Micromechanics analysis applied to the modelling of aluminium honeycomb and EPS foam composites

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Summary:

A 3D Finite Element model of an innovative composite material, configured as a layer of expanded aluminium honeycomb placed on top of a layer of expanded polystyrene foam, has been developed and validated against experimental data obtained from quasi-static tests.

Ls-Prepost was used to generate the model. Ls-Dyna was used to simulate the behaviour of this material under compressive loads. The objective was to reproduce deformation mechanisms and to compare the numerical load-displacement curves with those obtained from experiments. The loading direction was chosen perpendicular to the plane of the alignment of the honeycomb cell walls. Particular emphasis was given to the contact between the aluminium honeycomb cell walls and the surface of the foam.

Because of the periodicity of the geometrical and material properties, these composites were modelled as a unit cell according to the principles of the micromechanics analysis of periodic structures. In addition, to further reduce computational costs, the inner symmetries of the unit cell were exploited to generate and validate a smaller unit cell model (here called *sub-cell*).

The results obtained from analysis of both the unit cell and the sub-cell were compared with experimental data. Numerical results showed good accuracy even when the smaller unit cell was used.

Keywords:

Hybrid materials, unit cell, boundary conditions, quasi-static analysis.

1 Introduction

The energy absorption provided by motorbike helmets during an impact is of crucial importance for the safety of the rider during an accident. Because of its capabilities to provide a multidirectional protection against impact, light weight and relatively low costs of production, EPS foams are the preferred energy absorbing material available in the market. Nonetheless, motorbike riders are still among the most vulnerable of the road users. The improvement in helmet design could save up to 1000 lives per year across the European Union, as stated in the COST 327 Action. One way to achieve this aim is the use of innovative materials capable of superior energy absorption properties.

Previous studies from Kavi *et al*. (2004) showed that aluminium tubes combined with polymeric or metallic foams present higher energy absorption levels than the sum of those of the foam and the tube considered alone, due to an interaction effect between the two materials. Similar results were reported from other studies by Hannsenn *et al*. (2000), Seitzberger *et al*. (1997) and Hall *et al*. (2001) on hybrid structures in which aluminium tubes and polymeric foams were combined.

In this investigation, new materials (here called *hybrid*) for helmet liners, made by the combination of aluminium honeycombs and expanded polystyrene foams, are being studied. Because of the periodicity of the geometrical and material properties offered by this particular material configuration, micromechanics analysis of periodic structures is being applied. This technique has grown in popularity in the past few years, due to the simplicity with which is possible to obtain homogenized material properties of complex composite structures (Galvanetto et al., 1998; Whitcomb et al. 1999, Xiaodong et al., 2003). It is mainly based on the study of the mechanical response of a small representative volume (*unit cell*), which contains all characteristics of the composite material. Although there is no specific definition of unit cell, it is common to assume it as the smallest volume with which is possible to reconstruct the whole material by translations of the unit cell itself.

This paper describes the model of a unit cell representative of hybrids. This model has been used to reproduce the mechanical response and the deformation mechanisms of hybrids under quasi-static compression.

2 Approach

General techniques for exploiting periodicity and symmetries in micromechanics of composite materials have been applied to find the smallest unit cell to be used as model for the hybrids. To reduce computational costs, the inner symmetries of the unit cell chosen were furterly exploited to find an even smaller region to be used for the analyses. Fig. 1a shows a top view of the unit cell and the subcell chosen for this investigation, according to previous studies on the modelling of honeycomb panels as small representative volumes (Yamashita et al., 2005; Asadi et al., 2006).

The couplings of two different Expanded Polystyrene foam densities (40 and 50 kg/m^3) with the expanded aluminium honeycomb 5.2 Al 3003, kindly provided by Dainese s.p.a and Cellbond Composites, were analysed numerically.

