Composite Material Design for Rail Vehicle Innovative Lightweight Components

M. Grasso, A. Gallone, A. Genovese, L. Macera, F. Penta, G. Pucillo, S. Strano

***Abstract*— This paper describes the redesign activities of lightweight rail vehicle component using advanced composite materials. The activities have been carried out in the framework of the SCILLA-M National Project funded by Ministry of Research in collaboration with AnsaldoBreda. By exploiting the lightweighting and design integration benefits of composites, an innovative solution has been developed, which provides significant savings in mass, cost and part count compared to conventional designs. Several solutions have been evaluated among those reported in literature and related to the several transport systems. On the basis of the information acquired composite structure seems to be the ideal candidate for the design of lightweighting railway components. The current metallic design has been compared with the new proposed solutions in terms of weight saving, stiffness and strength. An innovative flatwise composite panel solution, which has been selected among those analyzed, seems to be applicable for the structural optimization of the railway vehicle carbody roof. The study underlines that the sandwich structure made of composite materials and polyurethane foam confirms to give good results in terms of weight and flexural stiffness. Consequently, the proposed sandwich structure can be adopted in the design of an innovative railway vehicle carbody roof.**

***Index Terms*— Rail vehicle; roof panel; composite material; sandwich structure; lightweight design.**

I. INTRODUCTION

Innovative lightweight structural component must be light and high in performance. This encouraged the development of composite structure which allow in plane and out of plane high strength. Moreover, the use of such solution in combination with carbon fibre reinforced composite allows to improve fabrication process as well as weight saving. Today, this structure is used in different engineering applications, e.g. automotive, aerospace vehicle and railways. In addition to weight savings, this structure can include other characteristics such as: space savings, fire resistance, noise control, and improved heating and cooling performance. In naval industry, the use, for example, of sandwich core is very common. Liang et al. [1] defined the optimum design of metallic corrugated core sandwich panel under combined axial and bending stresses. Several aerospace applications can be found in literature, among them corrugated core are used in wing structure to enhance the low bending strength of fibre-reinforced rubber [2]. Thill et al. [3] carried out experimental studies on wing structure made of sandwich woven fibre/epoxy prepreg materials. Robinson et al. [4] compared three fibre reinforced sandwich structure with different core configuration. These solutions have in common the use of composite layers wrapped around foam blocks having different shapes. To assess the shear and the compressive strength of the proposed solutions both three-point bending and compression tests were carried out. Early studies [5÷7] were dedicated to the implementation of sandwich panel made of carbon fibre-reinforced pyramidal lattice truss. The sheets are interconnected with truss cores, the facesheet and the truss cores are manufactured in one process. This geometry is widely used since offers a high stiffness/strength-to-weight ratio. Numerous investigations have been carried out on the bending stiffness of corrugated board. Luo et al. [8] investigated the bending stiffness of corrugated board providing analytical solutions to design such kind of structures. They considered different shape of the corrugated medium including sinusoidal, arc-and-tangent, and elliptical representations. Using numerical and analytical method compared with experimental data, Dayyani et al. [9] characterize the flexural and tensile behaviour of corrugate fibre reinforced prepreg panels. Xiong et al. [10] proposed two solutions of corrugated geometries, which allow to reduce the weight by cutting the inclined part of the corrugated fibre reinforced plate without affecting the bonding surfaces between facesheets and core. These features using the oblique or vertical strut instead of the inclined sheet imply weigth reduction saving the stiffness and strength of the final component. Experimental tests carried out on samples implementing the aforementioned solution showed that under shear loading struts delamination and fracturing occurred. Zhang et al. [11] improved the bending strength and energy absorption of corrugated sandwich using foam insert. This solution is very effective for transport vehicles since weight saving is a key element in such means of transport. Other benefits are the following: styling flexibility, good noise/vibration/harshness characteristics and good corrosion resistance. Lighter and

---

M. Grasso is with the *Department of Industrial Engineering*, *University of Naples Federico II*, 80125 ITALY (e-mail: marzio.grasso@unina.it).

