Structural Behaviour and Vibro-Acoustic Analysis of a Composite Rail Vehicle Car Body Roof

A. Genovese, S. Strano

***Abstract*— This paper describes a numerical/experimental study of the structural behaviour and the vibro-acoustic performance of an innovative composite rail vehicle car body roof. The traditional metallic roof has been compared with the new proposed solution in terms of structural and vibro-acoustic performances. An innovative flatwise composite panel solution has been proposed for the rail vehicle car body roof. The different stiffness and the different mass of the roof change the vibrational behaviour of the entire vehicle. For this reason, a vibro-acoustic analysis has been performed in order to define the transmission loss. The study underlines that the sandwich structure made of composite materials provides good results in terms of weight, flexural stiffness and vibro-acoustic behaviour.**

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

I. INTRODUCTION

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, vibroacoustic characteristics, insulation and voltage withstand properties, electromagnetic compatibility, ambient conditions [1]. 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 main challenge in implementing the composite roof of a railway car body is related not only to the structural assessment but also to the compliance of the requirements prescribed by the CEI EN 45545-2 [2] Standard concerning smoke and fire prescriptions. For this reason, the solutions implemented so far have been developed using a particular thermosetting resins including specific additive, which 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 carbon-fibre composite material that meets the requirements CEI EN 45545-2 HL2 and can be cured without autoclave, significantly reducing production costs. 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. STRUCTURAL ANALYSIS

The actual car body 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 car body cross section [3].

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

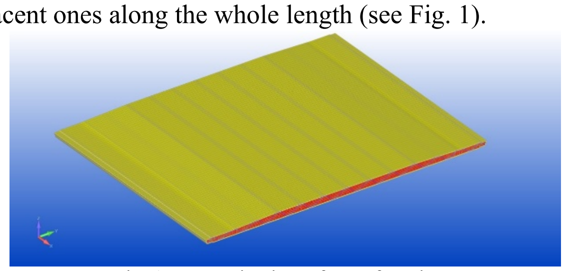


Fig. 1. Isometric view of a roof section.

The roof built in one piece is set down on the remaining part of the car body shell and welded to the upper part of the

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

side walls. Residual stress, which affects both the strength of the car body 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 [4].

In order to compare the bending stiffness and strength of the three proposed solutions, finite element analyses have been carried out. An extensive material characterization has been conducted in order to obtain the define the material properties in the FE model [5]. The values in Table I have been implemented in the laminate composite material card of the FE software.

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 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.

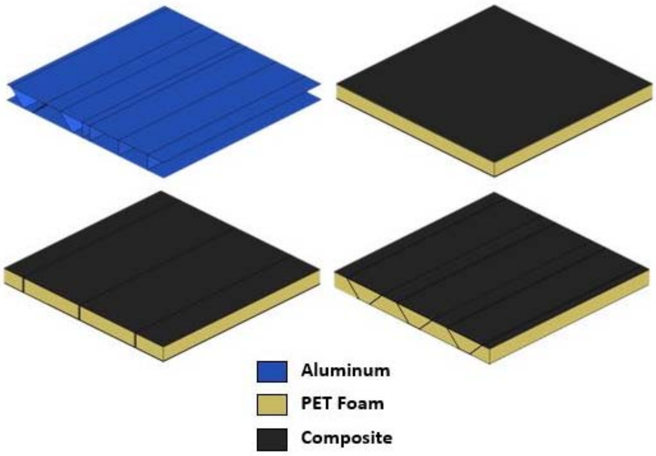


Fig. 3. Details of the considered panels.

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/m^3)	100
Young Modulus	E (MPa)	52000
Poisson's ratio	ν	0,33

TABLE III
MECHANICAL PROPERTIES OF ALUMINIUM

Mechanical Property		
Nominal Density	ρ (kg/m^3)	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

ISBN: 978-988-14048-0-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

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.

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 [6]. 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.

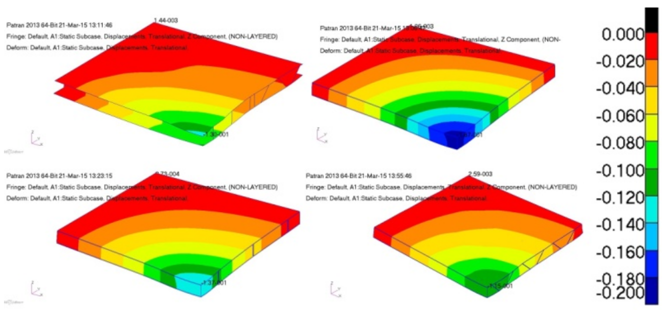


Fig. 4.Details of the considered panels.

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. 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.

