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Compressive deformation and energy-absorption capability of aluminium honeycomb core

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Abstract

In this study, the crush behaviour and the energy absorption capability of an aluminium honeycomb core is discussed. A three-dimensional finite-element model of a honeycomb-core structure was developed using the commercial code Abaqus. Flatwise and edgewise experimental compressive tests were made to validate the numerical model and good agreement was found between the experimental data and the numerical results. Virtual compressive tests varying the cell size, cell-wall thickness, and material properties were performed. The deformation mode, compressive core behaviour and its energy-absorption capacity were examined. The crushing parameters at in-plane directions were more affected by the variations of the characteristic core parameters; although, in general, increasing the cell-wall thickness and the yield stress of the aluminium alloy give higher crush loads, and therefore the absorbed energy increases. However, if the cell size increases, the energy-absorption capacity decreases.

Keywords: Honeycomb core, crushing behaviour, sandwich structure, modelling, crushing parameters.

1. Introduction

Composite sandwich structures are widely used as lightweight components in several industrial sectors, mainly the transport industry, due to great bending stiffness and strength, combined with low-weight and high-energy absorbability. A typical composite sandwich structure consists of two thin composite face-sheets and a lightweight core, which under the given loading conditions keeps the face-sheets in their relative positions. In this regard, honeycomb cores are widely used as their high strength-to-weight ratio is greatly appreciated in several engineering applications.

Composite structures are vulnerable to damage by impact-load cases during their operating life from a variety of causes [1], such as bird strikes and tools dropping on the structure during maintenance. Specifically, low-velocity impacts can lead to a reduction in structural stiffness and strength by 50% [2-4] and, consequently, the damage caused propagates under further loading. The type of damage usually found in sandwich face-sheets is similar to that observed after impacts on monolithic structures, and loading-failure mechanisms such as laminate bending failure, core/face-sheet interface delamination, and core compression may appear [5]. However, the contact laws for sandwich structures significantly differ, and indentation is dominated by the core material, which becomes crushed as transverse stresses intensify [6]. In this context, the crushing behaviour of the core becomes a decisive factor for evaluating the energy-absorption performance of sandwich structures [7-9].

The compressive properties and strength of the core have a large effect on the failure mode [10]. A honeycomb structure is anisotropic because of the construction method, and its properties depend on the loading direction [11]. Most numerical and experimental studies conducted on honeycomb cores are focused on the out-of-plane properties under dynamic [12] and static conditions [13], being fewer the studies

focused on the in-plane properties [14 -16]. Khan et al [14] studied experimentally the in-plane and out-of-plane crushing behaviour of aluminium honeycomb cores. It was found that the out-of-plane was the strongest direction. Among in-plane properties, L direction (ribbon direction) was twice as strong as compared to W direction (expanding direction). Papka and Kyriakides [15] developed a two-dimensional model to study the in-plane mechanical behaviour of honeycombs. The results confirmed that honeycombs developed an instability localised into a narrow band of cells and that the size of the specimen affected the results. Hu et al [16] explored various cell-wall angles of hexagonal honeycombs both experimentally and numerically. It was shown that the geometric configuration of cells have important influence on the mechanical properties of honeycombs.

Few studies analyse the energy-absorption capabilities of honeycomb cores in the out-of-plane direction [17], in which Meran et al predicted that the crashworthiness parameters depend on the cell geometry. However, in some applications as an energy absorption layer in aircrafts, the crushing could occur along any direction of the honeycomb [18]. Thus, a complete study of the crushing response of honeycomb cores should include a deep analysis of both out-of-plane and in-plane energy absorption capabilities.

A detailed analysis of the global crushing properties of this type of core depends of numerous parameters. Therefore, to evaluate their influence in every direction would require a large number of experimental tests, these being both time-consuming and cost-intensive [13, 19]. On the other hand, numerical simulations based on the finite-element method (FEM), which reproduces the experimental tests (virtual tests), can be a time- and cost-efficient technique, since the experimental tests are then limited to validating the numerical model.

As a result, in the present work, the influence of certain core parameters (material

properties, cell size, and cell-wall thickness) on the crush behaviour and energy absorption capability of aluminium honeycomb cores was analysed. Virtual tests were performed using a numerical model implemented in Abaqus finite-element code, which was validated by carrying out edgewise and flatwise experimental tests. Particular attention was given to the variation of global crushing parameters in the in-plane and out-of-plane directions, and the resulting deformation mode.