A rigid stonewall with prescribed motion was used to simulate a quasi-static compressive loading. A second rigid stonewall was used as base for the hybrid model. Forces recorded from the fixed rigid wall were plotted against the vertical displacement of the moving rigid wall, and compared with those obtained from experimental tests

2.1 Mesh generation

The honeycomb model was generated using 13500 Belytschko-Tsai shell elements, while the foam was modelled using 1116 tetrahedral constant stress solid elements. Due to the complex mechanical behaviour of honeycombs, three through integration points were defined for each of the shell elements. The dimensions of the honeycomb elements were chosen following the guidelines provided by Cellbond Composites. The thickness of the shell elements was chosen equal to the actual thickness of the aluminium foils used for the manufacturing of the honeycombs used in this investigation (t = 75 micron). The dimensions of the solid elements used for the foam were chosen referring to a study conducted at Imperial College on the influence of the element dimensions in the numerical analysis of EPS foams (Cernicchi et al., 2008). To simulate the penetration of the honeycomb in the foam, phenomenon observed during experiments, the foam elements aligned with the honeycomb cell walls were bisected by planes coincident with the honeycomb cell walls themselves, up to one third of the total thickness of the foam model. As result of this operation, couples of unmerged nodes occupying the same position were generated, as highlighted by small circles in Fig. 1b

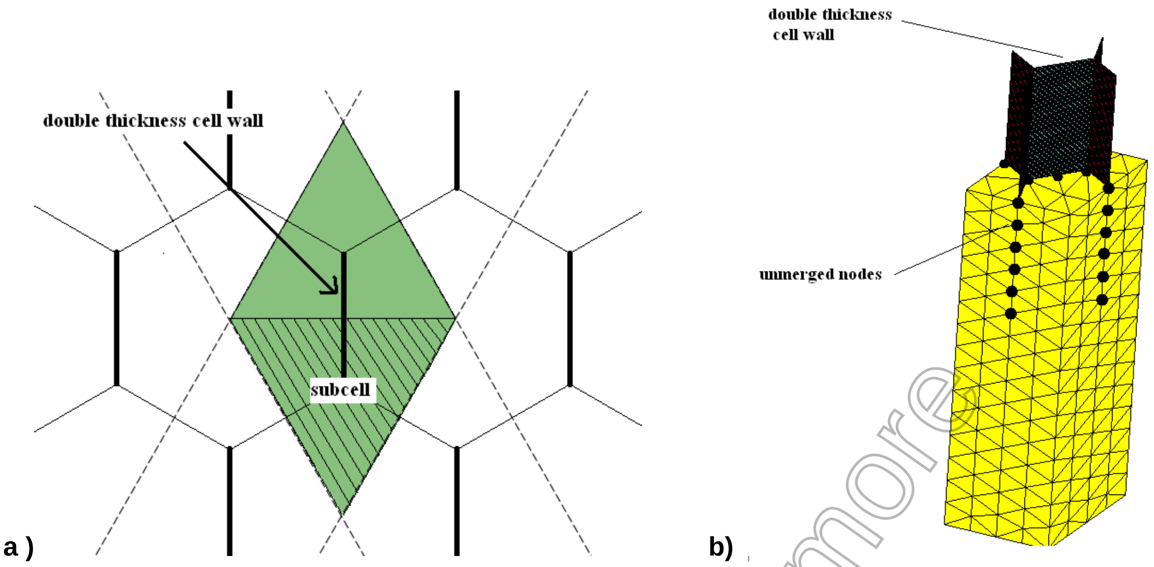

Figure 1 – Hybrid unit cell and subcell models

In this way, when the contact occurred, the honeycomb cell walls pushed the nodes away, and then sled inside the foam model.

2.1.1 Pre-crush of the honeycomb

The honeycombs used for the experiments were pre-crushed using a quasi-static standard compressive machine. The aim of this work was to facilitate the plastic collapse of the honeycomb layer during the compression of the hybrids. This condition was reproduced in the model as a distortion of the honeycomb geometry. In particular, a preliminary numerical compression was applied to the honeycomb unit cell alone. The force history was recorded and the deformation of the honeycomb was observed. In the post processing phase, it was generated an output file containing the honeycomb node coordinates at the stage of the deformation in which the honeycomb began collapsing plastically. This file was then introduced in the hybrid model as initial geometry, so that the honeycomb presented the desired pre-crushing effect. Fig.2 shows the result of this operation.