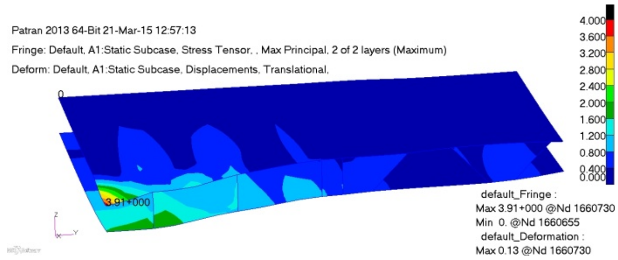


Fig. 5. Contour plot of the maximum principal stress in the metallic solution.

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.

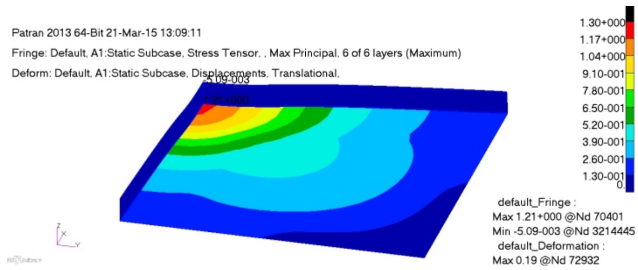


Fig. 6. Contour plot of the maximum principal stress in the classic sandwich solution**.**

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.

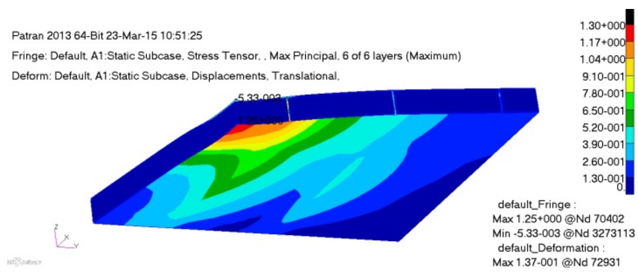


Fig. 7. Contour plot of the maximum principal stress in the rectangular solution.

For the shaped solution, the stress contour reported in Fig. 8 highlights the benefit produced by the possibility of

ISBN: 978-988-14048-0-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

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.

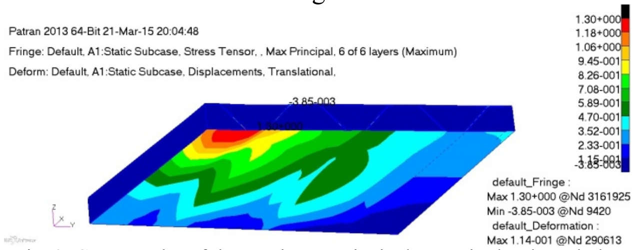


Fig. 8. Contour plot of the maximum principal stress in the shaped plates solution.

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.

III. Vibro-Acoustic Analysis

The vibro-acoustic analysis has been developed both numerically and experimentally.
Fig. 9 shows a sketch of the new sandwich panel based on the shaped solution presented in section II.

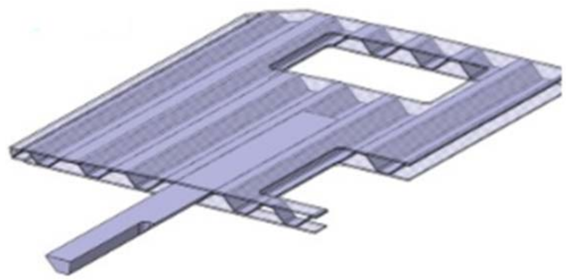
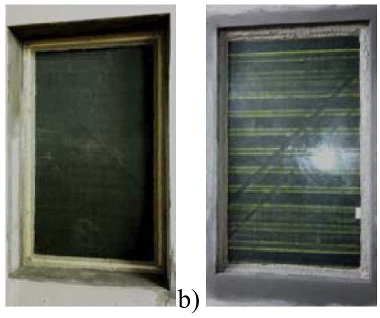


Fig. 9. 3D CAD model of the roof.

The sandwich panel has a corrugated shape with the function of stiffening the structure providing cavities for the insertion of the foam. The skins and the corrugated panel are made of composite material.