2. Problem description

For the study of the crushing behaviour of honeycomb cores, a three-dimensional numerical model was developed using the finite-element code Abaqus/Explicit, which can provide quasi-static analysis using an explicit approach by ensuring that the ratio of the kinetic energy to the strain energy is a small value during the analysis [20]. Both out-of-plane and in-plane crushing behaviour were analysed by simulating uniaxial compression tests in the selected T (out-of-plane direction), L (in-plane ribbon direction, parallel to the strips of material), and W (in-plane transverse direction, in which the core is expanded), as shown in Fig.1.

Figure 1. T, L and W directions of the honeycomb core

For the determination of the energy-absorption characteristics of aluminium honeycomb cores, some crushing parameters were determined from the load-displacement curves obtained numerically, following the recommendations of the ASTM standard D7336/D7336M [21]:

- Crush Force Efficiency (CFE) is a parameter to measure the performance of the structure during the compression process. It is defined as the ratio of the mean crushing load, which correspond to the averaged load in the plateau stage (F_{av}), to the peak force (F_{max}), as shown in Eq. (1):

$$CFE = \frac{F_{av}}{F_{max}} \quad (1)$$

It is a very important parameter used to evaluate the performance of energy absorbing structures and is related to the structural effectiveness. A value of unity of the structure represents an ideal energy absorbing element which is very difficult to achieve in reality.

- Total Energy Absorption (TEA) is defined as the area under the load-displacement curve, calculated as follows:

$$TEA = \int F_i ds \quad (2)$$

where F_i is the instantaneous force, and s the displacement corresponding to this force.

- Specific Energy Absorption (SEA) is an important parameter to consider in the energy-absorption-capacity analysis. The SEA is the energy absorbed per unit mass of the honeycomb structure (m), given by Eq. (3):

$$SEA = \frac{\int F_i ds}{m}$$

The effect of the variation of some core parameters, such as yield stress, cell-wall thickness and cell size on the load-displacement curve, and consequently on the crushing parameters of the structure, was analysed for T, L, and W directions.

3. Numerical model

The numerical model considers a honeycomb specimen, with a cell size of 3.175 mm, and a flat plate made of steel, which is included to apply the compressive load in each direction, as shown in Fig. 2.

Figure 2. Numerical model configurations: a) T out-of-plane direction, b) L in-plane direction and c) W in-plane direction.

The aluminium of the honeycomb core was modelled as an elastic perfectly plastic material, with isotropic hardening [22-24], which properties are 2700 kg/m³ in density, 70 GPa in Young's modulus, 0.35 in Poisson's ratio, and 290 MPa in yield stress. Due to the manufacturing process, aluminium honeycomb cells have sets of double-thickness walls bonded to each other, thus in this numerical model the honeycomb core was simulated as a monolithic structure, and thick walls were represented by assigning a double thickness to the corresponding single-shell element, which was 0.0254 mm thick. Since no deformation was detected in the loading plate after the experimental test, the steel of the compressive plate was modelled as a linear elastic material ($E=210$ GPa, $\nu=0.3$).

A sensitivity analysis was made to ensure that the model was capable of accurately

calculating the stresses and associated deformations; as a result, the mesh of the honeycomb core consisted of 12,480 four-node linear shell elements (12,053 nodes) with reduced integration (SR4 in Abaqus). The surface-to-surface contact interaction was used to define the contact between specimen and plate; in addition, to prevent the interpenetration of the honeycomb core, a general contact interaction for the cell walls was also included in the analysis.

4. Experimental tests

For the experimental tests, honeycomb cores (HexWeb 4.5-1/8-10(5052)T) supplied by Hexcel Composites were used. The tested honeycomb specimens had a square cross-section of 2500 mm², height of 20 mm, a cell size of 3.175 mm and a wall thickness of 0.0254 mm.

Quasi-static flatwise and edgewise compressive tests were performed using an Instron universal testing machine, model 8516, with a loading cell of 5 kN. The recommendations of ASTM C365/C365M and C364/C364M standards were followed [25,26]. A total of nine specimens were tested with a constant crosshead displacement rate of 3 mm/min.

