Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 8 (2018) 332–344

Structural Integrity Procedia

www.elsevier.com/locate/procedia

AIAS 2017 International Conference on Stress Analysis, AIAS 2017, 6-9 September 2017, Pisa, Italy

Aluminum honeycomb sandwich for protective structures of earth moving machines

A. Bonanno[a]; V. Crupi[b]; G. Epasto[b]*; E. Guglielmino[b]; G. Palomba[b]

[a]*Institute for Agricultural and Earthmoving Machines - IMAMOTER, C.N.R., via Canal Bianco 28, 44124 Ferrara, Italy*
[b]*Department of Engineering, University of Messina, Contrada di Dio, Sant'Agata, 98166 Messina, Italy*

Abstract

The design and the assembly of the vehicles subjected to the risk of crushing from falling objects have to consider such danger and provide the operators with suitable safety systems. Generally, falling object protective structures for earth moving machines consist of vertical elements, connected by transversal elements, covered by a roof. The latter has the aim to protect the operators from falling objects and it is usually made of a steel skeleton with a metal plate. In this study, sandwich panels were proposed as technical solution for the impact protection from falling objects in earth moving machines. A very light and cheap aluminum honeycomb core (AA3003 alloy and cell size = 19 mm) was considered as design solution and was subjected to static and dynamic full-scale tests. The results were analysed according to the performance requirements of ISO 3449 standard. The experimental results confirmed that the honeycomb structures are well suitable for designing absorber devices in vehicles protective structures in order to ensure occupant safety.

Peer-review under responsibility of the Scientific Committee of AIAS 2017 International Conference on Stress Analysis

Keywords: Aluminum honeycomb; Lightweight design; Impact behaviour; Full scale tests; Crashworthiness; Earth moving machines.

---

* Corresponding author. Gabriella Epasto, Department of Engineering, University of Messina, Contrada Di Dio, 98166 Messina, Italy
Tel.: +3990377505; fax: +39903977464.
E-mail address: gabriella.epasto@unime.it

Peer-review under responsibility of the Scientific Committee of AIAS 2017 International Conference on Stress Analysis
10.1016/j.prostr.2017.12.034

1. Introduction

Earth moving machines are of great importance in industrial, agrarian, and construction applications. The mechanization of human activities through these devices, lead to acceleration and simplification of work, in comparison to manual methods, increase in production capacity, reduction in work costs and improvement in safety (Budny et al., 2009). The application fields for earth moving machines are inherently hazardous, both for machines' integrity and for operators' safety. These devices are involved in risky activities, such as heavy and large objects handling - for example concrete blocks, earth, construction tools - and the activation of several tools, for example hammers, mills, buckets (Bonanno, 2008). In order to reduce the risks to which the operators are exposed, earth moving machines are provided with protective structures integrated in the cabins, which demand strict safety and ergonomic requirements, since they represent the work place for the operators. Indeed, safety issues in construction sites and mines are often related to falling objects on cabins. According to INAIL guide regarding risk reduction in earth moving activities (INAIL, 2003), the first cause of injury is the fall of objects. As a result, the introduction of appropriate protection systems for cabins is of primary importance. These structures are named Falling Object Protective Structures, or FOPS. The urgency for prevention of risks in work places resulted in the development of rules and regulations, which establish some requirements for earth moving machines, in terms of falling object impact resistance. The international standard, which defines test procedures for the evaluation of FOPS characteristics, is ISO 3449 (ISO, 2005). The Standard distinguishes two impact protection levels. Level I defines the protection from small falling objects, as bricks or small tools; first level protection structures must resist the impact of a round object falling from a height sufficient to develop an energy of 1365 J. Level II defines the protection from large falling objects, such as trees, concrete blocks, rocks, etc.; in order to ensure a second level impact protection, a structure must resist the impact of a cylindrical test object falling from a height sufficient to develop an energy of 11600 J.

As stated by the International Standard, falling object protective structures are systems of "structural members arranged in such a way as to provide operators with reasonable protection from falling objects (trees, rocks, small concrete blocks, hand tools, etc.)". Such protective structures may be integrated in the vehicle or provided separately.

The design and the assembly of the vehicles subjected to the risk of crushing from falling objects have to consider such danger and provide the operators with suitable safety systems. Generally, protective cabins for earth moving machines consist of vertical elements, connected by transversal elements, covered by a roof. The latter has the aim to protect the operators from falling objects and it is usually made of a steel skeleton with a metal plate (Karliński et al., 2008), possibly with a polymeric cover with an aesthetic function. Protective cabins may have an open or closed structure, their height may be adjustable and they can be an integral part of the vehicle or can be an optional. A representative case of falling object protective structure is described in the patents EP 2 763 873 B (Merli, 2016) and EP 1 728 689 A1 (Chun-Ho and Jin, 2006). The combination of safety issues and acoustic comfort for earth moving machines' operators, led to the invention protected by patent US 6 322 133 B1 (Yantek et al., 1999). Even in the earth moving machines market greater attention is put on the aesthetic features of the vehicles, which must be combined with safety requirements and weight-saving solutions. This led to the idea of producing the protective structures with polymeric materials (Bonanno, 2008).