A. Gallone is with the Department of Innovation & R&D Funded of AnsaldoBreda S.p.A., 80147 ITALY (gallone.antonello@ansaldobreda.it)

A. Genovese is with the *Department of Industrial Engineering*, *University of Naples Federico II*, 80125 ITALY (e-mail: andrea.genovese2@unina.it).

L. Macera is with the *Department of Industrial Engineering*, *University of Naples Federico II*, 80125 ITALY (e-mail: lu.macera@gmail.com).

F. Penta is with the *Department of Industrial Engineering*, *University of Naples Federico II*, 80125 ITALY (e-mail: penta@unina.it).

G. Pucillo is with the *Department of Industrial Engineering*, *University of Naples Federico II*, 80125 ITALY (e-mail: gpucillo@unina.it).

S. Strano is with the *Department of Industrial Engineering*, *University of Naples Federico II*, 80125 ITALY (corresponding author, phone: +390817683277; e-mail: salvatore.strano@unina.it).

energy-efficient vehicle systems are a big challenge which is common to different transport systems [12-13]. In the railway field, corrugated solutions have been extensively investigated numerically and experimentally for structural applications and in particular for crashworthiness design of railway components [14÷17].

The main challenge in implementing the composite roof of a railway carbody is related not only to the structural assessment but also to the compliance of the requirements prescribed by the CEI EN 45545-2 [18] Standard concerning smoke and fire prescriptions. In particular, the solutions implemented so far have been developed using thermosetting resins, which is a resin that complies with the prescription of the CEI EN 45545-2. Standards. In the present case study, the design activities have been focused on the optimization of the geometries and masses under service loads of flatwise panel composed of elements made of new generation of thermosetting composite material that has additive elements giving the capability to comply with the prescriptions of the CEI EN 45545-2 Standard. The implementation of such a solution allows to make the existing metal components of railway vehicle lighter. The work is still in progress and due to the strict confidence of the results, most details related to the materials and the design solutions will not be fully presented.

II. LIGHTWEIGHT ROOF DESIGN CONCEPT

The actual carbody shell is mainly made up of metallic components hold together by welds and/or bolts and covered using metallic sheets. In some cases the structure is made up of aluminium extruded components, which are welded together to create the carbody cross section.

The current design structure is made up of aluminium extruded components having a length equal to the total carbody length. Each extruded component is welded to the adjacent ones along the whole length (see Fig. 1).

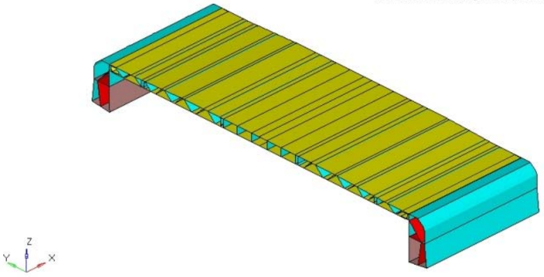

Fig. 1. Isometric view of a roof section.

The roof built in one piece is set down on the remaining part of the carbody shell and welded to the upper part of the side walls. Residual stress, which affects both the strength of the carbody shell and tolerances in the connections of several components, arises due to the welding process. The possibility to adopt a different solution in which the connection among parts does not introduce residual stresses saving the weight has been investigated. Using the same space occupied by the metal solution, different cross sections made of composite material are proposed and analyzed comparing the results in terms of stiffness and strength. In particular, three different configurations were studied: in relation to a sandwich philosophy the solutions analysed have been as follow: 1 - classic sandwich panel having composites sheets and polyurethane foam as core; 2 - rectangular polyurethane foam blocks; 3 - trapezoidal foam blocks with shaped composites plates (Fig. 2).

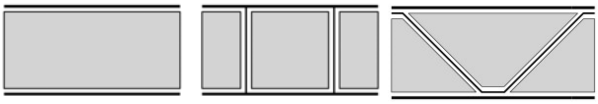

Fig. 2. Details of the cross sections of the composite solutions.