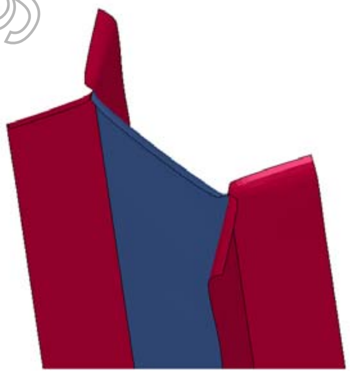

Figure 2: Pre-crush effect

2.2 Contact

Due to the interaction between very thin shell elements and thick solid elements, the correct choice of the contact logics was crucial for the correct reproduction of the mechanical behaviour of hybrids. Four contact algorithms were used in this model. The keyword AUTOMATIC_NODES_TO_SURFACE was used to take in to account the first contact between the edges of the honeycomb cell walls and the surface of the foam. Preliminary analysis performed without this contact card showed a sudden failure of the contact when honeycomb edges touched the foams surface. The contact logic AUTOMATIC_SURFACE_TO_SURFACE was used to model the sliding of the honeycomb inside the foam. Some difficulties arose from the consistent difference between the element dimensions and stiffness, which leaded to unrealistic behaviours. To overcome this problem, SOFT = 1 penalty option was activated for all of the contact logics mentioned and the soft penalty scaling factor was set equal to 0.1.

The contact logic AUTOMATIC_SINGLE_SURFACE was used to correctly reproduce the progressive folding of the honeycomb, without incurring in the self-penetration of the cell walls.

The INTERIOR contact algorithm was used to avoid self-penetration (and so negative volumes in the model) of the foam elements, when high local deformations occurred.

2.3 Configuration of quasi-static experiments

The hybrids tested were squared prismatic samples with 50 x 50 mm area and 40 mm total height. Three different thickness combinations of EPS foams and aluminium honeycombs, reported in Table 1 as hybrid 1, 2 and 3, were studied. The honeycombs used to build the hybrids were aluminium honeycombs produced at Cellbond, with relative density 80 kg/m3, crush strength σ_h = 1.6 MPa, cell diameter d = 6.35 mm, foil thickness t = 0.075 mm.

.Table 1: Hybrids configurations tested

Hybrid	EPS foam density used to build hybrids	Honeycomb height [mm]	Foam height [mm]
1	40	10	30
2	40	20	20
3	50	14	26

A standard compressive Instron machine was used. The specimens were placed between two steel circular plates of 250 mm diameter, one of which was moved by a hydraulic system along a two vertical guides. The specimens were pushed against the fixed plate at a speed of 2 mm/min. Force versus displacement curves were then plotted from the load cell recordings.

In the FE analyses, the loading conditions were simulated using a rigid moving stonewall with prescribed speed equal to the compressive rate (2 mm/min) adopted for the experiments. A second rigid stonewall was placed underneath the hybrid. The mass of the model was scaled to increase the minimum time step and so reduce computational time. Force versus displacement curves were plotted from post-processing and compared with those obtained from tests on real specimens. A scaling factor was applied to take into account the difference between the model scale and the real dimensions of the specimens used. In particular, the scaling factor was chosen equal to the rate of the cross-sectional area of the hybrids used for the experiments and the cross-sectional area of the unit cell.

2.4 Boundary conditions

2.4.1 Unit cell

To introduce these constraints in Ls-Dyna, additional coordinate systems were defined. Figure 3 shows a top view of the unit cell and the reference systems defined. In particular, the boundary conditions prescribed to the nodes lying in the face 2 were the same as those applied to nodes on the face 3 and referred to the coordinate system I. In the same way, boundary conditions prescribed for the nodes on the face 1 were also applied to nodes lying on the face 4, with reference to the coordinate system II. Please note that in all of the systems, the z axes are perpendicular to the plane of the page, the positive direction being pointing to the reader. Further boundary conditions were applied to the central nodes (highlighted by circles) and to all of the nodes at the corners and the bottom of the hybrid.

The constraints applied to the set of nodes lying on the corners and those in the centre of the unit cell (highlighted by a circle in Fig.3) are referred to the coordinate system G.

For the nodes on the faces 1-4, the following degrees of freedom were removed:

- displacement along y;

For the nodes in the centre and the nodes in the corners, the following degrees of freedom were removed:

- displacement along x;
- displacement along y

Concerning the nodes at the bottom of the hybrid, it was chosen to eliminate any degree of freedom.