The current study is aimed at introducing innovative and engineered materials for falling object protective structures, in order to improve and optimise their purpose, reducing the weight of the vehicles.

Aluminum honeycomb sandwich structures are considered particularly suitable for this aim, since they present excellent energy absorption properties combined with low density. In order to achieve an efficient design of a protective structure with honeycomb sandwich, the mechanical properties of the materials need to be analysed, considering that the dynamic response of sandwich structures depends on numerous variables and presents significant non-linearities, which make it difficult to describe in a theoretical form. Consequently, experimental investigation of their impact behaviour is of primary importance in order to obtain information to aid the design of lightweight impact absorbers.

The theoretical evaluation of the energy absorption capabilities of honeycomb sandwich structures is a crucial point in the design of impact protective elements. A recent model was proposed by Wang et al. (2016), who developed and verified a theoretical approach to evaluate the total energy absorption (TEA) and the specific energy absorption (SEA). According to the ASTM standard D7336, these parameters are defined in Ivañez et al., 2017.

There are several studies in literature about the mechanical properties (Crupi et al., 2016a; Crupi et al., 2016b; Mozafari et al., 2015a; Crupi et al., 2014; Zhu and Chai, 2013; Hazizan and Cantwell, 2003; Raju et al., 2008) and the applications (Mozafari et al., 2015b; Shin et al., 2008; Akatay et al., 2015) of honeycomb sandwich panels.

In the present study, the design of a real falling object protective structure for small earth-moving machine was supported by an extensive experimental campaign, combined with the theoretical analysis of the results.

The study was divided in two steps. The first step was the experimental analysis on the honeycomb structure on a small-scale level, involving quasi-static crushing tests. The data obtained were applied to theoretical models, in order to investigate their consistency and use them as a reliable tool for the prediction of energy adsorption capacity. Afterwards, a realistic lightweight FOPS was designed on the basis of small-scale experiments' results. The designed structure was subjected to a quasi-static full-scale test to confirm the effectiveness of the solution. A full-scale FOPS test on the real structure was carried out in accordance with the instructions of ISO 3449, with the aim of verifying the feasibility of the innovative lightweight falling object protective structure.

2. Materials and methods

2.1. Materials

A very light and cheap design solution was subjected to dynamic and static full-scale tests and analysed according to the performance requirements of ISO 3449 standard. The tested specimens were commercial aluminum honeycomb sandwich with hexagonal cells of 19 mm diameter made of AA3003 aluminum alloy whose thickness is equal to 80 mm; polyurethane resin provide bonding between core and skin. The properties of the tested material are reported in Table 1.

Table.1: Properties of tested materials.

Cell diameter [mm]	19
Core thickness [mm]	80
Face-sheet thickness [mm]	1
Cell wall thickness [mm]	0.070
Core alloy	AA3003
Skin alloy	AA6061
Honeycomb density [kg/ m3]	28
Crush strength [MPa]	0.31
Adhesive between core and skin	polyurethane resin
Cross – section	

2.2. Methods.

In the current study, quasi-static flatwise crushing tests were performed in order to obtain the crush strength of the honeycomb sandwich. The tests were conducted by a universal testing machine Zwick-Roell® Z600 with a load cell of 600 kN. The testing conditions are similar to those reported in literature (Pollard et al., 2017; Feraboli et al., 2010; Lane et al., 2016) and follow the ASTM D7336. The crushing tests were performed on specimens of honeycomb sandwich whose dimensions are 220 x 220 mm. The test was conducted on the whole sandwich structure and not only on the core, in order to obtain information also on the effect of the skin and to improve the uniformity of load distribution. The load was applied uniformly on the specimen through a flat square steel plate, which measures 250 x 250 mm. The honeycomb was pre-crushed with a load of 100 N. According to the ASTM Standard, such operation increases the stability of results. The test was performed at several displacement rates (2 mm/min; 5 mm/min; 10 mm/min; 20 mm/min; 50 mm/min) in order to investigate the strain rate effect on the material response. During the test load and displacement were recorded, as long as the load increased after plateau phase.

In order to build a realistic protective system for Level I Standard, a commercial skid loader was used as a reference for dimensions and clearances; in particular, the example model is the skid loader GEHL® 3840.
The main characteristics of the reference model are reported in Table 2.

Table 2. Main features of the reference skid loader.

Roof width [mm]	840
Roof length [mm]	980
Distance operator head-roof [mm]	200
Operator position	Central

The system destined to the full-scale test was sized referring to the example model's features. The cabin was modelled as a tubular steel frame, with an upper system able to clamp the honeycomb protective roof along all the sides. The clamping system consists of a two frames, made of L-steel bars, welded together by arc welding. Six angle plates with a central hole are welded along the frame's edges. The two frames are fastened together by means of six bolts M6 grade 8.8. A particular view of the clamping system is displayed in Fig. 1.