A. *Experimental analysis*

The experimental vibro-acoustic analysis has been conducted via laboratory measurements of airborne sound insulation on panel according to standards UNI EN ISO 10140-2:2010 and UNI EN ISO 717-1:2013. Successively, the experimental results have been compared with the simulation ones.
The tests have been carried out according to the standard UNI EN ISO 10140-2:2010 dated 21/10/2010 “Acoustics - Laboratory measurement of sound insulation of building elements – Part 2: Measurement of airborne sound insulation” and UNI EN ISO 717-1:2013 dated 04/04/2013 “Acoustics - Rating of sound insulation in buildings and of building elements - Part 1: Airborne sound insulation”.
The test environment consists of two chambers, one of which, known as “source room” (Fig. 10a), contains the noise source, whilst the other, known as “receiving room” (Fig. 10b), is characterised acoustically by the equivalent sound absorption area. The sample, after being conditioned for at least 24 h inside measurement environment, has been installed in the test opening between the two rooms.



a) b)

Fig. 10. a) Photograph of sample, source room side; b) Photograph of sample, receiving room side

The results of the laboratory tests have been used for the verification of the numerical model.

B. *Numerical analysis*

This section presents the results obtained from the numerical vibro-acoustic analysis for the proposed configuration of a sandwich panel made of composite material.
The main goal is to validate numerical models concerning the vibro-acoustic behavior of the roof [7].
Two configurations have been investigated. The configurations differ by the number of plies and are called respectively *conf_A* and *conf_B* (see Table V for reference).
A comparison of the acoustic performance of the new composite sandwich configurations with the one made of aluminium has been carried out.

TABLE V
LAY-UP CONFIGURATIONS

Configuration	*conf_A*	*conf_B*
Skin	[0 90 0 45 0 90 0]	[0 45 0]
Corrugate	[0 0 0]	[0 0 0]

The software VAOne has been used for the evaluation of the sound transmission loss (TL). In particular, the periodic periodic theory developed in [8] for 2D structures has been considered. In this numerical simulation, the repetition of a cell in the x and y directions enables to rebuild the original structure. The cell is presented in Fig. 11 and in Fig. 12 the unit cell implemented in VAOne is shown.

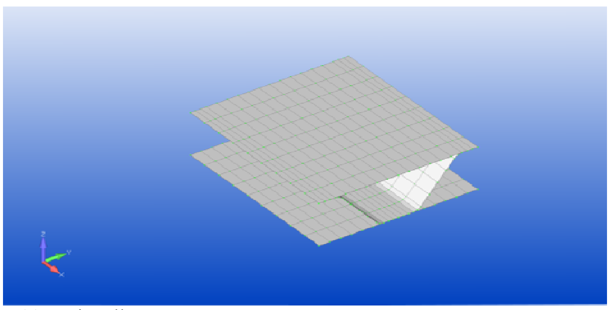


Fig. 11. Unit cell.

ISBN: 978-988-14048-0-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

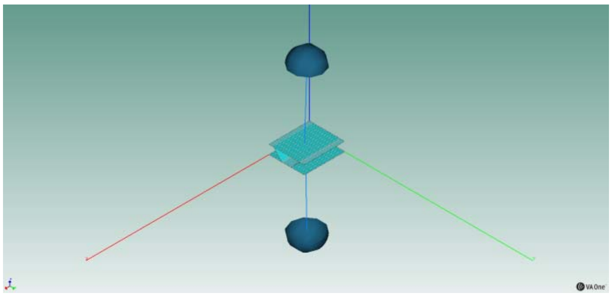


Fig. 12. Unit cell implemented in VAOne.

Fig. 13 shows the results concerning the comparison between *conf_A* and aluminium panel. The *conf_A* differs for both geometry and materials compared to the metallic configuration of the sandwich panel. Therefore, with the purpose of making a comparison, the analysis has been carried out on a sandwich panel made of aluminium with the same geometry of the *conf_A*.
In general the performance in terms of TL of a panel made of aluminium (green curve) is higher compared to the same panel made of a composite; but the use of aluminium results in a significant increase in weight. Indeed, for the geometry of *conf_A* the composite panel has a weight of 56.4 kg, while the one in aluminium is 97.5 kg with a reduction of 42% in terms of weight.

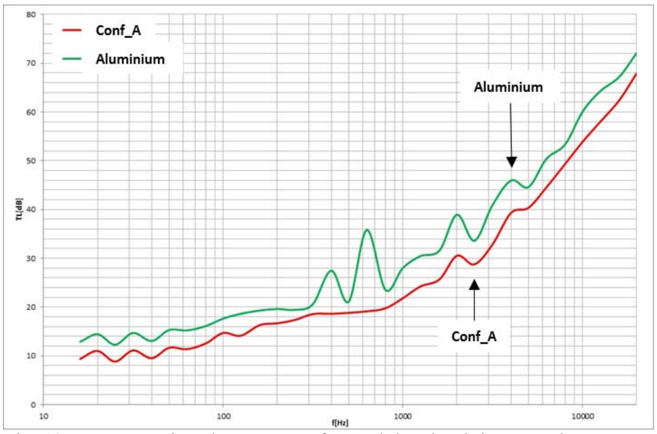


Fig. 13. TL comparison between *conf_A* and the aluminium panel.

