GLOBAL RESIDUAL DAMAGE EVALUATION OF IMPACTED SANDWICH PANELS AT LOW ENERGY

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Abstract

This paper focuses on the behavior of impact damaged sandwich panels at low energy.

The aim of the work is to assess the residual mechanical properties of a helicopter main cabin panel after the impact and their correlation to the percentage of global damage.

Finite element analysis was used to solve the problem. Due to the contact boundary condition, large displacements and plasticity, the dynamic impact problem treated here presents a nonlinear numerical character, which has to be taken into account in order to choose an appropriate solution technique.

The numerical procedure applied consists of a local evaluation of damage (geometry and elastic constant variation) produced by a semi-spherical impactor. To achieve this, a continuum mechanics approach of a sandwich structure detailed model was implemented. Once this analysis was performed, new equivalent mechanical properties corresponding to the damaged area were utilized in the construction of different global models with increasing percentage of damage.

1 Introduction

Nowadays honeycomb sandwiches have many applications as structural components owing to their weight-saving characteristics.

Sandwich construction components are external skin, core and core-to-skin bonding materials. The separation of skins by the core increases the moment of inertia of the panel with a small increase in weight, producing an efficient high stiffness structure to resist bending and buckling loads. They also have good impact energy absorption and acoustical-thermal insulation characteristics and low manufacturing cost.

These properties make this type of structural configuration ideal for constructing aircraft, satellites, antenna reflectors, portable structures, car safety devices, etc. In this work, the main cabin panel of a helicopter has been analyzed. Despite the great advantages of sandwich structures, a serious obstacle to a wider use in the industrial applications is the their high sensitivity to localized impact loads [1], which means low damage resistance and consequently a significant degradation of the principal structural properties which encourage such large diffusion. In particular, low velocity impact can be dangerous. The causes of this kind of impacts are maintenance and operative conditions, such as tool drops, routine handling, debris swept up during aircraft taxiing maneuvers or even hail stones during service. Low velocity impact is considered potentially dangerous mainly because the damage might be left undetected. In many situations, the level of impact at which visible damage is formed is much higher than the level at which substantial loss of residual properties occurs. Thus, analytical or numerical prediction of sandwich behavior under these conditions [2] is considered of interest for design purposes and maintenance. However, as outlined in this paper, these predictions have to be checked using experimental results due to the diversity of factors that affect this kind of analysis. Most of the reported experimental research on the impact on sandwich plates was conducted to determine the effectiveness of different core materials and various core thickness [3], to study the energy absorbing mechanisms such as delamination, matrix and fiber cracks [4] and how these failures can reduce the compressive strength, and to predict the residual properties after the impact [5, 6]. Moreover, due to the impossibility of avoiding impacts and the variety of applications and materials employed in manufacturing the panels, further studies need to be conducted regarding the response of these structural components under established impact conditions. Keeping in mind these concepts, the present study attempts to investigate the behavior of impact damaged sandwich panels at low energy, to estimate the extent and the distribution of resultant damage, to find a correlation between impact energy, damage geometry and material residual properties.

2 Energy absorbing mechanisms

Composites exhibit different modes to absorb the kinetic energy from the impactor depending on the configuration and the materials employed such as matrix cracking, fiber fracture, delamination and fiber/matrix debonding. Sandwich structures present a further way to absorb a great amount of energy via the core. The core is typically composed of honeycomb; in this case the buckling of the cell walls will provide an efficient mechanism, especially if the honeycomb consists of aluminium, through the formation of plastic hinges and the subsequent folding of the material [7, 8]. But also the use of foam cores is a very suitable method to absorb energy through the crack of the foam, approximately parallel to the facesheets [9].