5. Model validation

The numerical model was validated using experimental results. The variable used in the validation was the applied load-displacement curve recorded during the tests. The curves recorded from both tests performed, flatwise and edgewise, showed three different regions: in the first stages, the load increased linearly, until a peak was reached. In the second region, there was a sudden drop of the curve while the load remained almost constant (plateau), as a result of the cell collapse by plastic yielding. Experimentally, it was observed that the constitutive properties of the honeycomb cores under compression in this plateau zone can be approximated by an elastic perfectly-

plastic material. Given that, this zone is the part of the load-displacement curve used for computing the crashworthiness parameters. The third zone started when the load began to increase again, since the cell collapse ended when the opposing cell walls began to make contact with each other, densifying the core [27]. Figs. 3-5 show the comparison of load-displacement curves for T, L and W directions, respectively. Given the repeatability of the experimental tests, a load-displacement curve obtained in a specific test was selected for the comparison in each direction.

Figure 3. Experimental and numerical load-displacement curves in the out-of-plane direction.

Figure 4. Experimental and numerical load-displacement curves in the in-plane L direction.

Figure 5. Experimental and numerical load-displacement curves in the in-plane W direction.

Differences between experimental and numerical results were less than 10% for each direction. It was found that the out-of-plane peak and plateau loads are of two orders of magnitude higher than those from the in-plane directions results. Furthermore, in L and W directions the difference between the peak and plateau load values was negligible in comparison with the one found in the out-of-plane results due to the plastic yielding of the cells. In L and W directions, the honeycomb cell walls rotate, resulting in lower peak-load values and higher crush-force efficiency than in the out-of-plane results, in which local buckling further decreased the plateau load.

Given that the numerical results agree reasonably well with the experimental data, the numerical model was used to study the crush behaviour of honeycomb-core structures, analysing the deformation mode, as well as the influence of the variation of yield stress of the aluminium alloy, cell-wall thickness, and cell size in the results in T, L, and W directions.

6. Results and discussion

The effect of the variation of some core parameters, such as yield stress, cell-wall thickness and cell size on the load-displacement curve, and consequently on the crushing parameters of the structure, was analysed for the T, L, and W directions.

6.1. Deformation mode

It is important to study the deformation mode of the core and its relationship with the results for the three directions studied.

In the out-of-plane direction, the load first increased linearly due to the elastic bending of the cell walls, resulting in a sharp peak of the load. Afterwards, the formation of folds developed along the cell walls leading to oscillations of the load-displacement curve, corresponding to a plastic behaviour of the honeycomb core at the plateau stage. The densification started when the folds were completely developed [12,14]. Fig. 6 shows different instants of the crushing of honeycomb core in the T direction.

Figure 6. Deformation modes of honeycomb specimen in the T out-of-plane direction: a) numerical and b) experimental.

The deformation mode in the L direction occurred by the progressive collapse of the rows of cells of the structure, as shown in Fig. 7. In this direction, double-thickness walls were parallel to the direction of load application. The initial crushed row was located in the middle of the core, since free edges can be deformed more easily than the rest of the structure. During the compression process, this row destabilised the adjacent cells, propagating the deformation mode until the bottom of the structure. This behaviour led to fluctuations in the resulting plateau stage of the load-displacement curve. Double-thickness walls, which showed a higher crushing resistance than simple-thickness walls, rotated around their prism without warping. Thus, as the compression process progressed, the core was crushed through the cell collapse row by row to result in the densification. The same behaviour was observed by several researchers [14-16,28], in which the bands appear perpendicular to the loading direction at the upper middle position of the model.

Figure 7. Deformation modes of honeycomb specimen in the L in-plane direction:

a) numerical and b) experimental.

The W-direction is the expansion direction of the core during its manufacturing. When crushing loads are applied in this direction, the structure tended to recover its original shape afterwards. Furthermore, the W-direction showed a particular deformation mode, given that the double-thickness walls were perpendicular to the direction of load application. As a result, these walls remained in their original position, barely rotating, while simple-thickness walls crushed, causing the appearance of shear bands. The first shear band was developed from the top of the core, which was in contact with the compressive element. After the first shear band was completely developed, a second one appeared from the opposite upper end of the structure. As the crushing process continued, the two shear bands converged, showing the appearance of an X-shaped band along the honeycomb core [14,16,28], as shown in Fig. 8. Afterwards, the cells were deformed in a symmetric manner until the core was completely densified. The deformation of cell-walls and later development of a shear band, led to fluctuations in the load-displacement curve.

