufacturing techniques, a nonlinear finite element simulation, with a simplified bumper beam model, as displayed in Fig. 1, is carried out using the commercial code ABAQUS/Explicit version 6.12-1. A mass of 1,000 kg is rigidly attached at the two rear extremities of the crash boxes, in order to simulate the vehicle mass, and it is allowed to move with the desired initial velocity towards the rigid wall. For integrated solution hollow tapered truncated square based pyramids were proposed for crash boxes, in order to obtain a progressive failure and considering the load path, different sections have been used at different portions of the proposed structure as shown in Fig. 1 (b).

### 2.1. E-Glass/Epoxy pultruded beam solution

Pultruded beam solution have been studied by a number of researchers [12, 13], for roadside barrier structures which is a similar to lateral loading case as in vehicle bumper. Roadside barrier are usually designed to shield motorists from man-made or natural hazards and to redirect errant vehicles back on to roadways and for energy dissipation in case crashing. These studies indicated that pultruded composite materials were viable for use in guardrail system due to their pseudo-ductile characteristics that arise primarily from material fragmentation (crushing, separation and tearing of composite materials) and large changes in the tubes cross-sectional geometry when the tube undergoes large flexural deformation.

The present proposed pultruded bumper beam solution intended to utilize and optimize the pseudo-ductile behavior of pultruded composite beam for effective energy dissipation at low velocity vehicle frontal crash. The pseudo-ductile behavior was optimized through a structural optimization procedure of the beam section profile (that can be easily obtained by means of a properly shaped die section) and of the curvature (that at present is not feasible with this technology) aimed to obtain a progressive energy absorption and a stable flexural failure of the composite bumper beam.

A numerical study has been conducted according to the methodology developed in [2] in order to explore the possibility of substituting the current metallic bumper beam with E-Glass/epoxy pultruded composites beam. The resulting structures are compared in terms of shape and in terms of energy absorbing capability, comparison is also established with steel normal production solution.
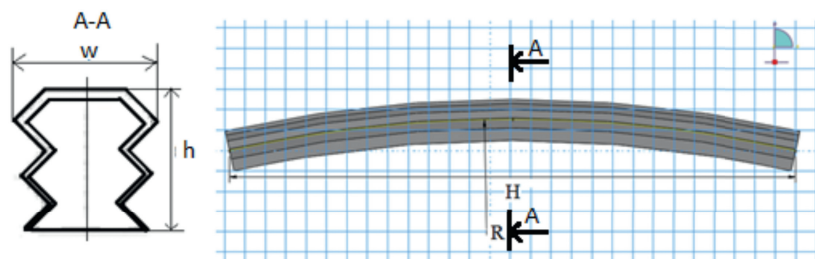


Fig. 2. Optimized beam end section profile and curvature for pultruded solution

As stated in the previous paragraph, the pseudo-ductile of pultruded beam arise from material and large changes in the tubes cross-sectional geometry when the tube undergoes large flexural deformation. Therefore, the current analysis were conducted based on the hypothesis that a properly optimized and predefined stress concentration zone or beam corners (through end profile optimization) can serve as crash triggering mechanism, i.e. to initiate cracks formation and to develop progressive tear along beam longitudinal axis. The optimization is then conducted through optimizing the number of folds on the height (h) of the beam end profile and varying the thickness toward the crash box. The comparison among the proposed end profiles were done through the investigation of impact event characteristic data, such as force-time, force-deflection, energy-displacement and deflection-time curves. The optimized beam end section profile is presented on Fig. 2.

Even if the current pultruded manufacturing technology is mainly limited to straight beam (curved pultrusion technology is still in infant stage) an optimization also conducted on beam curvature (R) Fig.2. A large number of beam curvature radius, form straight to smaller radius were considered and the failure phenomenon were closely monitored using a similarly impact event characteristic data.