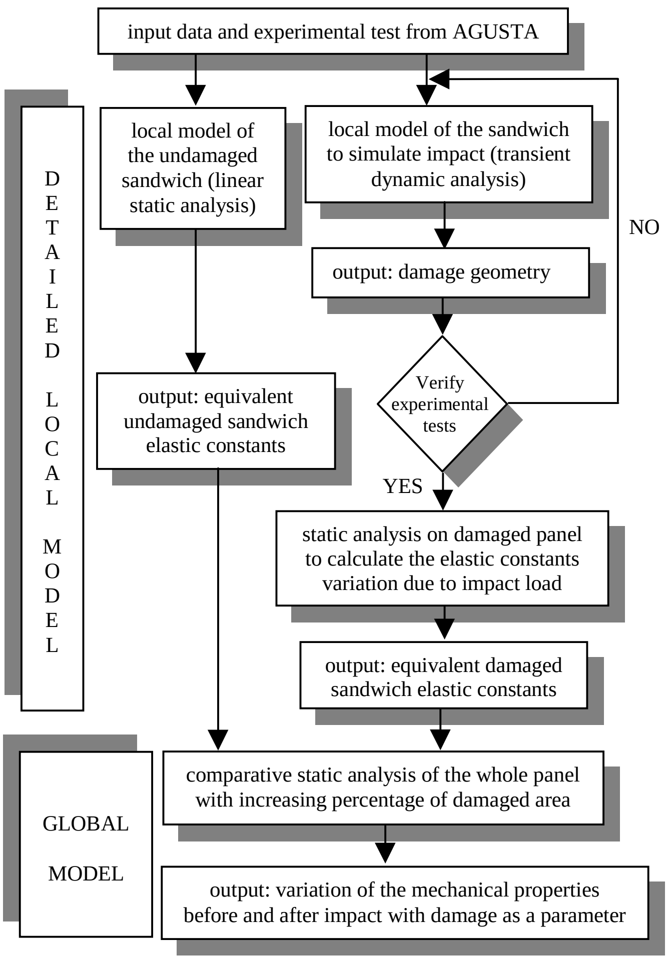
3 Preliminary experimental test

AGUSTA performed some preliminary experimental tests on different sandwich panels of a helicopter main cabin, utilizing a drop weight machine, in order to assess the correlation between the impact energy and the resulting damage geometry (damaged area and indentation depth), to establish the minimum energy level not economic to repair and to define an impact energy level which do not reduce the strength below the required value. The criterion applied is the Barely Visible Impact Damage (B.V.I.D.) which considers only damages induced by impacts which cause indentation of 0.3-0.4 mm in the composite part. The panel that exhibited the best behavior concerning the impact damage has been represented numerically to carry on further investigations. Numerical data were compared with the experimental tests and the analytical formulation provided by Gibson [10].

4 The finite element analysis

The numerical results have been obtained using the structural analysis program MARC. In order to simulate the mechanical behavior of impacted sandwich panels, and to study the consequent degradation of their properties, the problem has been subdivided in two different analyses, as shown in the figure below.

In the former, a three dimensional detailed



model of a small portion of the sandwich has been implemented, representing the core through the cellular structure of the honeycomb, in order to be as close as possible to reality. The investigations of this model have been very useful in evaluating the equivalent elastic constants variation due to impact phenomenon which will represent the sandwich in the successive analysis.

In the latter analysis, the whole panel has been reproduced, always running a 3-D finite element model, utilizing an equivalent orthotropic material whose properties have been calculated in the previous study. This choice is determined by the excessive number of elements that would have been introduced to obtain the same accuracy of the previous model and which would have made the computational analysis extremely heavy. This study is important to assess the global reduction of the mechanical properties of the whole panel after multiple impact damages occur.

4.1 Sandwich equivalent properties

In order to create a representative model of whole panel is absolutely necessary to know the elasto-plastic characteristics of the orthotropic material which will represent the sandwich: that is the values of the nine linearly independent elastic constants and the plastic collapse strength. This research has to be carried out both for damaged and undamaged sandwiches.

Unfortunately the only available data in literature are those provided by Hexcel [11] referred to honeycomb. They are the flatwise compressive modulus, in the honeycomb thickness direction "T", and the two shear moduli in the characteristic directions "L" (the ribbon direction) and "W" (orthogonal to ribbon), the specific strength and the crushing strength.