**Figure 8. Deformation modes of honeycomb specimen in the W in-plane direction:
a) numerical and b) experimental.**

6.2. Variation of yield stress

Three different yield stresses were analysed: 290 MPa (baseline model), halved and doubled values (145 MPa and 580 MPa, respectively). The variation of the yield stress, shown in Fig. 9, strongly affected the values of bare compressive load (peak load) and average crush load (plateau load). Both values rose with the increasing yield stress due to the greater crushing resistance of the structure. The peak and plateau load values in L and W-directions were smaller by an order of magnitude than those obtained in T-direction. For the out-of-plane direction, the peak and plateau loads of the halved-yield-stress model were, respectively, 48% and 39% lower than the values found in the original model. These values were 65% and 51% higher in the double-yield stress model, as reflected in Fig. 9a.

The L-direction (Fig. 9b) showed an increment in both the peak and plateau loads by 50% and 69%, respectively, in the 580 MPa yield-stress model. The halved-yield-stress model decreased these loads by 39% and 40%, respectively. In the W-direction (Fig. 9c) and for the 145 MPa yield-stress-model, both peak and plateau loads decreased by 45% and 62%, respectively.

Figure 9. Numerical results of the effect of the yield-stress variation on the load-displacement curve for the honeycomb specimen: a) T out-of-plane direction, b) L in-plane direction and c) W in-plane direction.

Fig. 10 shows the deformation mode of the double-yield stress model. The shear-band formation occurred on the top of the structure, leading to a flattening in the curve, in which no peak load is clearly differentiated. Thus the peak and plateau loads were, respectively, 78% and 81% higher than in the baseline model, as shown in Fig. 9c.

Figure 10. Deformation mode of honeycomb-core model corresponding to a 580 MPa yield stress in the W-direction.

Once the load-displacement curves were drawn, Crush Force Efficiency (CFE) was calculated (Fig. 11).

Figure 11. Crush Force Efficiency as a function of the yield stress.

In the out-of-plane direction, the CFE value decreased with the increasing yield stress due to the higher sensitivity to buckling of the walls of the honeycomb core when this parameter changed. The in-plane directions showed an increment of the CFE value. The load-displacement curves in these directions showed more similarities between the values of the peak and plateau load with the growing yield stress. Thus, for a yield

stress value of 580 MPa the CFE parameter reached 0.87 and 0.92 for L and W-directions, respectively.

As expected, the TEA value increased almost linearly with the increasing of the yield stress, due to the load endured by the core also following this trend (Fig. 12).

Figure 12. Total Energy Absorption (TEA) as a function of the yield stress.

6.3. Variation of cell-wall thickness

Three different cell-wall thicknesses were modelled: 0.0254 mm (baseline model) and 0.5 and 2 times this value (0.0125 mm and 0.05 mm, respectively). Wall-thickness variations (Fig. 13) were found to strongly affect the applied force-displacement curves in terms of peak and plateau load. Both values increased with greater wall thickness as cell walls became more resistant to local buckling and crushing, and absorbed more energy due to plastic deformation. For the out-of-plane direction (Fig. 13a), compared to the original model results, in the model with 0.0125 mm wall thickness (0.5 times the original thickness), the peak and plateau loads decreased by 60.91% and 60.99%,

respectively. For greater thicknesses, the peak and plateau loads increased by 175% and 143% (doubled thickness model, 0.05 mm) over the original model.

Figure 13. Numerical results of the effect of the cell-wall thickness on the applied load-displacement curve for the honeycomb specimen: a) T out-of-plane direction, b) L in-plane direction, and c) W in-plane direction.

The L in-plane direction (Fig. 13b) showed a rise in both peak and plateau load by 361% and 352%, respectively, for the doubled cell-wall thickness, and a decrease in

these values by 82% and 79%, respectively, for the halved wall-thickness model. The values for the W-direction model (Fig. 13c) with 0.0125 mm wall thickness were, respectively, 79% and 78% lower than the peak and plateau values found in the baseline model. However, the doubled-wall thickness model increased these values by 321% and 155%, respectively. This pronounced decrease of the plateau load was due to the deformation mode of the core -see Fig.14, which shows that the formation of the shear bands was not completed during the virtual test, causing a non-symmetric crushing of the core.