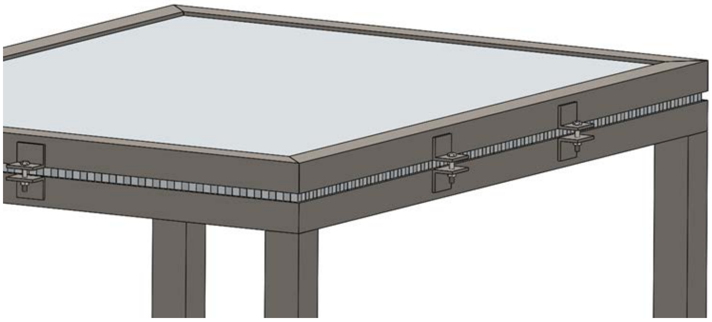
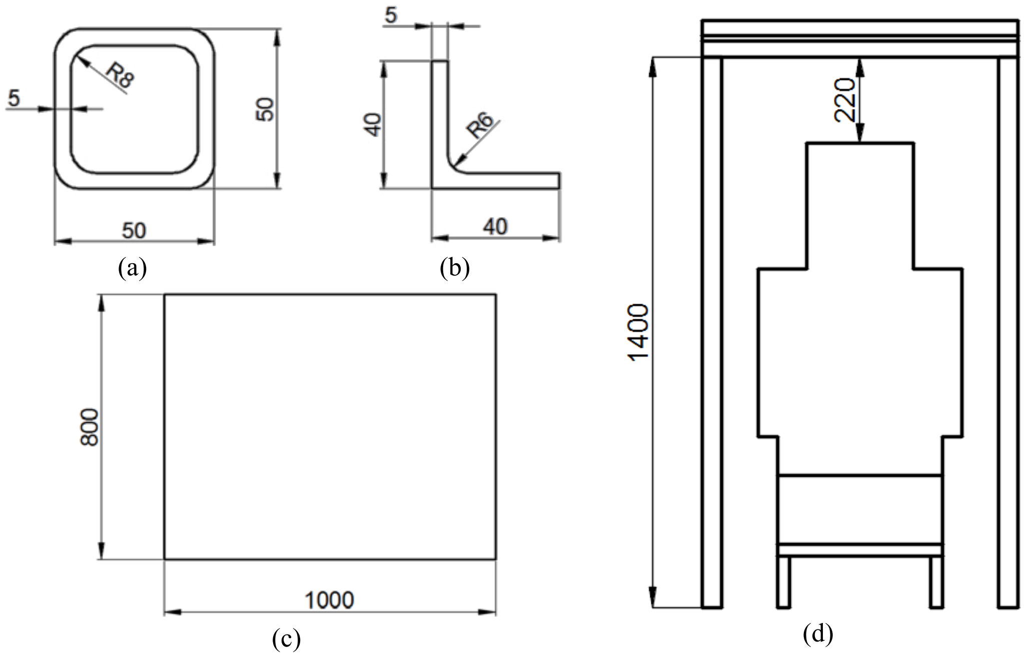


Fig. 1. Clamping system for the full-scale FOPS.

The design solution for the clamping system results in a configuration similar to that used on small-scale tests in previous studies of Crupi et al. (2016a; 2016b). In addition, the frame system has a good flexibility, because the substitution of the honeycomb roof is easy and fast, allowing the use of the same frame for numerous tests. A similar configuration could represent also a valid alternative for a real earth moving machine, on account of the possibility to change only the upper protective structures in case of damage. The distance between the operator head and the protective roof was established equal to 220 mm, in order to guarantee enough space for the FOPS deformation. The operator head centre was aligned with the roof centre. The main geometrical data of the honeycomb roof and the frame for full-scale FOPS test are displayed in Fig. 2 and are summarised in Table 3.



(a) (b) (c) (d)

Fig. 2. Cross sections and dimensions of (a) struts and (b) L bars used for the frame; (c) dimensions of the honeycomb protective roof; (d) Deflection Limiting Volume (DLV) - roof distance and struts height.

Table 3. Geometrical characteristics of protective structure and frame for full-scale FOPS test.

Honeycomb sandwich panel width [mm]	800
Honeycomb sandwich panel length [mm]	1000
Struts geometry	Squared
Struts transverse length [mm]	50
Struts wall thickness [mm]	5
Struts height [mm]	1400
L bars transverse length [mm]	40
L bars wall thickness [mm]	5
L bars longitudinal length [mm]	800 or 1000
Distance operator head-roof [mm]	220

The steel bars and struts employed for the frame ensured a high stiffness of the system and guaranteed that, during the dynamic test, the only deformable element was the honeycomb sandwich.

In the current study, an experimental setup for the full-scale indentation test was designed for resembling the real loading conditions. For the full-scale tests, the honeycomb panel was constrained with the same clamping system designed for the real protective structure, which was placed on I-beams, in order to replicate the same conditions of an earth-moving machine cabin. The chosen indenter was a steel cylinder with the same diameter of the impacting object prescribed by ISO 3499 (200 mm) and a weight of 25 kg. Such test settings were applied to have a condition similar to the impact test prescribed by ISO 3449. Indeed, geometry and boundary conditions have a great influence on the indentation response of sandwich panels. An experimental study by Flores-Johnson and Li (2011) on foam core sandwiches, demonstrated that the damaged area depends on the indenter shape, and in particular flat and truncated indenters produce the largest damage. In addition, different boundary conditions resulted in different indentation load: a clamping solution, similar to that applied in the current study, allowed the bending of the sandwich with a subsequent decrease of indentation resistance, but also of the localised damage.