Missing data have been obtained through the finite element model of the undamaged sandwich described above and through the bare honeycomb [12]. Moreover, analytical formulation for the calculation of honeycomb equivalent elastic constants, based on single cell analysis, has been verified [10].

For the choice of the model dimensions [13] the requirements of ASTM test methods have been followed. The equivalent properties have been determined through a linear elastic analysis, fixing one face of the specimen and loading the opposite end with imposed displacements. For instance the Young modulus in x direction is:

$$E_{xx} = \frac{N_{xx} l_x}{A_x u} \qquad (1)$$

Where N_{xx} is the reaction force (the sum of the single forces applied in the nodes) caused by imposed displacement u at $x=l_x$, l_x is the sandwich length in the x direction, and A_x is the sandwich projected area on a plane with normal along the x direction. The remaining properties are reckoned in a similar manner.

The sandwich analyzed here is composed of aluminium both the facesheet and the core: the core is 10 mm high, with 0.001 inch foil thickness and 3/16 inch cell diameter; the facesheets are 0.3 mm thick.

The aluminium properties are summarized below.

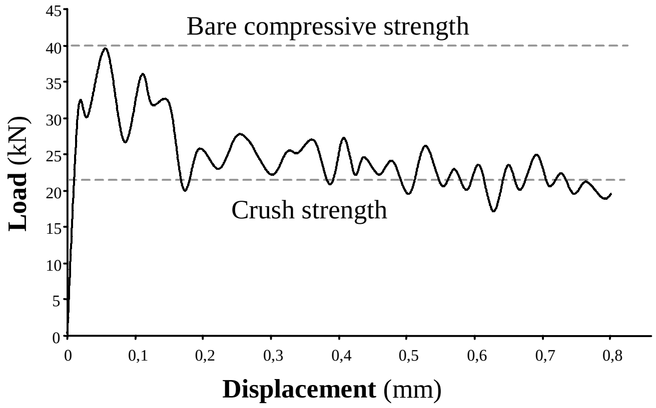
	Type	**E** (GPa)	**ν**	**ρ** (g/cm^3)	**σ$_Y$** (MPa)
Skin	Al 2024T3	72.4	0.33	2.77	345
Core	Al 5052	69.3	0.33	2.68	255

The numerical model (46,63 x 47,51 mm^2) consisted of 1516 nodes and 2732 elements, 1364 to represent the core and 1368 (342x2) to represent the facesheets. The core height has been subdivided in four parts and the cell walls thickness have been reproduced, as in real manufacturing, with double cell walls thickness in the ribbon direction; this asymmetry leads to anisotropy also in in-plane properties, as in reality occurs. Symmetry properties have been utilized to reduce the computational cost.

Elements employed in the analysis are 3-node triangular thick shells for the facesheets and 4- node bilinear thin shells for the core.

The standard test ASTM C 365-57, which has been reproduced numerically, gives all the information about sandwich compressive behavior. The data are all included in the load-displacement curve and the typical crushing of the honeycomb core has been verified.

The results of this analysis are the values



of the equivalent elastic constants for the honeycomb core and undamaged sandwich (last column), shown below.

