CRASHWORTHINESS ANALYSIS OF A COMPOSITE AND THERMOPLASTIC FOAM STRUCTURE FOR AUTOMOTIVE BUMPER SUBSYSTEM

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Abstract

In addition to protecting nearby components during low velocity impact, great care should be taken for pedestrian and occupant safety during bumper subsystem design. choice of proper material and appropriate connecting mechanism will significantly varies the crash behave of the bumper and reduce one of the most important factor which is peak load

This paper covers material characterizations of hot melt adhesive (Prodas 1400), 30% glass fibre in polyamide matrix and CFRP, for analyze their usage for a bumper subsystem and comparing them with the commonly used bumper materials. Furthermore the currently used mechanical joint between bumper beam and polymer foam is compared with adhesive solution on the bases of crash resistance and stiffness. Result shows, CFRP composite beam has comparative performance with better energy absorption and weight saving and adhesive solution gives reduced peak load.

1. Introduction

In automotive industries, factors, such as vehicle weight reduction and energy absorption through the large deformation but in a controlled manner of the frontal vehicle structure, is getting researcher attention over the last few years, with particular reference to pedestrian safety. Now a days an increasing knowledge of mechanical properties of composite materials makes this group of material as a potential candidate for this applications.

Different researchers have analyzed bumper beams which are made from different types of composite materials, such as carbon fiber reinforced plastic (CFRP), glass fiber reinforced plastic (GFRP), sheet molding compound (SMC) and glass mat thermoplastic (GMT) in order to improve the bumper subsystem performance by weight reduction and energy absorption, [2-4]. Even though CFRP and GFRP can offer better mechanical performances, SMC and GMT are widely used material due to their easier formability and lower material and manufacturing costs.

Currently, in the European Union (EU) countries, about 75%, in fleet average, of each vehicle is recyclable at its end-of-life, in particular its metallic parts. The rest (~25%) of the vehicle is considered to be wasted and generally goes to landfills [5]. EU legislation requires the reduction of this waste to a maximum of 5% by 2015. Taking in to account this important directive, in this study the implementation of recyclable material, and specifically polyamide with 30% glass fiber, for the bumper beam construction is developed and the resulting bumper performance is compared with the alternative solutions made of the reference material, steel, and CFRP, i.e. a composite material that has recycling problem.

This paper intends to address material characterizations, design aspects and method of analysis with particular reference to the application of composites (CFRP or, in alternative, 30% glass fiber in polyamide matrix), recyclable thermoplastic foam and adhesives materials to automotive front bumper design. Particular attention is also paid to energy absorption, reaction pick load, weight reduction and manufacturability of the bumper transverse beam to evaluate the performance of proposed solutions.

2. Numerical modelling of Fiat-500 frontal transverse beam

The FIAT-500 transverse beam is studied to obtain lightweight bumper subsystem. The reverse engineering process was applied to the actual frontal transverse bumper beam which was taken from commercially available automotive spare parts, as shown in Figure 1 and Figure 2. Detailed dimensions of each section were taken carefully to avoid the influence of inappropriate geometry representation on the actual response of bumper subsystem during impact phenomenon. The CAD model was developed using CATIA from the measured dimensions. Furthermore, the geometries were edited in ABAQUS geometry editor to prepare the model for meshing and numerical simulation. Besides, joining techniques, method of manufacturing process and type of materials for each part were studied carefully in order to use the appropriate design and material parameters inside ABAQUS environment.