The first solution is essentially a "classic" sandwich panel with two composite faces, having internal core blocks made of polyurethane foam. In order to increase the stiffness of the composite sandwich, vertical webs have been added, spacing them as for the extruded aluminium panels. Polyurethane foam blocks are placed in the rectangular areas among webs. In order to avoid the stress concentration which arises at the web-faces connections, a further improvement has been evaluated: an internal shaped plate bonded to the external faces was introduced. The possibility to distribute shear stresses over an area allows to increase the strength of the faces-web connections and the interlaminar shear strength becomes the weakest point [3].

In the present paper the strength of the aforementioned solutions was studied through the FE approach. The comparison was made by evaluating the maximum vertical displacement and the maximum principal stress for each modulus. The applicability of such an approach is closely linked to the knowledge of the mechanical properties of the composite material, which requires an extensive experimental characterization in order to assess the orthotropic constants and the failure parameters [19 - 20]. Moreover, failure parameters are needed to carry out the structural assessment of the optimized structure to evaluate possible damages produced in the structure under the action of the service loads. In the next section details of the experimental campaign will be provided.

III. MATERIAL SELECTION

The applicability of a new material in railway applications involves not only the assessment in terms of stiffness and crashworthiness but also other requirements as fire protection, vibroacustic characteristics, insulation and voltage withstand properties, electromagnetic compatibility, ambient conditions. Among these the evaluation of the fire behaviour of materials and components, in accordance with European Standard CEI EN 45545-2 with hazard level HL2, was the most challenging to comply. It is well known that for example a sandwich structure is characterised by three distinct layers: two outer layers, the so-called skins or faces, and a centre core. The faces, which are commonly made up of high performance material are separated at a certain distance from each other by the core, a lower performance and light weight material, e.g. balsa wood, honeycomb structures or polymer foams. These structures can greatly increase the stiffness and strength without increasing the weight of the component accordingly. Therefore, the utilization of sandwich structures can be very effective. Moreover, the use of a particular material core can be useful to meet the vibro-acoustic requirements stated in the railway field. Furthermore the mechanical characterization of composite structures must be verified by requires laboratory test (mechanical, fire reaction) to validate both the solution and the numerical models; the relevant tests are in progress and we hope for the end of this year to achieve the needed results. The selected material was used to pursue the goal of lightening so that to ensure the proper impact resistance and stiffness of the structure. Furthermore the new solution meets the requirements HL2-of CEI EN 45545-2 (HL2 for requirement R8) and can be carried out with significant reducing production costs.

IV. MATERIAL CHARACTERIZATION

Composite material design requires the knowledge of several mechanical parameters which are not generally provided by manufacturers. Therefore, mechanical characterizations of the selected composite material were assessed in order to define the basic material properties useful for structural design and FE analysis.

A. *Tensile tests*

Tensile tests were performed on ten composite coupons. Five specimens were tested in longitudinal direction 0° (warp fibers parallel to the load) and other five coupons were tested in the transverse direction 90° (weft, warp fibers perpendicular to the load). These tests were performed in accordance with the ASTM D3039M standard [21]. Tests were performed at a constant cross head velocity of 2 mm/min. Ultimate tensile stress and strain, elastic modulus, and Poisson's ratio have been measured for both the warp and weft directions.

B. *Compressive tests*

Compressive tests were performed in accordance with the ASTM D6641 standard [22]. Ten coupons were tested: five in the longitudinal direction 0° (warp) and five in the transverse direction 90° (weft). Tests were performed at a constant cross head velocity of 1 mm/min. Ultimate tensile stress and strain and elastic modulus have been measured for both warp and weft directions.

C. *In-Plane Shear Tests*

In-plane shear tests have been conducted in accordance with the ASTM D3518 standard [23] on five coupons. Tests were performed at a constant cross head velocity of 2 mm/min. Ultimate in-plane shear stress and strain and in-plane shear modulus have been derived.

D. *Interlaminar shear tests*

Interlaminar shear tests have been performed in accordance with the ASTM D2344M standard [24]. Tests were conducted at a constant cross head velocity of 1 mm/min.