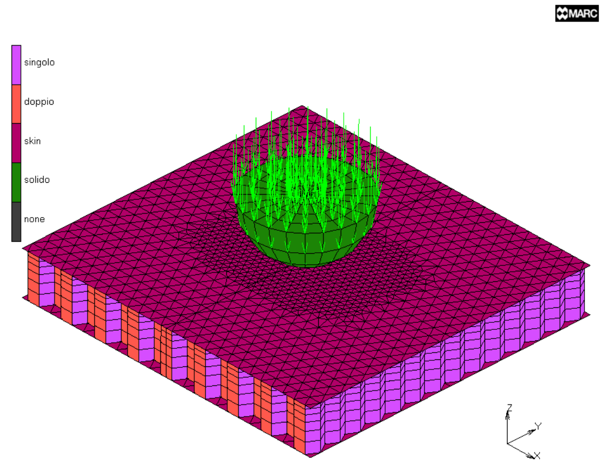
		SI	Hexcel	Gibson	Marc core	Marc sandwich
E	xx	MPa	-	0.126	0.156	4171
	yy		-	0.126	0.153	4103
	zz		517.10	985.60	1074	1090
G	xy	MPa	-	0.053	0.059	1070
	yz		151.68	138.67	141.2	149.7
	zx		310.26	231.11	210.5	230.6
ν	xy		-	1	0.98	0.33
	yz		-	0	0	0.001
	zx		-	0.33	0.33	0.33
S_B		kPa	1999	-	1815	-
S_C		kPa	896	684	827	-

It can be seen from the table that in-plane properties of the sandwich are mainly controlled by the facesheets while the flatwise (through the thickness) properties are controlled by the core.

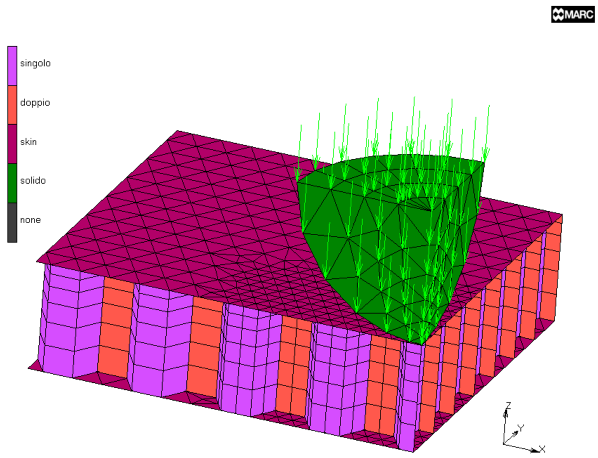
The discrepancy in some values, for example in the compressive Young modulus E_{zz}, depends on the core density. More specifically, the uncertainties about such thin aluminum foils which constitute honeycomb, cannot be perfectly checked in the experimental specimens.

4.2 Impact modeling

The finite element model employed in the impact analysis is a three dimensional one constituted of 2844 elements and 1737 nodes.



Applying the geometry (sandwich and semi-spherical impactor) and boundary conditions symmetry properties, the whole model can be simplified to a quarter, reducing the physical dimensions and, using the same number of elements, improving the accuracy.



Due to the small dimension of FEM model (33,34 x 35,75 mm^2), the boundary conditions applied have not to stiffen too much the structure and permit the portion of the panel to bend; thus, only displacements are neglected on the boundaries.

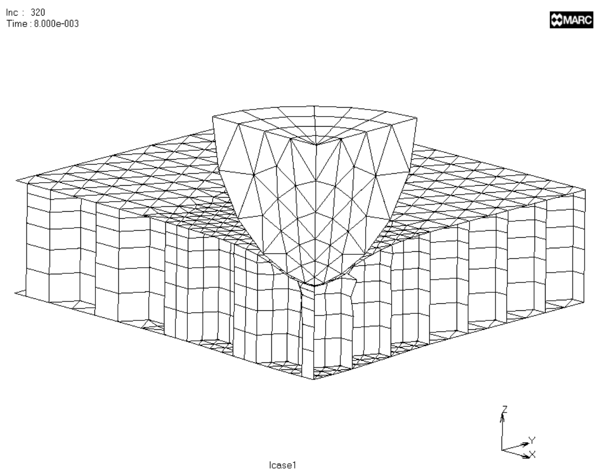
The impactor has been represented as a semi-sphere with 25 mm diameter, with the properties of steel except for the density. To respect the equivalent energetic principle the 4 J impact has been simulated with an initial velocity of 3.046 m/s and a fictitious density of 0.21 g/mm^3, so the total mass of the impactor will be 862 g, equivalent to the impactor used during the experimental tests.