## 2.2. GMT/GMTex die forming integrated crash box-beam solution

One of the critical challenges of using composite part in automotive structure is joining, as structures are often weakened where their parts are joined together. Die forming manufacturing technology is cable of producing structurally integrated crash box and beam as a single component Fig. 3. Therefore, the concept of integrating crash box-beam using die forming will improve both manufacturing/assembly rate and reduced the number of components.
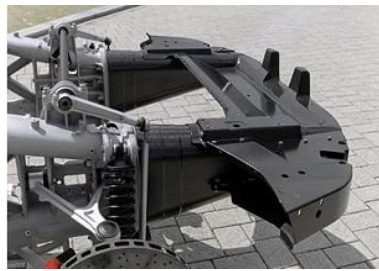


Fig.3. Integrated composite solution used on Mercedes for top class vehicle

For die forming integrated crash box-beam solution, the proposed materials under investigation were compared with the reference material (steel) by two ways:-
*   by direct substitution of the current steel beam by integration of a composite beam with crash box and with minor modifications of the base plate only for joining purpose and using the thickness recommended by the company i.e. 8mm. and
*   through equal stiffness approach, i.e. , for a given thickness and stiffness of the reference material, the thickness of the targeted material can be approximated by equation 1.

$$h_s = h_s \sqrt[3]{\frac{E_s}{E_X}} \qquad (1)$$

where $h_s$ and $h_x$ are thickness and $E_s$ and $E_x$ are the elastic modula of steel and the targeted material respectively .

During low velocity impact, such as, small parking load, the bumper beam is expected only to bump i.e. it has to operate within elastic limit without any form of permanent damage. Therefore, for the current study, the allowable minimum thickness of the bumper for such small load was determined through monitoring impact energy curve.

Having got the threshold value the thickness, it was gradually increased up to a value where the beam gives the similar impact performance as with the reference material and the reduced mass was compared.

## 3. Results and discussion

### 3.1. Pultruded bumper beam solution

The beam end profile has been optimized through the number of groves on the height (h) of the beam and the distribution the wall thickness. The detailed optimization process has been reported in [2]. When the bumper beam is subjected to frontal impact, concentrated stresses develop at the grove vertexes; points on the fold sides at equal distance from the impacted surface have the same stress levels. This is substantially uniform in case of straight beam while a change in the beam curvature has an effect both on the stress distribution along the beam and on the stress values.
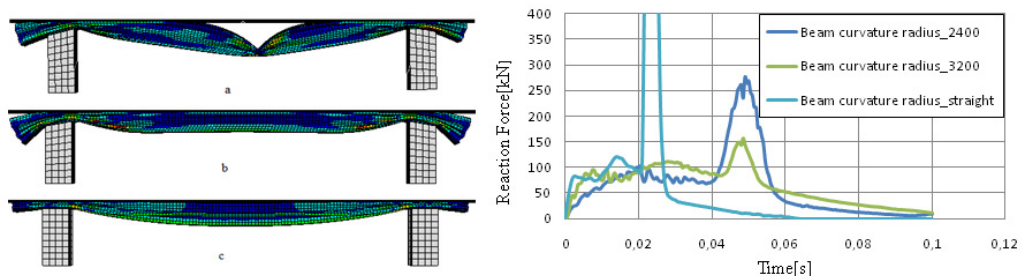


Fig.4. Failure mode  and peak load for curvature radius (a) 2400 mm, (b) 3200 mm and (c) straight [2]

Fig.4. is showing the final deformed shape of the bumper beam for three different solutions characterized by different values of the curvature radius from 2400mm (case a) to straight beam (case c). Fig.4 also shows the reaction force histories for those three solutions. It is well visible that the case of the small curvature radius is generating a concentrated failure hinge close to the beam mid-span and a very large load peak comes out; the other two cases are giving more diffuse energy absorption and smoother curves; the solution with the intermediate values of the curvature radius is giving the minimum load peak. As a first general observation on low velocity impact analysis, when the beam curvature radius is increased, the formation of local stress concentration is reduced. This is due to the fact that larger zones of the bumper beam are in contact with the flat rigid wall at the same time. This leads to higher load peak that promote the formation of diffuse fractures on the portions of the folds which have the same stress level.

The worst case is when the bumper beam is straight Fig. 4c , which corresponds to a solution currently used by some vehicles. In this situation the portion of the beam extremities just in front of the crash box, with length equal to the crash box width will fracture at the same time, since that portion of the beam is under equal stress level and there is not possibility for crack propagation and proper energy absorption.

On the other hand, when the beam curvature radius is reduced below some critical curvature radius, 2862mm in this particular case, crack propagation is not taking place, but instead a high local stress line is developed at the apical portion of the beam, which results in unstable localized failure, as shown Fig.4a.