The test was performed with a 100 kN actuator, arranged vertically. The indenter was positioned on the honeycomb panel and the load was distributed on it by means of a plate fastened to the actuator. The assembled setup is visible in Fig. 3.

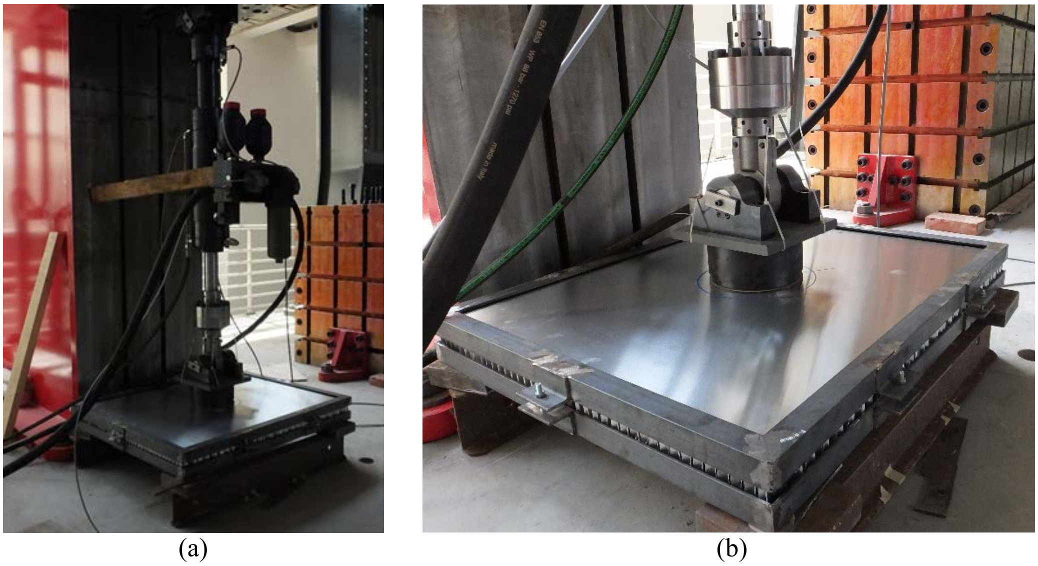

(a) (b)

Fig. 3. (a) Indentation test setup; (b) particular of the cylindrical indenter.

The real-scale structure was subjected to a preload of 1 kN in order to stabilise the position of the indenter and the response of the panel. The honeycomb sandwich was loaded at the centre of its surface at crosshead displacement rate of 2 mm/min. The load and the crosshead displacement were measured with a sampling frequency of 100 Hz.

A second frame for full-scale test was assembled and welded to a rigid base frame, used for FOPS tests, which fulfils the role of the real skid loader frame. A Standard Deflection Limiting Volume (DLV) made of styrofoam was used to represent the operator and it was collocated on a support structure, in order to comply with the dimensions established in the design phase. The real system prepared for the FOPS test is shown in Fig. 4.

Two circles, one with diameter equal to 200 mm, and another with diameter equal to 400 mm, were drawn on the honeycomb sandwich in order to identify the FOPS centre and the impact area.

According to the ISO 3449 for Level I FOPS, the impact object is a mass of 45 kg, with a spherical contact surface, whose diameter is equal to 200 mm. The mass was lifted to the height of 3.1 m above the honeycomb FOPS, to develop an impact energy equal to 1365 J. The alignment of the mass with the sandwich centre was obtained by means of a plumb line. The impact object was dropped on the FOPS activating a pneumatic system.

Fig. 4. (a) Front view of the test structure; (b) lateral view.

The honeycomb panel, damaged after the full-scale FOPS test, was subjected to radiographic inspection aiming to investigate the consequences of the impact event. The radiographic evaluation was performed with a Bosello SRE m@x system. The radiographic machine is equipped with a shielded cabin and an X-ray high power tube of 1800 W, with a maximum voltage of 320 kV and a variable focal spot size of 0.4 mm or 1 mm. The detector is a flat panel with a resolution of 1024x1024 pixels. The system is equipped with a manipulator with an automatic 4-axes movement control system. The large dimensions of the cabin allowed the inspection of the panel subjected to the full-scale FOPS test, with the aim of evaluating the residual core thickness in the impacted area and the damage mechanism of the cells. The impacted honeycomb panel positioned in the X-ray system is shown in Fig. 5. The radiographic images were obtained setting the X-ray source at a voltage of 49 kV and at a current of 0.7 mA.

Fig. 5. Honeycomb FOPS in the X-ray system.

3. Results and discussion

3.1. Low - scale experimental tests.

The load-displacement trend is similar for all the specimens and perfectly follows the theoretic behaviour of honeycomb structures. The load-displacement curves of the crushing test are reported in Fig. 6.