2.4.2 Sub-cell

The same boundary conditions prescribed for the unit cell were applied to the nodes lying on the sides 3 and 4, the nodes in the centre, the nodes at the corners and at the bottom of the hybrid. The only difference consists in the removal of the following degrees of freedom for the nodes lying in the face 5, with reference to the coordinate system G:

- no translation along y;

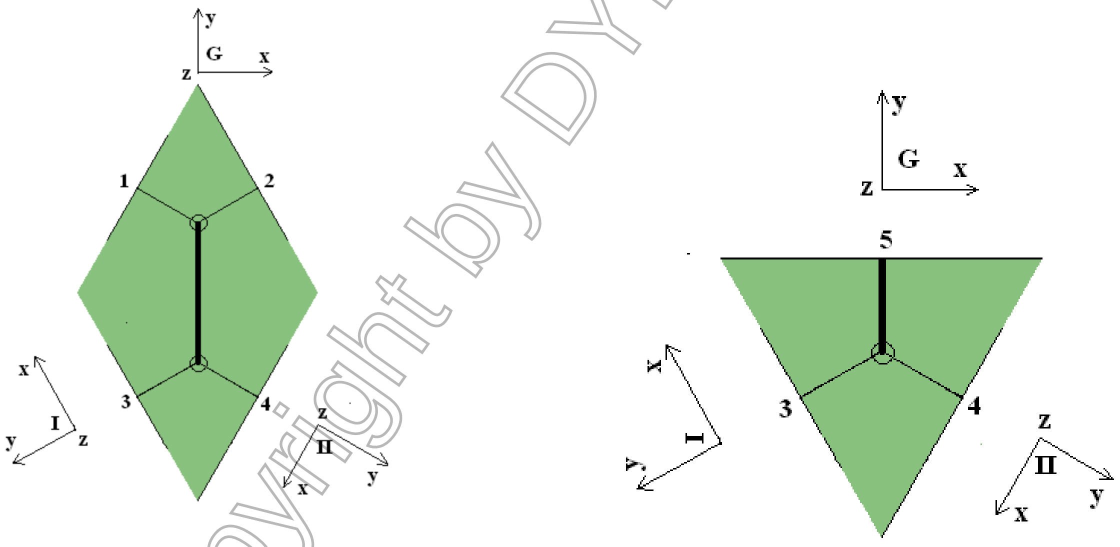

Figure 3: Subcell reference systems

2.4.3 Material properties

The isotropic material model CRUSHABLE_FOAM was used to model EPS properties, while PIECEWISE_LINEAR_PLASTICITY was used to model the honeycomb material properties. Table 2 shows the mechanical properties introduced in the model.

Table 2: Material properties

	Material			
	EPS foam			Aluminium 3003 H18
Density [kg/m^3]	40	50	60	2730
Young's modulus [MPa]	16	16	24	6890
Poisson Ratio	0.01	0.01	0.01	0.33
Cut-off tension [MPa]	0.21	0.32	0.42	-
Yield stress [MPa]	-	-	-	186
Plastic hardening modulus [MPa]	-	-	-	5.5

The foam material properties were obtained from quasi-static compressive tests performed on EPS foam samples at Imperial College London. The aluminium properties were instead obtained from the online database www.matweb.com.

2.4.4 The strain rate effect

The aluminium strain rate dependence was modelled by introducing an arbitrary curve in the material card adopted for this investigation, showed in Fig. 4. This curve represents the scaling factor to be applied to the quasi-static crush strength of the bulk material with which the honeycomb is made, to obtain the correspondent dynamic crush strength when the strain rate is known. A bilinear law was used, on the base of Cellbond Composites experience.

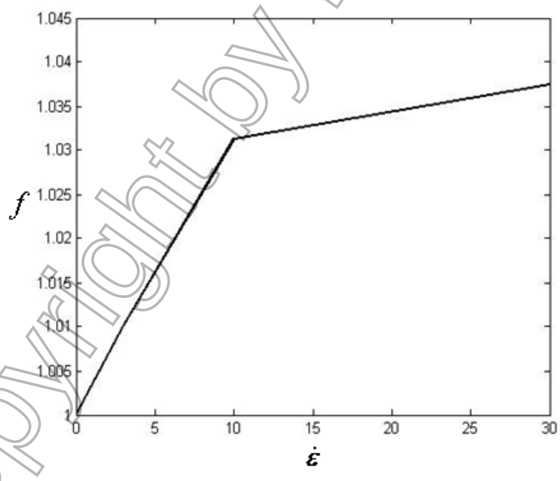

Figure 4: Strain rate effect

3 Results

Figures 5a, 5b and 5c show force versus-displacement obtained from FE simulations for each of the hybrid configurations tested, in comparison with those recorded from experiments. In addition, a lateral view of a hybrid unit cell with the loading direction is showed. The experimental curves are the mean of five tests results carried out on each of the hybrids treated.