Figure 14. Deformation mode of honeycomb-core model corresponding to a 0.05 mm cell-wall thickness in the W-direction.

For the study of the effect of the cell-wall thickness of the honeycomb core on the crushing parameters, the CFE and the SEA were calculated. Since geometric changes, such as cell-wall thickness and cell size, cause a change in the mass of the honeycomb, SEA was calculated instead of TEA.

The Crush Force Efficiency trend calculated for the three directions was reduced, as shown in Fig. 15, due to the resistance to local buckling and crushing when the cell-wall was thicker.

Figure 15. Crush-Force Efficiency (CFE) as a function of the cell-wall thickness.

The W-direction showed the highest decreasing, until a value of 0.55, due to the deformation mode discussed above. The CFE decrements of the out-of-plane and L in-plane directions were less than 30% between the lowest and the highest value of the wall thickness. To compare the energy-absorption capacity of the three different values of the cell-wall thickness, the Specific Energy Absorption was determined. In Fig. 16, T-direction shows the highest SEA value when the wall thickened.

Figure 16. Specific Energy Absorption (SEA) as a function of the cell-wall thickness.

The deformation mode for the 0.05 mm cell-wall thickness value in the W-direction was found to influence the SEA result, which rose in value but not in the expected way, surpassing the result for the L-direction.

6.4. Variation of cell size

Simulations of honeycomb specimens of 1.5875 mm (0.5 times the size of the original model), 3.175 mm (baseline model) and 4.80 mm (1.5 times the size of the original model) are compared in Fig. 17. An increased cell size lowered the number of hexagons in the modelled specimen. The results revealed that specimens with smaller cells had higher energy-absorption levels as the contact area for bearing the compressive load was larger, leading to a greater average crush force.

Figure 17. Numerical results of the effect of the variation of the cell size on the load-displacement curve for the honeycomb specimen: a) T out-of-plane direction, b) L in-plane direction and c) W in-plane direction.

The 4.80 mm cell-size model for the out-of-plane direction (Fig. 17a) gave lower peak and plateau loads (22% and 43%, respectively) than the values found in the original model, which may be related to the lower buckling stability. The 1.5875 mm cell-size model resulted in higher both peak load, by 300%, and plateau load, by 233%.

The in-plane directions showed a variation in the peak and plateau load very similar to that of the original model. In the L-direction, these values decreased by 60% and 64%, respectively, whereas the W-direction decreased by 57% and 56%, respectively, as depicted in Figs. 17b and 17c.

Fig. 18 presents the resulting Crush Force Efficiency on changing the cell size. The CFE value declined for the out-of-plane and in-plane L direction.

Figure. 18. Crush-Force Efficiency (CFE) as a function of the cell size changes.

For the W-direction the CFE value for a cell size of 4.8 mm, when compared to the baseline model results, increased by 4%. In this direction, it was impossible the development of the shear bands due to the limited number of cells contained in the core, see Fig. 19.

Figure 19. Deformation mode of honeycomb-core model corresponding to a cell size of 4.80 mm in the W-direction.

The Specific Energy Absorption is shown in Fig. 20. Once again, a diminished crushing load on the structure resulted in less SEA. The 4.80 mm cell-size model in the L- and W-directions lowered this value by 62% and 70%, respectively, while the out-of-plane direction decreased by 41%, compared to the baseline model.

Figure 20. Specific Energy Absorption (SEA) as a function of the cell size.

7. Conclusions

In this work, the deformation mode and the influence of several core parameters on the in-plane and out-of-plane crush behaviour and on the energy-absorption capacity on honeycomb-core structures were analysed. Virtual compressive tests varying the cell size, the cell-wall thickness, and the yield stress of the aluminium alloy were performed by developing a numerical model in Abaqus.

A typical deformation mode was observed, depending on the direction of load application and, therefore, its cell disposition. In out-of-plane direction, folds formed along the cell walls leading to oscillations at the plateau stage of the load-displacement curve. In addition, although the peak and plateau load in L and W directions were of the same order of magnitude, their deformation modes presented visible differences, and the deformation of a cell was clearly dependent on its position on the core. The deformation mode in the L direction was caused by the progressive collapse of the rows of cells located on the top of the honeycomb-core, due to the rotation of the double-thickness walls, which were parallel to the direction of the load application. In the W direction, shear bands with X-shape were observed. These bands were caused by the lower crushing resistance opposed by the simple-thickness walls when compared to that of the double-thickness walls, which in this load case were perpendicular to the direction of the load application.