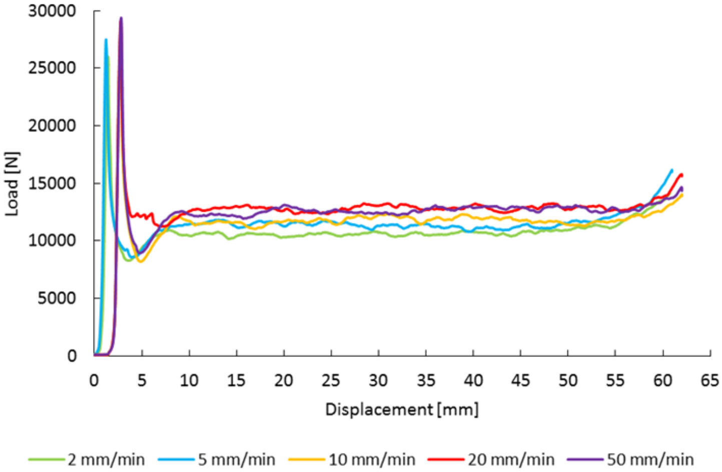


Fig. 6. Load-displacement curves of the crushing tests-

Honeycomb response was slightly influenced by the increasing displacement rate, which produced a growth of the peak load, of the crush load and of the absorbed energy. The values of these parameters are reported in Table 4, together with their mean value.

Table 4. Values of peak load, crush load and absorbed energy.

Displacement rate [mm/min]	Peak load [kN]	Crush load [kN]	Absorbed energy [J]
2	25.9	10.6	652
5	27.5	11.3	698
10	27.7	11.7	707
20	29.1	12.8	775
50	29.3	12.6	757
Mean value	27.9	11.8	718

The crush load increment, between the slower and the faster test, was of about 3 kN. Therefore, the dependency of honeycomb response can be considered negligible, as long as the displacement rate is low. Such results confirm the observations of Hazizan et al. (2003) regarding the independency of honeycomb mechanical properties on the strain rate.

The theoretical evaluation of the energy absorption suggested by Wang et al. (2016) can be applied in the current study to verify the energy absorption properties of the tested materials. In particular, the information needed for the application of the model were obtained for the honeycomb by means of the crushing test.

In order to apply Wang's model (Wang et al., 2016), the final core thickness after the crushing tests was measured. The properties of the examined honeycomb specimens are described in Table 5.

Table 5. Properties of the tested honeycomb specimens needed to apply Wang's model (Wang et al., 2016).

Honeycomb core initial thickness a_i [mm]	80
Core length a_L [mm]	220
Core width a_w [mm]	220
Cell wall length l [mm]	11
Cell wall length h [mm]	11
Cell wall thickness t [mm]	0.07
Core density [kg/m^3]	28
Core volume [mm^3]	3872000
Specimen's core mass [kg]	0.11
Yield stress core material [MPa]	145

Wang's model (Wang et al., 2016) was applied for each specimen subjected to the crushing test. The theoretical values were compared to the experimental results, as reported in Table 6.

Table 6. Wang's model results.

	1 (2mm/min)	2 (5mm/min)	3 (10mm/min)	4 (20mm/min)	5 (50mm/min)
Core final thickness a_f [mm]	21.4	21.4	22.3	21.9	21.8
Theoretical TAE [J]	596	596	587	591	592
Exp. TAE [J]	652	698	707	775	757
% difference	8.6 %	14.6 %	17 %	23.8 %	21.8 %
Theoretical SAE [J/kg]	5495	5495	5411	5448	5458
Exp. SAE [J/kg]	6014	6438	6521	7148	6982

The theoretical evaluation of the absorbed energy suggested by Wang et al. (2016) is in good agreement with the experimental results. The accuracy of the theoretical assessments is higher for the lower displacement rates, since it was used the formulation for quasi-static situations. The high values of the specific absorbed energy, both theoretical and experimental, confirm the possibility to obtain excellent energy absorption performance with a lightweight honeycomb structure.

3.2. Full-scale experimental test

A careful design of a falling object protective structure for earth moving machines needs to consider the influence of dimensions and geometry on impact response. For this reason, it was considered the possibility to investigate the impact features of the selected material also with a full-scale indentation test, in order to gain useful data on the behaviour of the real structure. Such experimental investigation could allow the comparison with the results from the small-scale experiments. The experimental data (Fig. 7) were interpolated with a power law in order to obtain the parameters of the Meyer's contact law. The resulting values are reported in Table 7.

Table 7. Contact law's parameters.