Interlaminar shear strength has been computed in correspondence of the ultimate applied load.

E. *Summary of Test Results*

Elastic properties and strength values obtained in static tests of the adopted FRP are reported in Table I.

TABLE.I
LAMINA MECHANICAL PROPERTIES

Mechanical Property			
Tensile Young Modulus	Warp	E1 (GPa)	58.2
	Weft	E2 (GPa)	57.4
Poisson's ratio	Warp	ν12 (-)	0.07
	Weft	ν21 (-)	0.069
Ultimate tensile Strength	Warp	F1t (MPa)	906.5
	Weft	F2t (MPa)	872.8
Ultimate tensile Strain	Warp	ε1u (%)	1.55
	Weft	ε2u (%)	1.77
Compressive Young Modulus	Warp	E1 (GPa)	54
	Weft	E2 (GPa)	55
In-plane shear Modulus		G12 (GPa)	4.6
Ultimate In-plane Shear Stress		F12 (MPa)	66.8
Interlaminar shear strength - ILSS		F66 (GPa)	39.2

The values in Table I have been implemented in the laminate composite material card of the FE software as described in the next section.

V. FEM ANALYSIS

In order to compare the bending stiffness and strength of the three proposed solutions, finite element analyses have been carried out. The component under evaluation is composed of a flatwise composite panel having the composite plates shaped as already discussed. In each model the panel is modified each time passing from the simple sandwich panel to the shaped plate ones. The total area of the investigated panel is 1 m^2. Due to the double symmetry planes, a quarter of the entire model has been modelled.

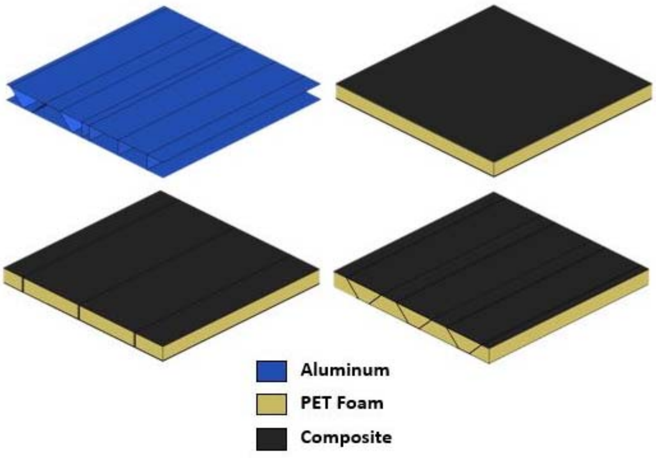

Fig. 3. Details of the considered panels.

The mechanical behavior of the polyurethane foam was modeled as homogenous, isotropic and linear elastic, whilst the material behavior of composite panels was modeled as linear elastic orthotropic (Table II and Table III).

TABLE II
MECHANICAL PROPERTIES OF POLYURETHANE FOAM

Mechanical Property		
Nominal Density	ρ (kg/m³)	100
Young Modulus	E (MPa)	52000
Poisson's ratio	ν	0,33

TABLE III
MECHANICAL PROPERTIES OF ALUMINUM

Mechanical Property		
Nominal Density	ρ (kg/m³)	2700
Young Modulus	E (MPa)	70000
Poisson's ratio	ν	0,33

The stacking sequence of the outer face, the shaped plates and the vertical sheet are reported in Table IV.

TABLE IV
COMPOSITE LAY-UP

Component	Lay-up
Classic sandwich configuration / External faces	0°/90°/45°/90°/0°
Webs of rectangular configurations	0°/0°/0°
Shaped plates	0°/45°/0°

In order to implement the symmetries along the longitudinal and transversal planes, boundary conditions have been applied, constraining the displacements and the rotations as required. Moreover, the lower edge of each model has been constrained along the vertical direction in order to simulate the simple supported condition. To make comparisons each model was loaded using the same vertical load equal to 0.4 kN. Total vertical load has been applied over a surface in order to avoid unrealistic peak stress.