As far as the variation of the different parameters, it was found that an increment of the yield stress of the aluminium alloy and the cell-wall thickness of the honeycomb core resulted in a more resistant structure to local buckling and crushing, and increased the peak and plateau load, augmenting the energy-absorption capacity. A reduction in the cell size increased the absorbed energy, as the contact area for bearing the compressive

load was larger in specimens with smaller cells. In view of all the parameters studied, cell-wall thickness is the parameter that most affected the results, reaching compressive load values of up to 3.5 times higher with the doubled cell-wall thickness model in the in-plane directions. It was observed that in-plane directions were more sensitive to the variation of the main core parameters than the out-of-plane direction. In particular, W direction is the most sensitive, due to the shear bands presented. Non-symmetric shear bands gave lower values of the crushing load supported by the core.

With respect to crashworthiness parameters, both in-plane directions showed higher crush-force efficiency than out-of-plane direction. In the T direction, differences between the peak and plateau load were higher than L and W directions due to the local buckling of the cell-walls. This fact caused a decrease of the crushing load on the plateau stage and consequently the reduction of the CFE value. In addition, either total energy absorption or specific energy absorption values found in the out-of-plane direction were two orders of magnitude higher than in-plane directions, as happened with the compressive load.

References

- [1] Ivañez I, Santiuste C, Barbero E, Sanchez-Saez S. Numerical modelling of foam-cored sandwich plates under high-velocity impact. *Composite Structures* 2011; 93(9): 2392-2399.
- [2] Davies GAO, Hitchings D, Besant T, Clarke A, Morgan C. Compression after impact strength of composite sandwich panels. *Composite Structures* 2004; 63: 1–9.
- [3] Sanchez-Saez S, Barbero E, Zaera R, Navarro C. Compression after impact of thin composite laminates. *Composites Science and Technology* 2005; 65: 1911–1919.

- [4] Daniel IM, Abot JL, Schubel PM, Luo JJ. Response and damage tolerance of composite sandwich structures under low velocity impact. *Experimental Mechanics* 2012; 52: 37–47.
- [5] Ivañez I, Sanchez-Saez S. Numerical modelling of the low-velocity impact response of composite sandwich beams with honeycomb core. *Composite Structures* 2013; 106: 716–723.
- [6] Abrate S. *Impact on composite structures*. Cambridge University Press; 1998.
- [7] Giglio M, Manes A, Gilioli A. Investigations on sandwich core properties through an experimental–numerical approach. *Composites: Part B* 2012; 43: 361–374.
- [8] Ivañez I, Santiuste C, Sanchez-Saez S. FEM analysis of dynamic flexural behaviour of composite sandwich beams with foam core. *Composite Structures* 2010; 92(9): 2285–2291.
- [9] Sanchez-Saez S, García-Castillo SK, Barbero E, Cirne J. Dynamic crushing behaviour of agglomerated cork. *Materials and Design* 2015; 65:743–748.
- [10] Mamalis AG, Manolakos DE, Ioannidis MB, Papapostolou DP. On the crushing response of composite sandwich panels subjected to edgewise compressive: experimental. *Composite Structures* 2005; 71: 246–257.
- [11] Petras A. *Design of Sandwich Structures*. PhD Thesis. Cambridge University, Engineering Department; 1998.
- [12] Heimbs S. Virtual testing of sandwich core structures using dynamic finite element simulations. *Computational Materials Science* 2009; 45: 205–216.
- [13] Zhang X, Zhang H, Wen Z. Experimental and numerical studies on the crush resistance of aluminum honeycombs with various cell configurations. *International Journal of Impact Engineering* 2014; 66: 48–59.