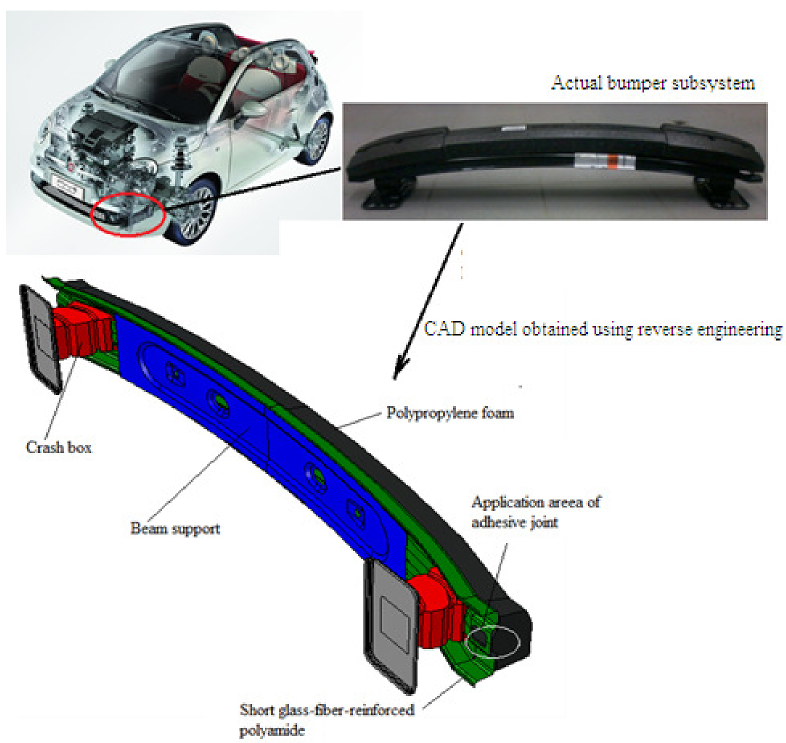

Figure 1. Bumper subsystem for FIAT-500 model

In this work some of the challenging tasks finalized to develop an optimized numerical model, in order to save computational effort, were the choice of element size and shape, contact definitions and assignment of appropriate constraints. To deal with these problems, the complex shapes were subjected to localize meshing to keep the desired shape of the bumpers beam. Also 3-node triangular general-purpose shells and 4-node doubly curved shell were considered to avoid analytical and convergence problems due to unacceptable element aspect ratio. At initial stage some preliminary analysis were performed to choose the element size and shape, contribution of additional components on the global response, and to control the required computation time. Based on the found results, new solutions were proposed: some parts such as crash box and joining techniques were modeled by appropriate equivalent constraints, this leads to relevant reduction of the computational time without significant variation of the dynamic response, such as impact force, acceleration and kinetic energy. The final FEM model is shown in Figure 3.