The sandwich has been represented with the same kind of elements as in the previous analysis, but with a different mesh (more accurate in the impact area), while the impactor has been reproduced with 204 6-node brick elements.

As stated before, three sources of nonlinearity are present in this problem: boundary condition (contact), geometry (large displacements) and material (plasticity). The Newton-Raphson procedure has been implemented to solve nonlinearities and the Von Mises material model was employed to represent plasticity. The transient dynamic analysis has been computed through the implicit direct integration operator Newmark-beta and damping was added to simulate the dissipation of energy in the structural system.

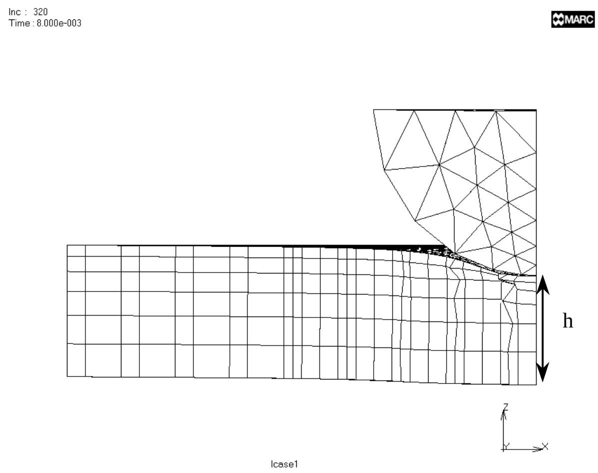
The total physical period analyzed is 8 msec (320 steps) which is the time necessary to exhaust the impact phenomenon and to bring the impactor and panel to a complete stop.

The deformed model is shown below.



The indentation depth has been determined by measuring the core height, before and after the impact, in the side view of the panel.

The damaged area, instead, has been determined measuring the distance between the center of the panel from the point in which the indentation depth does not meet the B.V.I.D. requirements (in this case damages with depth less than 0.5 mm are not considered).

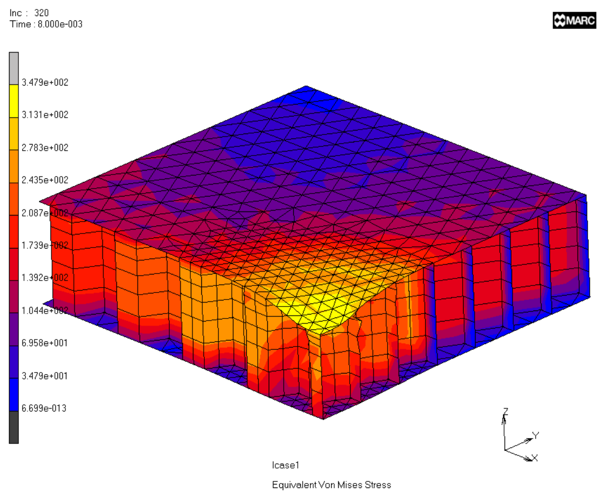


To fully understand the quality of numerical results a comparison with experimental tests is necessary. The indentation depth h_d and damaged area D_d are shown in the tables below.

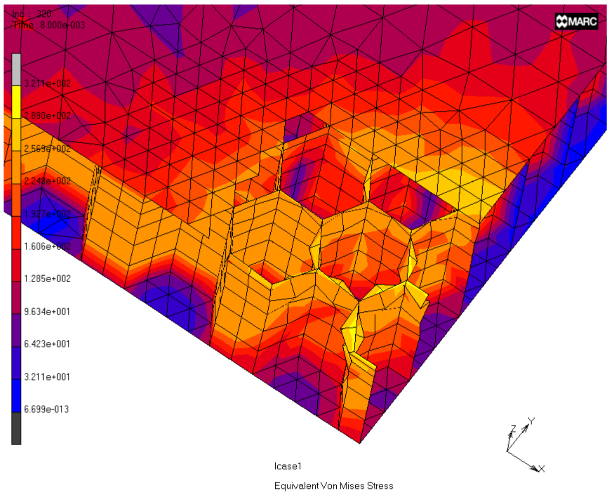
Test n°	$\mathbf{H_d}$ (mm)		
	AGUSTA	**MARC**	
1	1.6		(+8.12 %)
2	1.6	1.73	(+8.12 %)
3	1.8		(–3.88 %)
Mean value	1.67	1.73	(+3.59 %)