K_i [N/m^n]	677522
n	0,82

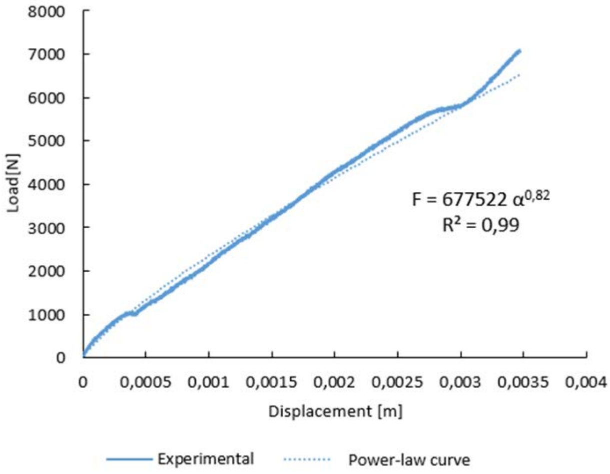


Fig. 7. Load-displacement curve of the full-scale indentation test.

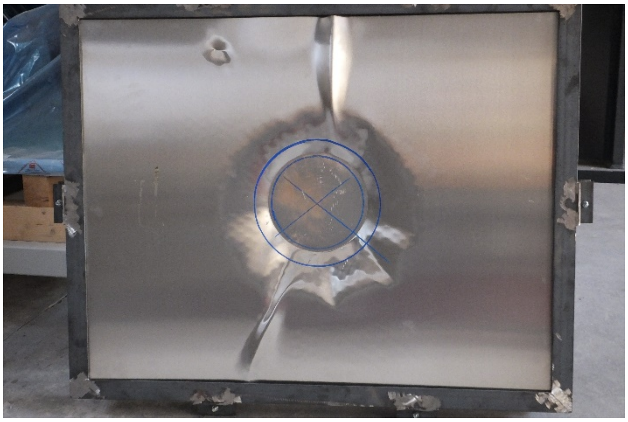


Fig.8. Upper skin after the test.

The obtained values are consistent with the results reported in literature (Hazizan and Cantwell, 2003) and with the values obtained for similar structures with the small-scale impact test. Consequently, the indentation procedure represents a valid option to assess the impact parameters of honeycomb structures. In addition, the full-scale test provides data directly on the real structure, significantly reducing the degree of uncertainty of the small-scale tests. After the load removal, a noteworthy elastic recovery was observed.

The final indentation depth was evaluated with a measuring tape and it resulted equal to 29 mm. During the indentation test, it was observed the propagation of a wrinkle along the transverse section of the panel, which caused a local debonding between the skin and the cells (Fig. 8). The out of plane displacement during the test was negligible.

The wrinkling event was associated to a load decrease (Fig. 7). Nevertheless, the skin didn't fail, confirming the important role played by this element in load distribution and energy absorption.

The overall energy absorbed during the indentation test was calculated to be equal to 770 J. This result confirms the high-level crashworthiness of the tested structure, which makes it ideal for FOPS applications.

The results of the real FOPS are reposted below. The impact object was dropped on the FOPS activating a pneumatic system. A sequence of photograms depicting the FOPS test is reported in Fig. 9.

The inspection of the impacted area revealed that the upper face-sheet did not fail during the impact. Along the middle plane, in the cross direction, the skin formed a fold, due to the wrinkling of the panel, as observed during the indentation test, which allowed also a partial debonding between the core and the skin along the wrinkle, as shown in Fig. 10. The indentation of the upper skin was evaluated with a measuring tape and it resulted equal to 60 mm. Due to the large dimensions of the panel, the out of plane deformation could not be measured with precision. Nevertheless, it was possible to measure the distance between lateral edge of the DLV and the roof, which resulted equal to 210 mm, instead of the initial 220 mm. The negligible out of plane displacement produced by the impact, suggests that a reduction of the distance between the protecting roof and the head operator is feasible, in accordance with the necessary space for the operator.

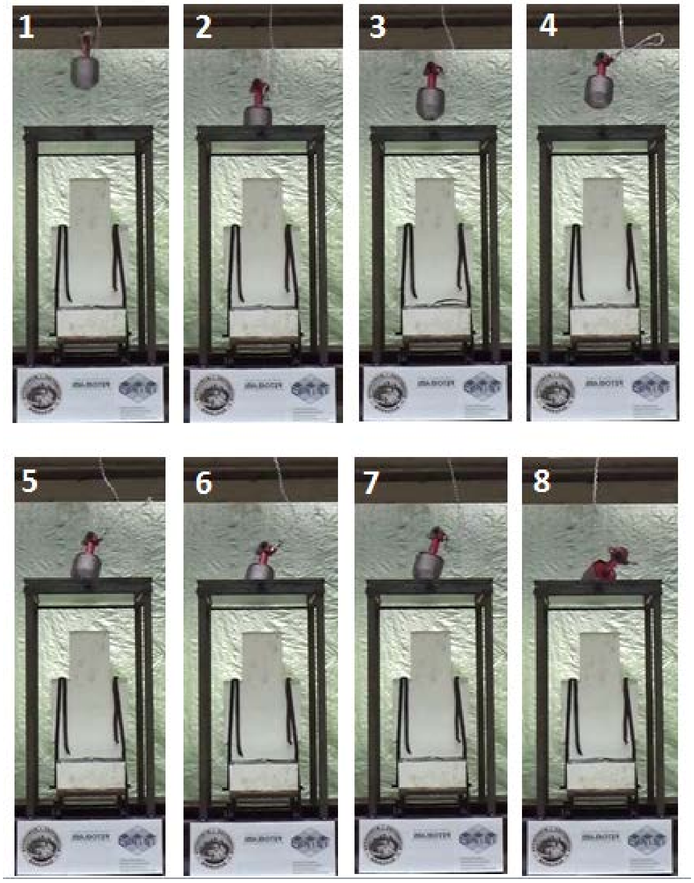


Fig.9. Photogram sequence of the FOPS test.