The interaction among the parts of the structure was modeled using bonded contact adopting a node-to-segment algorithm. This approach allows to use a different mesh size for different parts optimizing the computational time whilst ensuring the needed accuracy in the estimation of the strain and stress field. Moreover, joints between composite plates have been simplified merging the coincident nodes. This approach produces a local stress concentration that needs to be investigated in depth. However, the aim of the present study is to compare the overall behavior that is not affected by this simplification.

VI. RESULTS

The main challenge in the optimization of railway component is the weight saving, which allows to increase the payload reducing at the same time the rail and the wheel wear so that the damage produced on the track by the train [18]. In the present study the current solution, which implements metallic extrusions, is used as target solution and the three solutions proposed as alternative possibility to save weight will be compared to it. For this reason, the results of the metallic solution will be first presented. The other solutions will be compared to the target one in terms of:

- ✓ maximum vertical displacement
- ✓ maximum principal stress
- ✓ weight.

The reason is that the optimal solutions should guarantee at least the same maximum displacement and stress in respect to the metallic one with a reduction in weight.

The contour plots of the vertical displacement for the target solutions and the new solutions (in progress) are reported in Fig. 4.

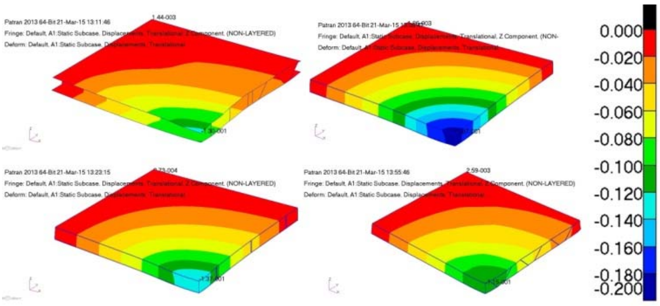

Fig. 4.Details of the considered panels.

The contour plot of the vertical displacement for the metallic solution reveals a sudden variation of the stiffness due to the location of the vertical metallic plates. In particular, the panel configuration is progressively stiffer from the middle plane toward the side. Based on these considerations, it can be stated that the flexural stiffness of the metallic panel is strongly affected by the spacing distance among vertical web over the longitudinal direction. As a consequence, vertical displacement is concentrated close to the mid plane while the rest of the panel suffers low deformations. All composite modules have a displacements contour which is more uniform than that of the metallic solution. This means that, in all considered configurations, the flexural stiffness is almost uniform along the two principal directions. The maximum displacement reached in the center of the metallic module is equal to 0,13 mm. In the classic sandwich configuration the maximum vertical displacement is reached still in the center and it is equal to 0,19 mm, greater than the metallic structure The rectangular box configuration enhances the flexural behavior on the longitudinal plane in respect to the classic sandwich configuration. However, the maximum displacement is equal to 0.137 mm, lower than the configurations previously investigated but greater than the metallic solution. The last configuration under investigation is the shaped one, which gives the best results: the maximum vertical displacement is equal to 0,115 mm. On the basis of the comparison of the maximum vertical displacements, it can be stated that the rectangular sandwich solution gives little enhancement in respect to the simple core even if its stiffness is still lower than that of the metallic panel. On the other hand, the shaped solution represents a better solution as it has a significant reduction in weight (36,5 %) and maximum deflection (11,5%). The comparison among configurations in terms of stresses was also considered. In the metallic solution (Fig. 5) the maximum stress is reached in the central region, as expected on the basis of the beam theory. Moreover, as already discussed, the central part is less stiff turning into a high stress level in this area.

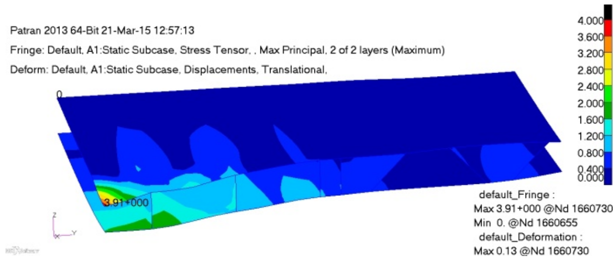

Fig. 5. Contour plot of the maximum principal stress in the metallic solution.