In Fig. 14, the results concerning the comparison between *conf_B* and aluminium panel are presented. Also in this case the TL curve of the aluminium panel is greater than the one of *conf_B* in the whole frequency range.

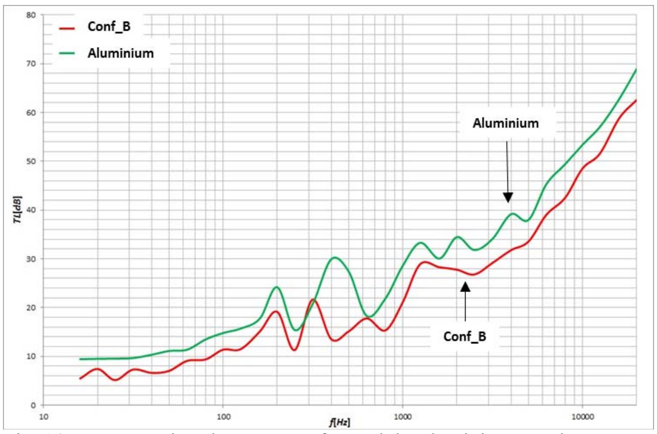


Fig. 14. TL comparison between *conf_B* and the aluminium panel.

Fig. 15 shows a TL comparison between *conf_A* and *conf_B*. It confirms the slight superiority of *conf_A* with respect to *conf_B*. This result is related to the mass, indeed, the *conf_A* has a greater mass (~ 75%) than the one of *conf_B*.

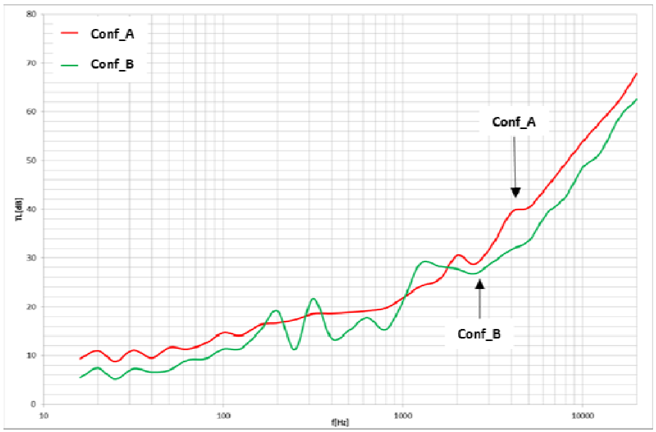


Fig. 15. TL comparison between *conf_B* and the aluminium panel.

A comparison between the experimental results and the numerical ones (aluminium and *conf_A*) is presented in Fig. 16.

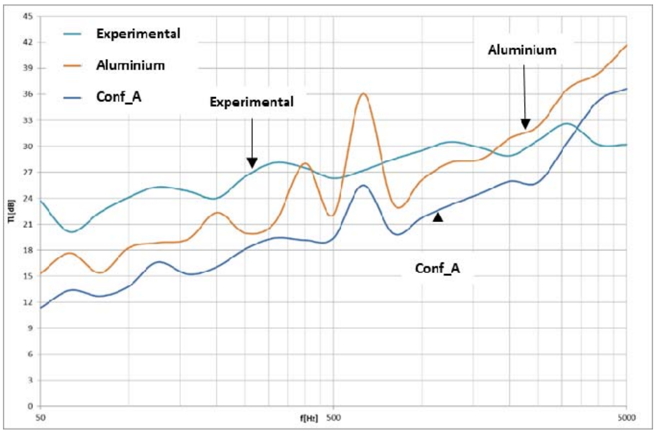


Fig. 16. TL comparison between the experimental results and the numerical ones (aluminium and *conf_A*)

Results of Fig. 16 show a performance of the composite structure comparable with that one of the aluminium solution. The comparison between numerical and experimental data highlights that the model underestimates the TL. Improvement of the model parametrization could lead to better results in terms of TL prediction. Numerical analysis carried out on the transmission loss has shown that the vibro-acoustic behaviour depends largely on the thickness of the base layer.

IV. Conclusion

In this paper different solutions for the design of multi-functional car body roof of a metro vehicle, using advanced composite materials, have been presented. An extensive mechanical characterization has been carried out to assess the mechanical data of lamina and to calibrate numeric models. Two main aspects have been investigated in detail: structural and vibro-acoustic performances. The results of the structural analysis clearly demonstrate that the proposed composite solution has performance in terms of stiffness and strength comparable to those achieved using aluminium counterpart with a significant weight saving. Concerning the vibro-acoustic study, both experimental and numerical results highlight good performance.

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.

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