Test n°	$\mathbf{D_d}$ (mm)		
	AGUSTA	**MARC**	
1	21.7		(+0.46 %)
2	21.7	21.8	(+0.46 %)
3	21.9		(–0.46 %)
Mean value	21.77	21.8	(+0.15 %)

The following figures show the damage caused by a 4 J impact on the sandwich panel. It can be noted that both part of the superior facesheet and the core have reached the yield strength and behave plastically.



The effects of the impact are mainly localized in the honeycomb core, where the plastic buckling of the cell walls closest to the impact area is well visible.



4.3 Equivalent damaged sandwich properties

By checking the numerical results with the experimental test data, we found the model gave good representation of reality. The next step was to evaluate the equivalent damaged sandwich properties.

As shown in the next column table, the equivalent constants subjected to more relevant modifications are the compressive modulus E_{zz} and shear modulus G_{zx} ; the other values remain substantially the same.

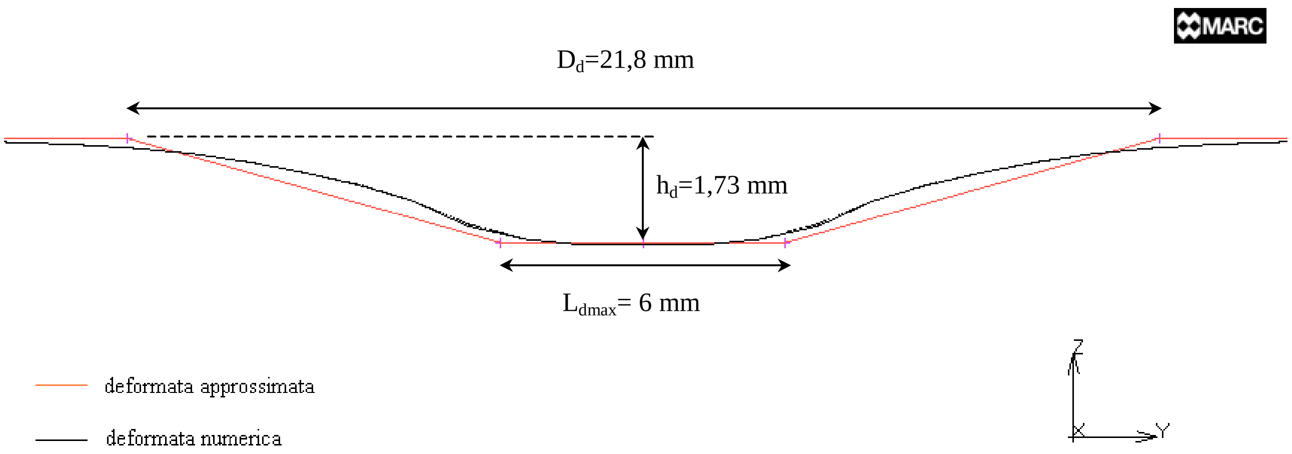
This leads to the evident conclusion, well visible in the damage geometry, that the sandwich component which absorbs the impact energy is the honeycomb core. The facesheets deform plastically, moreover in a more limited area, but they do not lose their capability to support load or their stiffness characteristics, which depend, more than anything else, on the properties of their constituent material. Honeycomb, instead, has in its particular geometric configuration, most of the peculiarity of its structural behavior, and if this geometry changes, it loses some of its properties which mark it from other materials; basically the characteristics of rigidity to out-of-cell-plane loads which is why is largely employed as core, in design and manufacturing of sandwich structures.