Finally, the performance of the proposed pultruded composite bumper beam solution can be compared with the steel and the glass fabric/epoxy composite solutions in terms of impact energy absorption and weight reduction. Three parameters, namely the amount of absorbed energy, the peak load value and failure mode, are considered for material comparison.
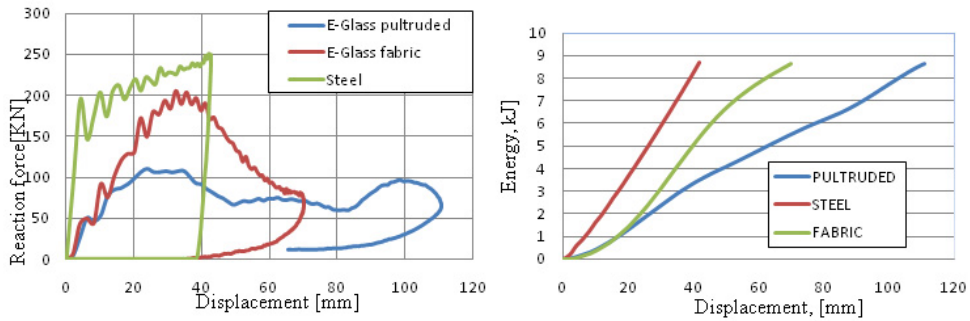
Fig.5. Reaction force vs. displacement and Energy vs. displacement for the three material considered [2]

A shown in Fig.5, the three design solutions absorbed the same amount of energy, however the peak load values and the mode of failure are completely different. During vehicle frontal crash, peak load is relevant for the vehicle occupant risk, as a matter of fact lower peak load yields to lower decelerations and vice versa, so this parameter should be carefully controlled. In additions, by comparison of the failure modes of the two composite material solutions, i.e. pultruded and fabric, it comes out that the energy - displacement curve of pultruded beam is almost linear and the load deflection curve of pultruded beam resembles the uniaxial stress-strain diagram of an elasto-plastic ductile material, that is technically termed as pseudo-ductile. Therefore, as far as it is possible to control the displacement or to keep the displacement within the design limits, the pseudo-ductile behavior of the pultruded solution is an important feature in the passive safety behavior of the bumper component.

### 3.2. Die forming integrated bumper beam – crash box solution.

From our previous related activity, it has been learned that a closed section beam has better structural integrity and energy absorbing capacity than an open section beam. Hence, even if an open section beam was considered and recommended by the material supplier company, for sake of production feasibility and simplicity, a closed section beam has also been numerically investigated.
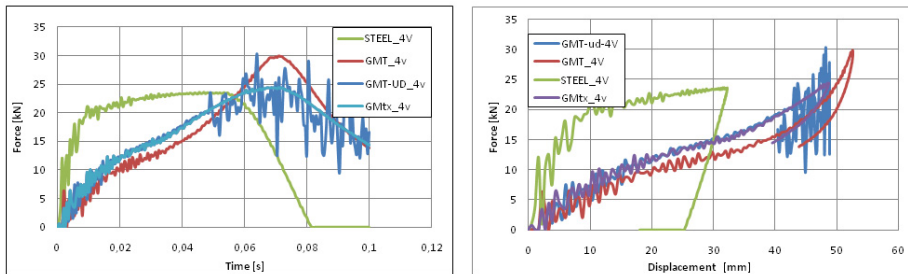


Fig.6. Force vs. time and force vs. displacement curves for the design solutions in steel and in equal thickness of the three considered materials

The first attempt was conducted by direct substitution of the current steel beam with integration of the crash boxes and with minor modifications on the base plate only for joining purpose. As recommended by the material supplier, the composite beam wall thickness for each material configuration was set 8 mm . As it can be seen on force vs. time and force vs. displacement curves resulting from the simulation of impact events a 4km/h (see Fig.6), all the three material solutions are structurally weak. GMT-UD and GMtx solutions show an early sharp break at the center of the beam while GMT solution shows relatively higher elastic deformation.

Table 1. Thickness and mass of the combined  beam- cashbox

| Material | Steel | GMT | GMtx | GMT-UD |
|---|---|---|---|---|
| Thickness [mm] | 2.2 | 7.1 | 6.1 | 5.8 |
| Mass [kg] | 7.67 | 3.72 | 3.32 | 3.2 |