For the simple core configuration the region in which the maximum stress is reached is as for the metallic solution in the central zone. The maximum and the mid principal stresses decreases linearly from the center to the edges. As shown in Fig. 6, the highest value of the maximum principal stress is 1.21 MPa.

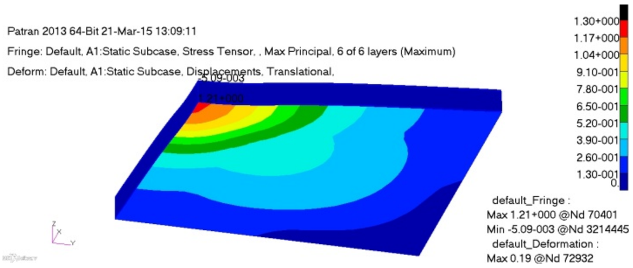

Fig. 6. Contour plot of the maximum principal stress in the classic sandwich solution.

The rectangular core has the same stress contour as the simple core configuration (Fig. 7). However, the vertical plates, which make the outer plates locally stiffer, affect the stress level introducing local concentrations related to the local changes in stiffness.

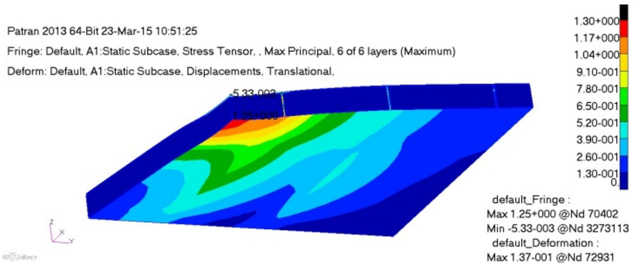

Fig. 7. Contour plot of the maximum principal stress in the rectangular solution.

For the shaped solution, the stress contour reported in Fig. 8 highlights the benefit produced by the possibility of bonding the shaped core with the outer plates on an overlapping area instead of a line. Moreover, the stiffness variation is smoother avoiding local stress concentrations.

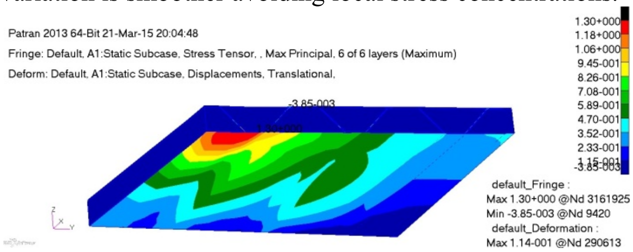

Fig. 8. Contour plot of the maximum principal stress in the shaped plates solution.

The last parameter considered for comparing the different solutions is the weight of each configuration. The weight of each configuration was evaluated theoretically on the basis of nominal dimensions and the equivalent densities. In particular, the weight of the composite plates was estimated by determining the equivalent density through the mixture rule. In Fig. 9 the maximum vertical displacement, the maximum principal stress and the weight of each module normalized by the metallic value are reported.

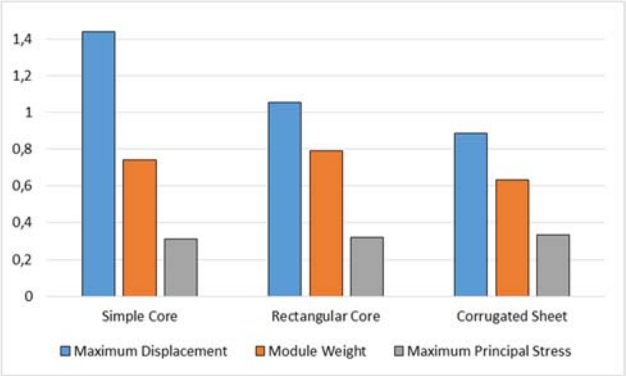

Fig. 9. Maximum displacement, weight and maximum principal stress normalized by the value of the metallic module.