Values in MPa (except ν_{ij})	**Undamaged sandwich**	**Damaged sandwich**	**Percentual variation**
E_{xx}	4171	4124	-1.13%
E_{yy}	4103	4039	-1.56%
E_{zz}	1090	825.13	-24.30%
ν_{xy}	0.33	0.33	-0.00%
ν_{yz}	0.001	0.001	-0.00%
ν_{zx}	0.33	0.33	-0.00%
G_{xy}	1070	1044	-2.43%
G_{zy}	149.7	147.9	-1.20%
G_{zx}	230.6	214.5	-6.98%

4.4 Global modeling

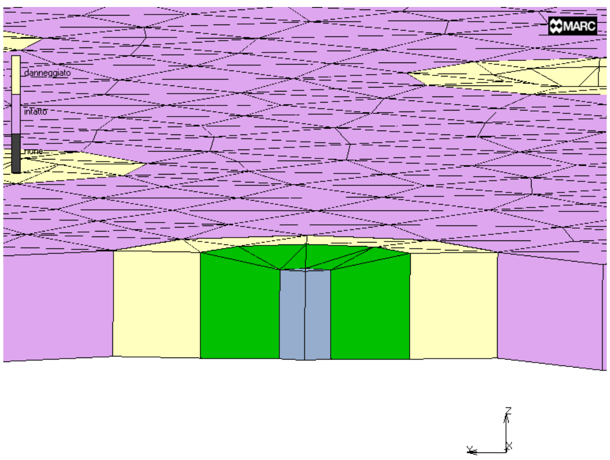
The results previously presented do not refer to any particular panel configuration and they can be utilized for any application that involve the same sandwich type.

The panel employed for the global analysis has the following dimensions: l_x=956 mm, l_y=387 mm, l_z=10.9 mm and the whole sandwich (facesheets and core) has been modeled as a 3-D orthotropic material with just one element through the thickness. Four different models have been implemented with an increasing number of 4 J impacts (0, 20, 40 and 60 impacts).



Modeling the impacted area both the damaged sandwich elastic moduli variation and the geometric deformation of sandwich have been taken into account, thus damage has been represented either geometrically, through the reduction of the thickness in the impacted area, or in the different elastic properties of damaged material.

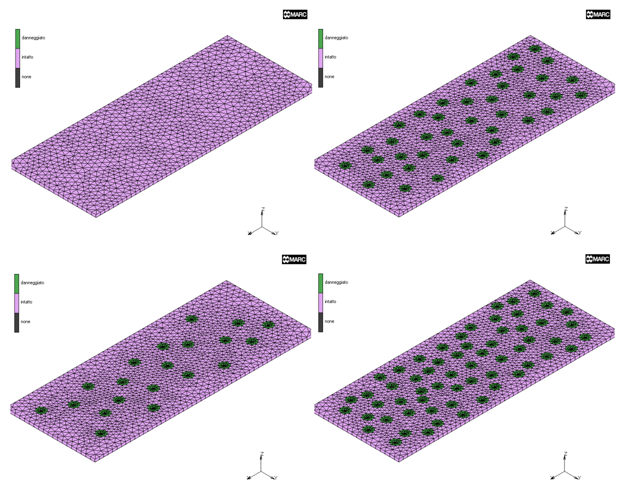
The damage geometry has been approximated through a linearization of the numerical indentation shape.



The detail of the three areas in which damage has been schematically represented. can be observed in the figure above

The central area corresponds to the maximum damage depth, a green ring follows that corresponds to geometric damage. Eventually an outer region indicates the border of the damaged material, that is the sandwich whose equivalent properties are estimated with the previous sandwich detailed model. Thus the damaged area is wider than the simple geometric indentation.

The four global models are shown in the figure below.



For all models the impact distribution is random. This choice was made by considering the literature [5] and considering that low velocity impact is a localized phenomenon.

The elements utilized were all 6-node bricks with different material properties.