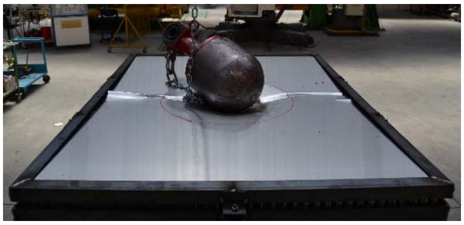


Fig. 10. Impact mass on honeycomb FOPS.

Fig. 11. Protective structure after the impact.

The full-scale tested system was subsequently subjected to radiographic inspection, with the aim of investigating the consequences of the impact event. The measure of the residual core thickness is reported in Fig. 12.

A residual core thickness equal to 22 mm is a promising result, since it is representative of the tested sandwich's capability of absorbing an impact energy superior than that applied. Such result demonstrates that the static evaluation of the core thickness necessary to absorb certain impact energy does not yield reliable information. According to the static procedure, the core thickness required to absorb impact energy of 1365 J should have been equal to 140 mm; on the other hand, the experimental results reveal that a sandwich structure with a core thickness of 82 mm is capable of bearing even higher impact energy. It follows that a static sizing of the energy absorbers systems is inadequate and leads to an oversizing of the structure, since it does not take into account the effect of the skin and the non-linearities involved in the dynamic impact event. As a result, an optimised design of the protective structure could include a reduction of the core thickness, with a subsequent lightening of the FOPS. The X-ray image confirms that the energy absorption driven mechanism is walls' buckling, whereas there is no evidence of cells' failure for shear load.

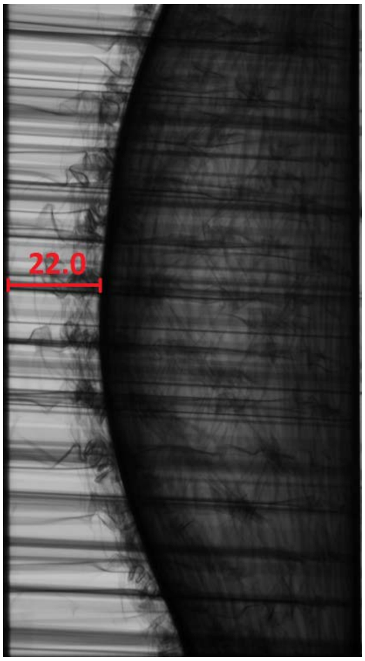


Fig. 12. Core residual thickness of the honeycomb FOPS.

4. CONCLUSIONS

The necessity of developing reliable and lightweight falling object protective structures for earth-moving machines, suggests the use of different materials from those traditionally applied. Aluminum honeycomb sandwich structures are excellent candidate for this role, since they combine exceptional energy absorption capabilities with low density. In addition, they can be designed in order to meet the desired requirements, varying the material of core and skins or the core structure and geometry.

The design and manufacturing of efficient crashworthy structure is strictly dependent on a deep knowledge of the dynamic behaviour of materials and structures. The numerous variables and the highly non-linear behaviour involved in impact response, require extensive experimental activities, to collect data and evidences on the mechanisms subsequent to impact events.

The current study presented an experimental procedure to support the design and the assembly of a new lightweight falling object protective structure for earth moving machines. The first step toward the design of a honeycomb impact absorber was the selection of the appropriate structures, which should conjugate the impact resistance with low weight and cost.

Small-scale experimental tests were conducted to investigate the energy absorption properties of the honeycomb structure. The experimental investigation involved crushing tests and the obtained results were useful for the application of a theoretical model. The combination between experimental results and theoretical formulations, aided the prediction of the impact behaviour of the sandwich structure. The selected material was considered the most suitable to meet the requirements of ISO 3449 for Level I FOPS.

The presented activity opens up new paths for future developments in energy-absorbing elements, both for earth moving machines and other purposes. One of the possible fields of investigation is represented by the analysis of honeycomb sandwiches, in particular to optimise the design according to the desired requirements. High-performance honeycomb structures may allow a successful application of lightweight systems also for Level II FOPS.

In addition, a crucial issue worth assessing is the theoretical formulation of the impact response of sandwich structures: reliable analytical approaches for energy absorbers' design may improve the performance of the protective structures against impact events and result in significant cost-saving.

Future tests are planned to optimise the designed FOPS and to verify its performance according to ISO 3471 requirements for rollover protection structure (ROPS) system.

Acknowledgements

The research reported in this paper was conducted with the facilities of the Research Project PONa3_00422 "CERISI" ("Research and Innovation Centre of Excellence for Structure and Infrastructure of Large Dimensions") and the facilities of IMAMOTER – C.N.R. – Institute for Agricultural and Earthmoving Machinery of the Italian National Research Council.