In order to evaluate the effectiveness of the optimization process, the proposed solution has been implemented in the current solution of the carbody shell, which was provided by AnsaldoBreda. The metallic solution has been considered as target solution, as already done with the reduced models. The optimized solution has been compared with the metallic one considering the saving weight, the torsional stiffness of the entire carbody and the maximum stress. The equipment and the boogie weight, increased of the 10%, have been applied on both models. The entire vehicle is supported by three “lifting plate”, as shown in Fig. 10. In correspondence of the forth plate a displacement equal to 15 mm has been applied. The inertial load was increased by 10%. The analyses of the entire vehicle underlined that the composite material gives the same results as the metallic one in terms of displacements and stress.

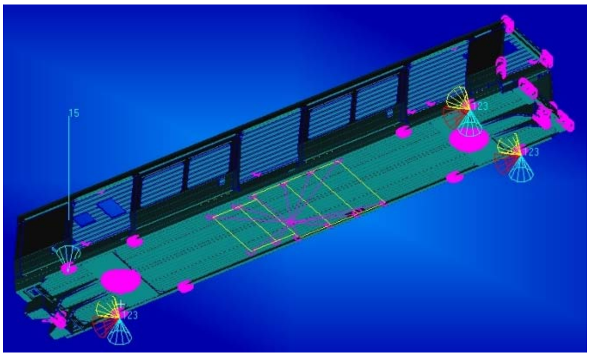

Fig. 10. FE model of the entire carbody.

VII. CONCLUSION

The results of this study confirm what was already known about composite materials applications in naval, civil, automotive and aeronautic fields, that is to say that the use of this material makes transportation more sustainable. Until today in the railway field the cost of the composite materials made this choice impossible. However, the recent development of their manufacturing process, i.e. the possibility to avoid autoclave curing and have the same mechanical behavior, made this choice possible. Moreover, composite thermosetting materials have a good vibrating damping ratio which reduces vibration and noise emanating from components made of composite materials [25].

In this paper different solutions for lightweight rail vehicle components have been discussed. An extensive mechanical characterization was carried out to assess the mechanical data of lamina and calibrate numeric models. A FE model in MSC Nastran® was used to analyses different designs, also implementing the chosen solution in the carbody shell to carry out the structural assessment of the final geometry under the action of selected loading conditions. The implementation of the proposed composite solution demonstrates performance in terms of stiffness and strength comparable to those achieved using aluminum counterpart with a significant weight saving. On the other hand, it should be checked whether the likely higher production costs of this composite in comparison with the costs of aluminum alloys nullifies the advantages implied in its lighter weight.

ACKNOWLEDGMENT

The activities have been performed in the context of the Italian Research Project "SCILLA-M" (Structures, Innovative Components, Light Applications for Metro) funded by the MIUR (Ministry of Education, University and Research), which are gratefully acknowledged.