As it can be seen, there is good agreement between the results obtained from numerical analyses and those obtained experimentally, confirming the pertinence of the contact logics, boundary conditions and material properties chosen. Numerical results indicate a little increase in the slope of the linear force curve at the beginning of the compression. This might be due to a slight excessive coefficient of friction adopted in the contact NODES_TO_SURFACE.

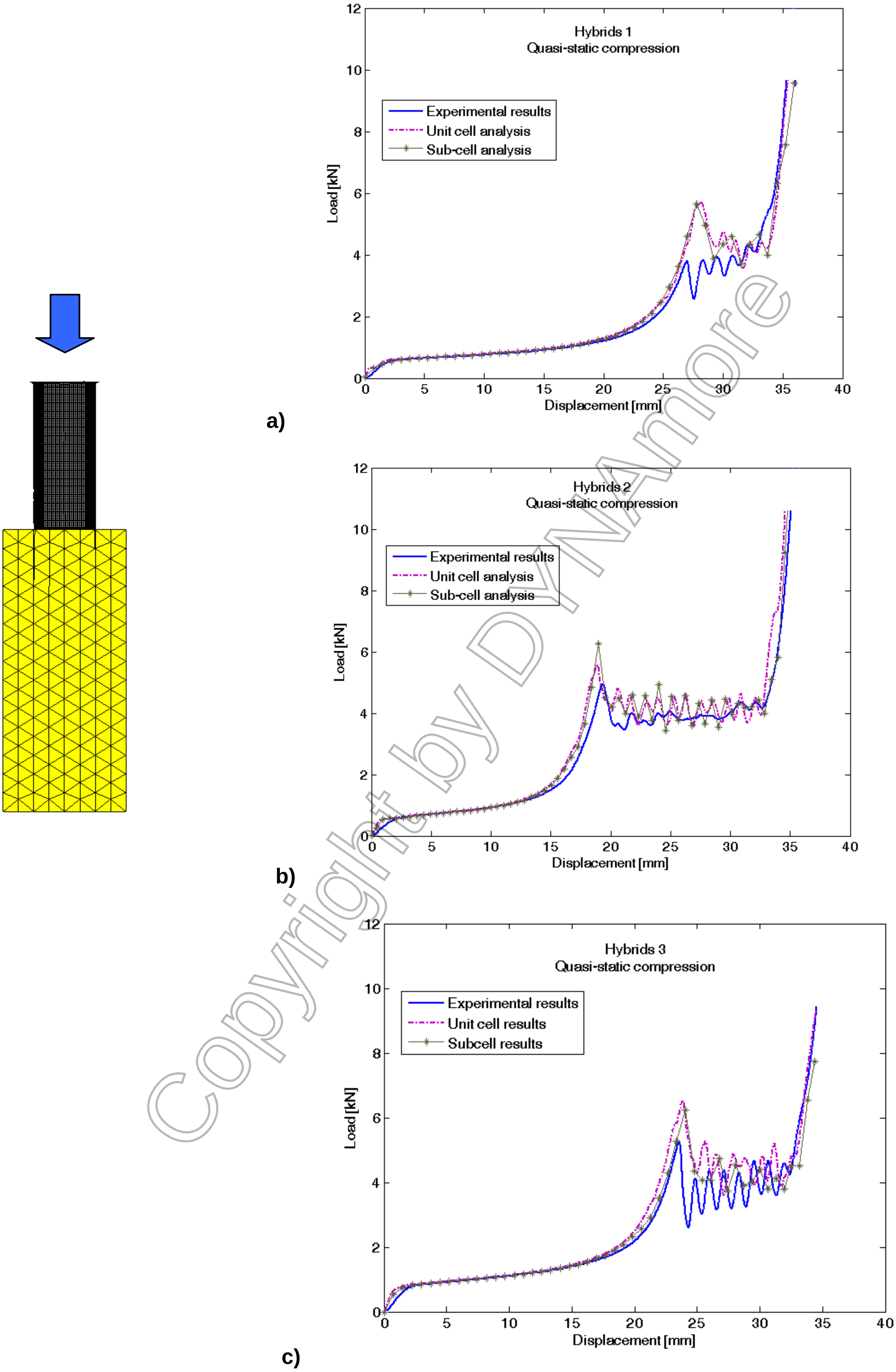

Figure 5: Force versus displacement curves - a) hybrids 1; b) hybrids 2; c) hybrids 3

It can be also noted that the numerical curves present a higher peak in the force value before the series of oscillations prior the densification of the specimen, with respect to that showed by experimental data. This phenomenon was found to be strongly dependent on the initial pre-crush of the honeycomb. In particular, the more severe the pre-crush, the lower the peak. Furthermore, results from numerical analyses on hybrids 1 and 3 suggest that the pre-crushing effect might have some influence on the average force value in the portion of the curve between the peak force and the onset of the densification.