References

Akatay, A., Bora, M. Ö., Çoban, O., Fidan, S., Tuna, V., 2015. The influence of low velocity repeated impacts on residual compressive properties of honeycomb sandwich structures. Composite Structures, 125, 425–433.

Bonanno, A., 2008. Application of innovative materials in operator's protective structures for agricultural and earth moving machinery. 16th International Conference of the International Society for Terrain-Vehicle Systems. Turin, Italy.

Budny, E., Chłosta, M., Meyer, H. J., Skibniewski, M. J., 2009. Construction machinery. In Springer Handbook of Mechanical Engineering. Springer Berlin Heidelberg, pp. 1149-1266.

Chun-Ho, J. and Jin, Y. C., 2006. EP1728689A1.

Crupi, V., Epasto, G., Guglielmino, E., Mozafari, H., Najafian, S., 2014. Computed tomography-based reconstruction and finite element modelling of honeycomb sandwiches under low-velocity impacts. Journal of Sandwich Structures & Materials, 16(4), 377-397.

Crupi, V., Epasto, G., Guglielmino, E., 2016a. Internal damage investigation of composites subjected to low velocity impact. Experimental Techniques, 50, 555 - 568.

Crupi, V., Kara, E., Epasto, G., Guglielmino, E., Aykul, H., 2016b. Theoretical and experimental analysis for the impact response of glass fibre reinforced aluminium honeycomb sandwiches. Journal of Sandwich Structures & Materials, First Published online February 2016, doi: 10.1177/1099636216629375.

Feraboli, P., Deleo, F., Wade, B., Rassaian, M., Higgins M., et al., 2010. Predictive modeling of an energy-absorbing sandwich structural concept using the building block approach. Composites Part A: Applied Science and Manufacturing, 41(6), 774–786.

Flores-Johnson, E. A. and Li, Q. M., 2011. Experimental study of the indentation of sandwich panels with carbon fibre-reinforced polymer face sheets and polymeric foam core. Composites Part B: Engineering, 42, 1212–1219.

Hazizan, A. and Cantwell, W. J., 2003. The low velocity impact response of an aluminium honeycomb sandwich structure .Composites Part B: Engineering, 34, 679–687.

INAIL, 2003. Riduzione del rischio nelle attività di scavo.

ISO, 2005. International Standard ISO 3449, vol. 2005.

Ivañez, I., Fernandez-Cañadas, L. M., Sanchez-Saez, S., 2017. Compressive deformation and energy-absorption capability of aluminium honeycomb core. Composite Structures, 174, 123–133.

Karliński, J., Rusiński, E., Smolnicki, T., 2008. Protective structures for construction and mining machine operators. Automation in Construction, 17(3), 232–244.

Lane, K. V., Yasuda, N. K., Lo, M. E., Mather, E. R., Shih, F. J., 2016. Experimental Characterization of Low Velocity Impact Energy Dissipation in Sandwich Composites with Porous Cores with Tailored Structure and Morphology. ASME 2016 International Mechanical Engineering Congress and Exposition, Volume 14: Emerging Technologies; Materials: Genetics to Structures; Safety Engineering and Risk Analysis. Phoenix, Arizona, USA. Paper No. IMECE2016-67901.

Merli, G., 2016. Patent EP2763873B1.

Mozafari, H., Molatefi, H., Crupi, V., Epasto, G., Guglielmino, E., 2015a. In plane compressive response and crushing of foam filled aluminium honeycombs. Journal of Composite Materials, 49(26), 3215-3228.

Mozafari, H., Khatami, S., Molatefi, H., 2015b. Out of plane crushing and local stiffness determination of proposed foam filled sandwich panel for Korean Tilting Train eXpress – Numerical study. Materials & Design, 66, 400–411.

Pollard, D., Ward, C., Herrmann, G., Etches, J., 2017. The manufacture of honeycomb cores using Fused Deposition Modeling. Advanced Manufacturing: Polymer & Composites Science, 340, 22–32.

Raju, K. S., Smith, B. L., Tomblin, J. S., Liew, K. H., Guarddon, J. C., 2008. Impact damage resistance and tolerance of honeycomb core sandwich panels. Journal of Composite Materials, 42, 385–412.

Shin, K. B., Lee, J. Y., Cho, S. H., 2008. An experimental study of low-velocity impact responses of sandwich panels for Korean low floor bus. Composite Structures, 84, 228–240.

Wang, Z., Lu, Z., Tian, H., Yao, S., Zhou, W., 2016. Theoretical assessment methodology on axial compressed hexagonal honeycomb’s energy absorption capability. Mechanics of Advanced Materials and Structures, 23(5), 503–512.

Yantek, D., Toohig, T., Meyers, K., 1999. Patent US6322133B1.

Zhu, S. and Chai, G. B., 2013. Damage and failure mode maps of composite sandwich panel subjected to quasi-static indentation and low velocity impact. Composite Structures, 101, 204–214.