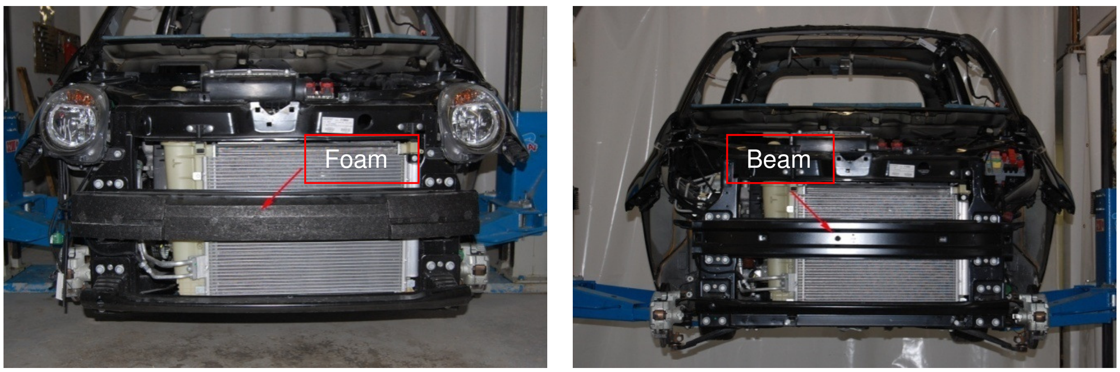

Figure 2. Fiat-500 model

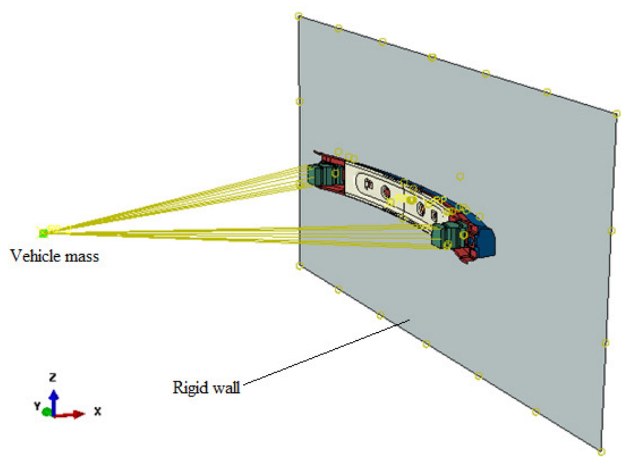

Figure 3. Numerical bumper subsystem model

3. Modelling of Composite material

Two types of materials were taken in to consideration to substitute the steel of the existing bumper beam and thus to obtain lightweight bumper subsystem: CFRP twill fabric, and 30% short glass fibers in polyamide matrix. In the case of polyamide material, two types of polyamide (i.e. thermoplastic materials), PA66 and PA66 with 30% short glass fiber, were considered and samples were manufactured using the injection molding machine available in CRF. At initial stage, unreinforced PA66 was chosen as a design option for bumper beam application. However, after material characterization, the results put in evidence that the strength and the stiffness of this polyamide plastic are much lower than the existing material solutions for bumper beam production. Hence, an alternative choice was implemented to improve the mechanical behavior PA66. In this regard, material and manufacturing costs were the main factor to choose feasible solution for bumper beam application. Based on these factors, short glass fiber material was selected to be the reinforcement inside PPA66 matrix. Then, 30% of short glass fibers was added inside PA66 matrix and samples produced using injection molding machine. Test results showed that the tensile strength and modulus of elasticity of PPA6 were improved by 125 % and 220 %, respectively. Detailed material data are listed in Table 1.

Composite	Fiber volume fraction	Max. tensile stress (MPa)	Max. compressive stress(MPa)	E (GPa)	ν_{12}
Polyamide 30% glass fiber	0.3	143.08	154.63	10.35	0.405

Table 1 Elastic properties for polyamide 30% glass fiber

CFRP and steel test data were taken from [6] and [7], respectively. Also the characteristic of polypropylene foam which was utilized as energy absorber for pedestrian safety was taken from previous work performed in the Department Labs [8]. Regarding adhesive material, Prodas 1400 hot melt adhesive was chosen and characterized for joining of composite transverse beam with polypropylene foam.

4. Standards for low-speed frontal impact

To setup the appropriate boundary condition and the needed general variables of the bumper subsystem, it is worth to survey existing standards related to design of bumper under impact load condition. Currently, there are three low-speed impact regulations to check the performance during crashing condition: the National Highway Traffic Safety Administration (NHTSA) Code 49 part 58 [9], the ECE Regulation No. 42 [10], and the Canadian Motor Vehicle Safety Regulation (CMVSR) [11]. The NHTSA safety regulation has the same safety requirement and damage limitation as the CMVSR, however, the speed is reduced by half. In this paper, NHTSA standard was chosen to perform car-into-barrier impact tests. The impact test against the barrier was conducted at 4 km/h on the full-width of the frontal bumper, as shown in Figure 3. This standard requires that the light system, bonnet and doors can be operated after the impact as in the normal operation conditions, beside all essential features should be still appropriately functional or serviceable.

5. Bumper beam thickness determination

To study crash behaviour of the above mentioned bumper beam materials, two approaches were adopted; material comparison with thickness equal to the reference solution (steel) and material comparison with deflection (bending stiffness) equal to reference solution. The first approach is the simplest one and allows substituting the material without altering the geometry profile of bumper beam. Whereas, the second approach needs to calculate the thickness of each proposed materials to obtain the same stiffness value with the reference solution based on proposed method in [13]. Calculated bumper beam thickness for each material type are reported in Table 2.

	CFRP $[0/90]_{4s}$,	30% glass fiber polyamide
Thickness, h_c[mm]	3.2	5.45

Table 2 - Bumper beam thickness for each material type

6. Result Discussion

In Figure 4 the crash performance of the bumper is compared based on material substitution. Steel bumper beam performed appreciably since it absorbs a quite interesting quantity of energy while the reaction force peak, that could be transferred to the passengers, remained the smaller. At the initial phase of impact scenario, steel bumper beam was stiffer than CFRP and 30% glass fiber polyamide bumper beams. This means that the steel beam resists better to the applied load, however, approximately after 20ms, it becomes weaker due large plastic deformation. As a consequence the remaining impact phenomenon asks for the crash box involvement. Hence, it can be clearly seen in the Figure 4 that the reaction force is increased monotonically because of rigid crashbox involvement. On the other hand, CFRP and 30% glass fiber polyamide bumper beam exhibited softer property from the very beginning.