3.1.1 Deformation shapes

During experiments, it was observed that hybrids subjected to compressive loads deform following a precise sequence:

- Elastic deformation of the foam;
- Plastic collapse of the foam;
- Densification of the foam and elastic buckling of the honeycomb;
- Plastic collapse of the honeycomb
- Densification of the hybrid

Fig. 6 shows a side view sequence of the deformation of the hybrid 3 unit cell. The deformation shapes showed by other hybrids are not reported, being similar to those illustrated in the figure. The deformed shapes of hybrids were recorded when the compressive displacement was equal to 5, 10, 15, 20, 25 and 30 mm. A picture showing the fully densificated hybrid was also included.

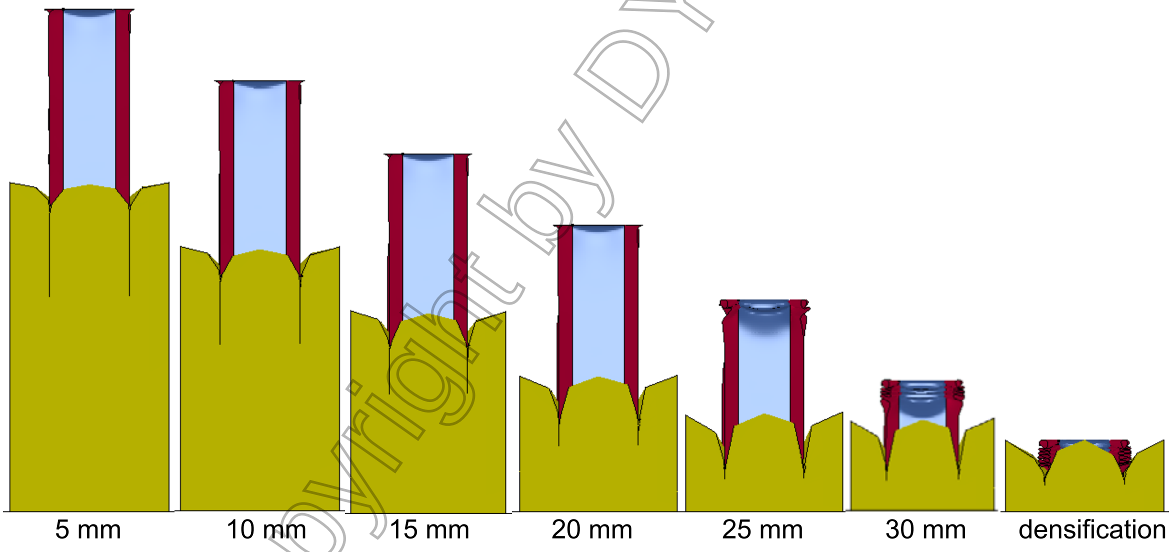

Figure 6: Hybrid 3 deformation sequence

Results showed very good agreement with experimental observations, confirming the pertinence of the shape of the unit cells and the boundary conditions chosen. In particular, the latter had a crucial influence in the correct reproduction of the deformation modes.

It can be also noted that the use of unmerged nodes allowed the representation of the penetration of the honeycomb in the foam.

Results from analyses of sub-cells presented similar results.

4 Conclusions

Innovative composites made of aluminium honeycombs and EPS foams were modelled as unit cells in Ls-Dyna environment. A sub-model was also created to further reduce computational costs. Results from numerical analyses showed good agreement with experimental observations. In addition, the simulated deformed shapes of the hybrids were very close to those observed during experimental tests. It was concluded that both the unit cell and the sub-cell could be used for the prediction of the quasi-static compressive behaviour of hybrids, when the correct boundary conditions are applied.

The use of the contact logic AUTOMATIC_NODES_TO_SURFACE had a crucial role in the modelling of the contact between honeycomb and foam.

The pre-crush of the honeycomb had a significant influence on the peak force recorded before the collapse of the honeycomb.

The correct choice of the boundary conditions allowed the reproduction of the real deformation modes of hybrids and the use of a smaller model, which introduced a saving in the computational costs. In particular, the analysis of the sub-cell required a half of the time necessary to perform simulations using the full model.

5 Acknowledgements

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