The second attempt was made by increasing the section dimension, particularly the base plate. The thickness of the integrated beam- cashbox was determined from the reference material. For a given thickness and stiffness of the reference material (steel), the thickness of the targeted material can be calculated approximately by the relationship indicated in Eq. 1. Using the proposed expression, the approximated thickness and the mass of the integrated beam-crash box solutions are reported in Table 1.
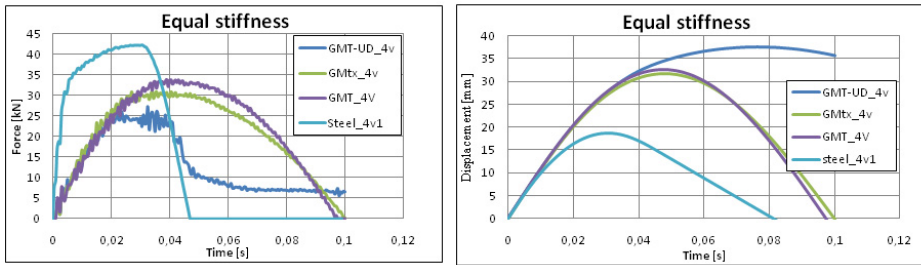


Fig.7. Force vs. time and displacement vs. time curve for the modified bumper system
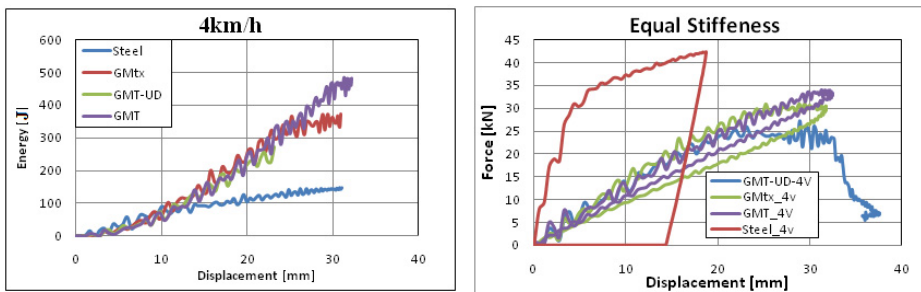


Fig.8. Energy vs. displacement and force vs. displacement curve for the modified bumper system

Through comparing force vs. time and displacement vs. time curves (see Fig. 8) of the targeted four materials, GMT-UD has minimum peak load i.e. 25 kN, which is one of the important parameters that the designer has to control and it has a similar failure mode as the reference material  but it has the maximum intrusion i.e. 37 mm since the beam is fractured at the selected loading. The failure behaviour can also be tracked using load displacement curve as shown in Fig.8.

The load vs. displacement curves of GMT-UD confirms that the material is already fractured at the selected velocity. Similar phenomenon is also observed on the reference material (steel), which might be due to the strength of the selected steel. As metallic materials have a higher plastic range, the energy dissipation through plastic deformation. Whereas, composite materials have very limited plastic range, therefore,  the energy dissipation resulted from the material fragmentation.

Whereas, both GMT and GMtx are within elastic range, this can be observed from load vs. displacement curves in Fig.8. For 4km/h impact velocity, which is closer to parking load, the bumper has to operate within elastic range, therefore besides bumping and, eventually, a minor cosmetic damage, a complete fracture, as we observed on GMT-UD solution, is not expected. Therefore, with the proposed beam configuration and loading i.e. at low velocity impact the thickness obtain from the above expression i.e. using equal stiffness approach only works for GMT and GMtx and can be considered for material replacement with significant weight saving but for GMT-UD , the beam fractured therefore the thickness need to be further optimized.

## 4. Conclusions

The design of the transverse beam of a front or rear vehicle bumper can be done using composite materials instead of steel. This leads to an effective decrement of the vehicle weight without affecting the structural safety performance.

The design of the composite solution needs a choice of material and production technology, as these two aspects are deeply influencing each other. Two solutions that are under development as part of a cooperative research between Politecnico di Torino and FIAT Research Center have been presented and discussed.

Advantages and disadvantages of the pultrusion and die forming technologies have been discussed, as they lead to completely different structural solutions.

As composite materials has completely different failure behaviour than the conventional metallic materials, the direct adoption of the traditional metallic energy absorbing geometry may lead to a catastrophic failure and yield higher peak loads. To prevent such a catastrophic failure for the case of pultrusion solution, since it is limited to a constant cross section, it is taken advantage from the pseudo-ductile characteristics, that arise from material fragmentation and large changes in the tubes cross-sectional geometry during deformation. Further design optimization has been utilized for choosing the beam end profile and curvature. For the case of die forming solution, besides assessing the advantage of beam- crash box integration into one single part to prevent joining related problems, the possibility of having variable section along the length of the structure is also utilized to integrate structurally the two parts and to get progressive failure.

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