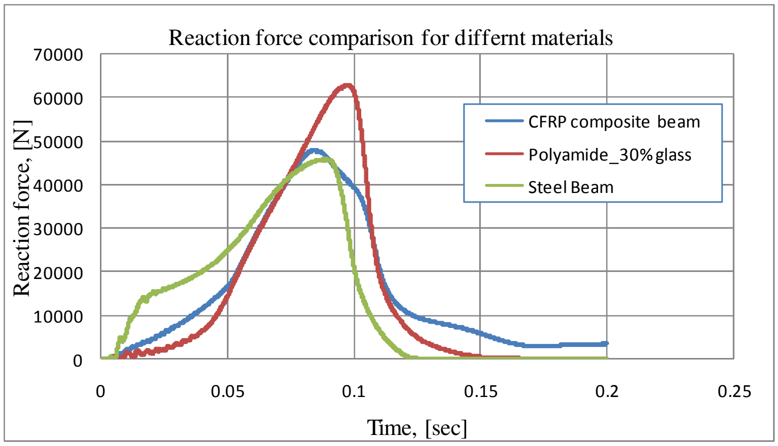

Figure 4. Reaction force vs. time curves of bumper beam on the bases of equal thickness, 2 mm (without reinforcement).

To obtain equivalent performance between the reference steel bumper beam and the alternative composite beams, the thickness of each composite beam was modified on the basis of equal bending stiffness criterion. Figure 5 shows the impact force response of modified composite beams. It can be clearly seen that some relevant improvements were obtained at the initial stage of impact scenario, especially in the case of CFRP bumper beam. For what concerns the reaction load peak, in the case of 30% glass polyamide, the pick decreased significantly, while insignificant improvement was observed in the case of CFRP beam.

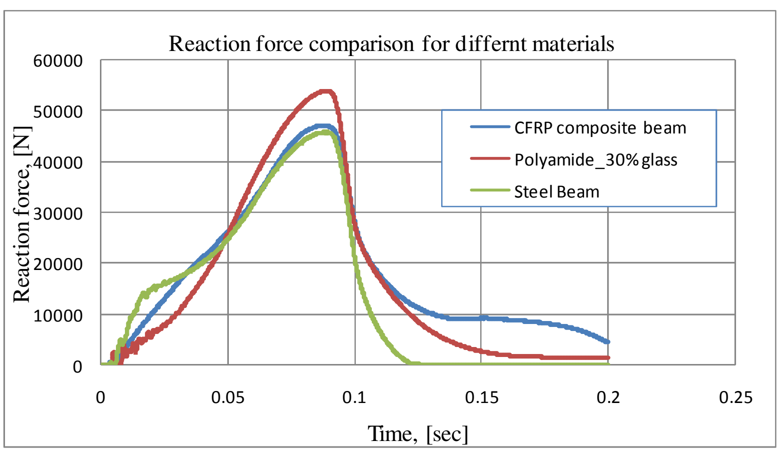

Figure 5. Reaction force vs. time curve of bumper beam on the bases of equal stiffness (without reinforcement)

To improve the composite bumper beam performance, the stress distribution and mode of deformation were analyzed, particularly at initial stage of impact. The results revealed that localized high deformation and stress were observed near to the end of beam back support which is adjacent to the crash box, as shown in Figure 6. In order to re-distribute the concentrated stress, reinforcements were incorporated as a design solution on both ends of beam back support, as shown in Figure 7. The reinforcement developed considerable stress redistribution and reduced the maximum principal stress peak on the main bumper beam by 23.6%. By applying this new design solution, appreciable improvements regarding peak reaction load were obtained, as shown in Figure 8.

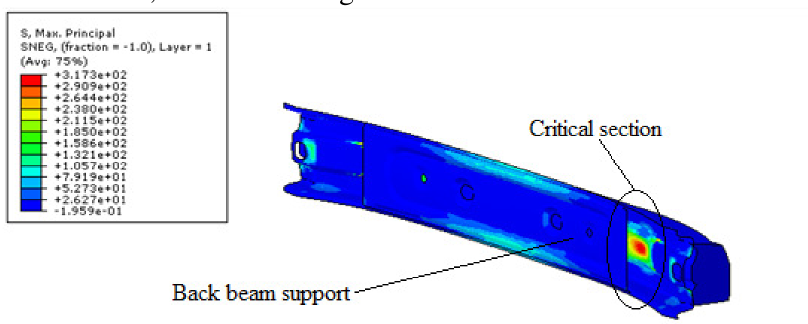

Figure 6. Local stress formation at the bumper critical section.