Models	geometric damage area	material damage area	n° of elements
Undamaged	0%	0%	1962
20 impacts	2%	6.8%	3724
40 impacts	4%	13.6%	4592
60 impacts	6%	20.4%	5244

Several linear static analyses were performed to evaluate in-plane, bending, compressive stiffness and out-of-plane shear rigidity variation due to increasing number of impacts.

The results obtained are summarized in the following tables and show good agreement with previous findings.

Models	In-plane shear load		Out of plane load	
	G_{xy}	σ_{max}	k	σ_{max}
20 impacts	0.35%	0.21%	-1.10%	12.48%
40 impacts	0.60%	0.35%	-1.73%	34.34%
60 impacts	0.85%	0.52%	-2.63%	41.80%

The damaged area variation doesn't provoke any substantial loss in the in-plane shear rigidity because this load is supported by the facesheets.

Concerning the out of plane load, the bending rigidity k suffers a slight weakening. However, the whole structure is more heavily loaded resulting in a strong increase of the maximum stress. Since the facesheets work alternatively in tension and compression, supporting the bending load, great variations were not expected but the reduction of the thickness in the impacted area decreases the local moment of inertia of the structure influencing the distribution of load.

Models	G_{zx}	E_{zz}
20 impacts	-5.1%	-14.19%
40 impacts	-6.3%	-18.00%
60 impacts	-8.6%	-19.45%

For the out-of-plane shear rigidity and the compressive modulus the progressive growth of damage is reflected in the progressive and significant loss of residual stiffness characteristics. This is expected, because these properties depend on the core and its integrity.

In all the analyses a stress concentration effect around the damaged area was found.

5 Concluding Remarks

In consequence of impact load, honeycomb shows a load peak, followed by a series of oscillatory crush loads with a nearly constant mean value, which corresponds to the onset of progressive plastic buckling and subsequent plastic folding of the cell walls. Such plastic deformation mechanisms have been examined in detail and they have been found again in the numerical analysis.

The previously published theoretical models underestimate damage provoked by impact, due probably to oversimplification of either the elastic deformation mechanism, regarding the mechanical constants determination, or of the cellular structure plastic buckling, concerning the compressive characteristic calculation.

All examined honeycomb types show a negligible elastic spring-back compared to plastic deformation, which therefore is the prevalent deformation mechanism.

The deformation mechanism of a sandwich structure, which enables absorption of impact energy, consists of the core crushing and the bending and stretching of the superior facesheet. The inferior facesheet remains virtually undeformed.

The best way to optimize sandwich to resist impact and to minimize damage, is to involve the largest possible sandwich portion, both for facesheets and core, to induce a large and global plastic deformation, which will absorb the greatest amount of energy. On the contrary highly localized damages and skin punctures have to be avoided.

The degradation of the sandwich equivalent mechanical properties have been verified only for properties that depend on the honeycomb core and only in certain directions; the equivalent constants which undergo greater loss are the compressive modulus E_{zz} and shear modulus G_{zx}; the other values remain substantially the same. As stated before, this leads to the conclusion that the sandwich component which absorbs the impact energy is the honeycomb core. Its particular cellular structure makes it capable to absorb a great amount of energy but, at the same time, makes it fragile and ready to lose all its advantageous properties.

In the stiffness analysis of the whole panel with damaged area as a parameter, the same effects as the local investigation have been found. When loaded with in-plane shear load, the panel does not lose its stiffness characteristics because this load is supported by the facesheets, while both compressive and out-of-plane shear load cause significant rigidity variations. Bending load does not cause stiffness variation but there is an increase in the maximum internal stress.

The finite element model implemented, gives results concerning the impact numerical simulation that are comparable to those obtained in the experimental tests (maximum deviation is 8% for indentation depth and 1% for damaged area diameter).

Regarding successive models created to evaluate residual mechanical properties, the obtained results match the effective plastic behavior of the examined materials however an experimental validation is needed.

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