- [14] Khan MK, Baig T, Mirza S. Experimental Investigation of In-plane and Out-of-plane Crushing of Aluminum Honeycomb. *Materials Science & Engineering A* 2012; 539: 135–138.
- [15] Papka SD, Kyriakides S. Experiments and full-scale numerical simulations of in-plane crushing of a honeycomb. *Acta mater* 1998; 46 (8): 2765-2776.
- [16] Hu L, You F, Yu T. 2013. Effect of cell-wall angle on the in-plane crushing behaviour of hexagonal honeycombs. *Materials and Design* 2013;46: 511–523.
- [17] Meran AP, Toprak T, Mugan A. Numerical and experimental study of crashworthiness parameters of honeycomb structures. *Thin-Walled Structures* 2014; 78: 87–94.
- [18] Mozafari H, Molatefi H, Crupi V, Epasto G. and Guglielmino E. In plane compressive response and crushing of foam filled aluminium honeycombs. *Journal of Composite Materials* 2015; 49(26):3215-3228.
- [19] Ivañez, I., Barbero, E., Sanchez-Saez, S. Analytical study of the low-velocity impact response of composite sandwich beams. *Composite Structures* 2014; 111: 459–467.
- [20] Hibbit, Karlsson, Sorensen, 2010. *Abaqus User's Manual*, Pawtucket, Rhode Island.
- [21] Standard Test Method for Static Energy Absorption Properties of Honeycomb Sandwich Core Materials D7336/D7336M – 07.
- [22] Horrigan DPW, Aitken RR, Moltschaniwskyj G. Modelling of crushing due to impact in Honeycomb Sandwiches. *Journal of Sandwich Structures and Materials* 2000; 2(2): 131-151.

- [23] Besant T, Davies GAO, Hitchings D. Finite element modelling of low velocity impact of composite sandwich panels. *Composites: Part A* 2001; 32, 1189-1196.
- [24] Chen C, Lu TJ, Fleck NA. Effect of inclusions and holes on the stiffness and strength of honeycombs. *International Journal of Mechanical Sciences* 2001; 43: 487-504.
- [25] Standard Test Method for Flatwise Compressive Properties of Sandwich Cores C365/C365M – 11.
- [26] Standard Test Method for Edgewise Compressive Strength of Sandwich Constructions C364/C364M – 07.
- [27] Gibson LJ, Ashby MF. *Cellular solids: structure and properties*. Cambridge University Press; 1997.
- [28] Ruan D, Lu G, Wang B, Yu TX. In plane dynamic crushing of honeycombs- a finite element study. *International Journal of Impact Engineering* 2003; 28: 161-182.

FIGURE CAPTIONS

Figure 1. T, L and W directions of the honeycomb core

Figure 2. Numerical model configurations: a) T out-of-plane direction, b) L in-plane direction and c) W in-plane direction.

Figure 3. Experimental and numerical load-displacement curves in the out-of-plane direction.

Figure 4. Experimental and numerical load-displacement curves in the in-plane L direction.

Figure 5. Experimental and numerical load-displacement curves in the in-plane W direction.

Figure 6. Deformation modes of honeycomb specimen in the T out-of-plane direction: a) numerical and b) experimental.

Figure 7. Deformation modes of honeycomb specimen in the L in-plane direction: a) numerical and b) experimental.

Figure 8. Deformation modes of honeycomb specimen in the W in-plane direction: a) numerical and b) experimental.

Figure 9. Numerical results of the effect of the yield-stress variation on the load-displacement curve for the honeycomb specimen: a) T out-of-plane direction, b) L in-plane direction and c) W in-plane direction.

Figure 10. Deformation mode of honeycomb-core model corresponding to a 580 MPa yield stress in the W-direction.

Figure 11. Crush Force Efficiency as a function of the yield stress.

Figure 12. Total Energy Absorption (TEA) as a function of the yield stress.

Figure 13. Numerical results of the effect of the cell-wall thickness on the applied load-displacement curve for the honeycomb specimen: a) T out-of-plane direction, b) L in-plane direction, and c) W in-plane direction.

Figure 14. Deformation mode of honeycomb-core model corresponding to a 0.05 mm cell-wall thickness in the W-direction.

Figure 15. Crush-Force Efficiency (CFE) as a function of the cell-wall thickness.

Figure 16. Specific Energy Absorption (SEA) as a function of the cell-wall thickness.

Figure 17. Numerical results of the effect of the variation of the cell size on the load-displacement curve for the honeycomb specimen: a) T out-of-plane direction, b) L in-plane direction and c) W in-plane direction.

Figure. 18. Crush-Force Efficiency (CFE) as a function of the cell size changes.

Figure 19. Deformation mode of honeycomb-core model corresponding to a cell size of 4.80 mm in the W-direction.

Figure 20. Specific Energy Absorption (SEA) as a function of the cell size.