REFERENCES

[1] Cho-Chung Liang, Ming-Fang Yang, Pin-Wen Wu. "Optimum design of metallic corrugated core sandwich panels subjected to blast loads". Ocean Engineering 28 (2001) 825–861
[2] Tomohiro Yokozeki, Shin-ichi Takeda, Toshio Ogasawara, Takashi Ishikawa. Mechanical properties of corrugated composites for candidate materials of flexible wing structures. Composites: Part A 37 (2006) 1578–1586
[3] C. Thill, J.A. Etches, I.P. Bond, K.D. Potter and P.M. Weaver. Corrugated composite structures for aircraft morphing skin applications. 18 th International Conference of Adaptive Structures and Technologies. October 3 rd , 4 th , 5 th , 2007 Ottawa, Ontario, Canada.
[4] M. J. Robinson, P.E. 1 ; and J. B. Kosmatka, P.E. Light-Weight Fiber-Reinforced Polymer Composite Deck Panels for Extreme Applications. 10.1061/(ASCE)1090-0268(2008)12:3(344)
[5] Bing Wang, Linzhi Wu, Li Ma, Yuguo Sun, Shanyi Du. Mechanical behavior of the sandwich structures with carbon fiber-reinforced pyramidal lattice truss core. Materials and Design 31 (2010) 2659–2663
[6] Queheillalt DT, Wadley HNG. Pyramidal lattice truss structures with hollow trusses. Mater Sci Eng A 2005;397:132–7.
[7] Jian Xiong, Li Ma, Linzhi Wu, Bing Wang, Ashkan Vaziri. Fabrication and crushing behavior of low density carbon fiber composite pyramidal truss structures. Composite Structures 92 (2010) 2695–2702
[8] Luo S, Suhling JC, Considine JM, Laufenberg TL. The bending stiffness of corrugated board, AMD-Vol.145/MD-Vol. 36, Mech Cellul Mater ASME 1992.
[9] Iman Dayyani & Saeed Ziaei-Rad & Hamid Salehi. Numerical and Experimental Investigations on Mechanical Behavior of Composite Corrugated Core.
[10] J. Xiong, L. Ma, A. Vaziri, J. Yang, L. Wu. Mechanical behavior of carbon fiber composite lattice core sandwich panels fabricated by laser cutting. Acta Materialia 60 (2012) 5322–5334
[11] Jin Zhang, Peter Supernak, Simon Mueller-Alander, Chun H. Wang. Improving the bending strength and energy absorption of corrugated sandwich composite structure.
[12] Brylawski M, Lovins A. Ultralight hybrid vehicle design: overcoming the barriers to using advanced composites in the automotive industry RMI, T95-39. Rocky Mountain Institute; 1995.
[13] Beardmore P, Johnson CF. The potential for composites in structural automotive applications. Compos Sci Technol 1986;26:251–81.
[14] G. Pitarresi and J.J. Carruthers and A.M. Robinson and G. Torre and J.M. Kenny and S. Ingleton and O. Velecela and M.S. Found. A comparative evaluation of crashworthy composite sandwich structures. Composite Structures 78 (2007) 34 - 44.
[15] Zangani, D. and Robinson, M. and Gibson, A.G. Progressive Failure of Composite Hollow Sections with Foam-Filled Corrugated Sandwich Walls. Applied Composite Materials 14 (2007) 325-342.
[16] Haibin Ning, Selvum Pillay, Uday K. Vaidya. Design and development of thermoplastic composite roof door for mass transit bus. Materials and Design 30 (2009) 983–991
[17] CEI EN 45545-2 Railway applications. Fire protection on railway vehicles. Requirements for fire behaviour of materials and components.
[18] Mark Robinson, Joe Carruthers, Conor O'Neill, Stephen Ingleton, Marzio Grasso, Transport of DE-LIGHT: The Design and Prototyping of a Lightweight Crashworthy Rail Vehicle Driver's Cab, Procedia - Social and Behavioral Sciences, Volume 48, 2012, Pages 672-681
[19] A. De Iorio, D. Ianniello, R. Iannuzzi, F. Penta, A. Apicella, L. Di Palma. Strength Criteria for Composite Material Structures, "4th Seminar on Experimental Techniques and Design in Composites, Sheffield (England) 1-2 settembre 1998.
[20] A. De Iorio, D. Ianniello, R. Iannuzzi, F. Penta, A. Apicella, F. Quadrini. Test Methods for Composites Mechanical Characterization. "4th Seminar on Experimental Techniques and Design in Composites, Sheffield (England) 1-2 settembre 1998.
[21] ASTM D 3039. Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials (2008).
[22] ASTM D 6641. Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression (CLC) Test Fixture (2009).
[23] ASTM D 3518. Standard Test Method for In-Plane Shear Response of Polymer Matrix Composite Materials by Tensile Test of a ±45° Laminate (2007).
[24] ASTM D 2344. Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates (2000).
[25] Zinno A., Fusco E., Prota A., Manfredi G. Multiscale approach for the design of composite sandwich structures for train application. *Composite Structures*, **92**, pp. 2208–2219 (2010).