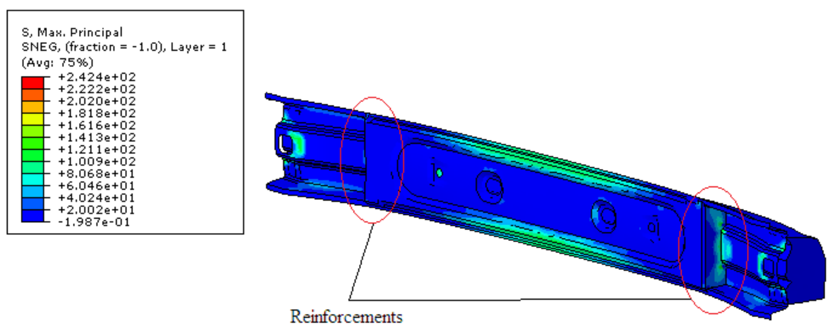

Figure 7. Introduction of reinforcements to reduce the stress concentration.

The CFRP solution reduced the peak reaction load by 20.3 % due these additional reinforcements. More interestingly, progressive failure was found in this solution which is very essential from the point of view of the energy absorption to improve the occupant safety. On the other hand, 30% glass polyamide based bumper beam solution exhibited insignificant reduction (-1.3 %) of the reaction load peak.

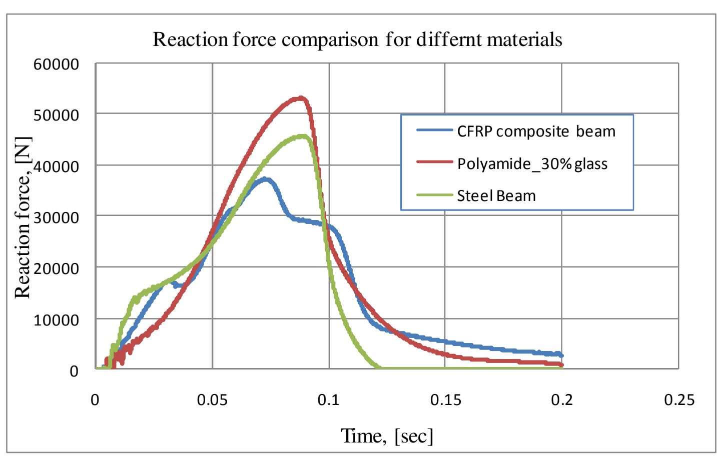

Figure 8. Reaction force vs. time curve of bumper beam on the bases of equal stiffness (with reinforcement)

This means that 30% glass polyamide material solution, despite of the above described structure modifications, still needs the involvement of the crash-box to absorb energy during this impact. This behavior can be explained by its lower strength, stiffness and strain to failure properties.
Another interesting result from the point of view of lightweight is weight reduction. With respect to the reference steel bumper beam solution, CFRP and 30% glass fiber polyamide bumper beams reduce the weight by 67.8% and 45%, respectively.

Regarding joining techniques, through analysis of beam and foam connecting techniques, the currently used mechanical press fitting approach, as shown in Figure 9, is compared with adhesive solution. As it is well known, mechanical press fitting, needs holes on the beam which usually cause stress concentration and ultimately beam strength reduction. Whereas, the proposed adhesive joining, as it is clearly shown in Figure 10, in addition to preventing the above mentioned problems, reduces slightly the reaction force peak, which is one of the main factors to be controlled during crashworthiness analysis.

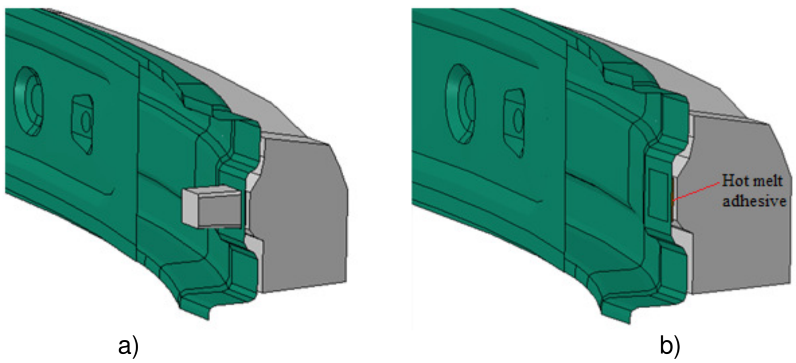

Figure 9. Joint techniques between bumper beam and energy absorver: a) mechanical fitting; b) adhesive joint

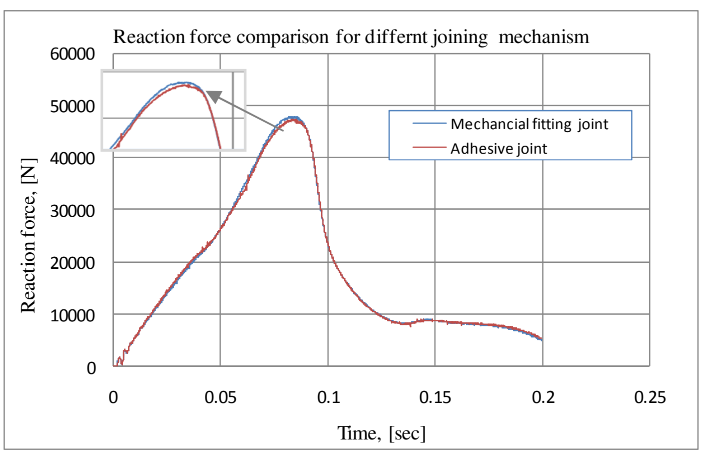

Figure 10. Comparison of reaction force vs. time curves of bumper beam using mechanical fit and adhesive joint

7. Conclusions

In the study, the re-design of a front bumper subsystem has been developed finalised to lightweight. Alternative solutions have been considered by substituting the used steel with other suitable materials. The bumper beam solutions, based on these alternative materials, have been developed on the bases of equal thickness and equal stiffness criteria. Comparison of the obtained FE simulation results illustrates how the choice of material can significantly affects the performance of bumper subsystem. The introductions of local reinforcements at the stress concentration point enhance the composite bumper beam performance by redistributing the stress and preventing local failures. However the PA66 solution, even if reinforced with short glass fibres, does not reach comparable result with respect to the CFRP solution. Looking at the results from another point of view, the polyamide with 30% glass solution leads to better results in term of possible material recycling at the end of life, while CFRP has still problematic perspective. Therefore, taking into account the EU recycling requirements, the polyamide with 30% glass solution can be considered an alternative solution. Some improvements can certainly be obtained with further geometry optimization.

Finally, regarding the joining techniques, the proposed adhesive joint using hot melt adhesive, in addition to prevent high stress concentration and inconvenient manufacturing process, reduces slightly the reaction force peak, which is one of the main factors to be controlled during crashworthiness analysis.

Acknowledgements
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References

[1] “Structural Bumper Beams made in GMTexTM“ Technical Information, Quadrant Plastic Composites site.
[2] Davoodi M.M., Sapuan S.M., Ahmad D., Aidy A., Khalian A., Jonoobi M. – “Concept selection of car bumper beam with developed hybrid bio-composite.”, Material and Design,
[3] Marzbanrad J., Alijanpour M., Kiasat M. S. – “Design and analysis of an automotive bumper beam in low-speed frontal crashes.”, Thin wall structures, 2009, vol. 47, pp.:902-911
[4] Cheon S.S., Choi J.H. , Lee D.G. – “Development of the composite beam for passenger cars.”, Composite Structures, 1995, vol. 32, pp. 491-499
[5] Kanari N., Pineau J.L., Shallari S. – “End-of-life vehicle recycling in the European Union.”, The minerals, metals & material society, 2003,
[6] Belingardi G., Koricho E.G. – “Implementation of composite material car body structural joint and investigation of its characteristics with geometry modifications”, proc. of the 14th European Conference On Composite Materials, 7-10 June 2010, Budapest, Hungary.
[7] Belingardi G., Koricho E.G. – “Implementation of Hybrid solution in car body structural joints”, AIAS XXXIX Nat. Conf., 7-10 September 2010, Maratea, Italy.
[8] Avalle M., Belingardi G., Montanini R. – “Characterization of polymeric structural foams under compressive impact loading by means of energy-absorption diagram”, Int. J. of Impact Engineering, 25 (2001), pp. 455-472
[9] NHTSA National Highway Traffic Safety Administration – “Laboratory Test Procedure for Regulation Part 581 Bumper Standard Safety Assurance”; 1990.
[10] ECE – “Uniform provisions concerning the approval of vehicle with regard to frontal and rear protective device”; 1980.
[11] CRC - “Canadian Motor Vehicle Safety Regulations”; 2009
[12] G. Belingardi, Ermias G. Koricho, Brunetto Martorana, Design Optimization and Implementation of Composite and Recyclable Thermoplastic Materials for Automotive Bumper. Fifth International Conference on Advanced Computational Methods in Engineering (ACOMEN 2011), 14-17 November 2011, Liège, Belgium