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Sandwich structures, crashworthiness, finite element method

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NUMERICAL SIMULATIONS OF SANDWICH STRUCTURES UNDER LATERAL COMPRESSION

Abstract

The current paper analyzes the effect of the cross-section on the energy absorption capabilities of sandwich structures under compressive loads. For this purpose, several cross-section including triangular, square, hexagonal and circular shapes were analyzed using Abaqus software. According to the results the hexagonal shape is the most favorable cross-section to increase the crashworthiness performance of the structures up to 700% of CFE with respect to the square arrangement.

1. INTRODUCTION

From the high safety standards for passengers, the crashworthiness performance is the most important requirement in automotive, aerospace and rail industry (Zhang, Xu, Wang, Chen & Wang, 2018). Thus, the structural designs should provide a controlled deceleration of the vehicles in order to reduce the injuries of the occupants during crash events. The use of thin-walled structures is widely used to tackle this harmful effect. The absorption of the energy is raised when the

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structures are plastically deformed. The crashworthiness performance is a function of many parameters such as geometry, cross-section, material and arrangement of the structures. In this way, several thin-walled structures have been studied such as single (Goel, 2015), bi-tubular (Estrada et al., 2019), multicell and sandwich/ honeycomb arrangements (Ivañez, Fernandez-Cañadas & Sanchez-Saez, 2017). In all cases, such structures are an effective and low-cost alternative to absorb energy during crash events. Moreover, honeycomb arrangements allow an increase of crashworthiness capabilities in relation to other kinds of structures (Crupi, Epasto & Guglielmino, 2013). A typical sandwich structure is formed by a core between two face sheets (Li & Wang, 2017). Considering the orientation of the panel with respect to the load direction, the honeycomb structures can be crushed in-plane and out-of-plane direction. In both cases, different crash-worthiness performances are obtained. In this context (Khan, Baig, & Mirza, 2012) it is reported an experimental investigation that deals with in-plane and out-of-plane crushing of aluminum alloy 3003 honeycomb structures. The local and global plastic strains were obtained by digital image correlation. It was concluded that the out-of-plane direction presented the highest energy absorption. Considering in-plane crashworthiness behavior, many studies have focused their efforts to analyze different core topologies. However, triangular configuration exhibits a better crashworthiness performance of bio-inspired hierarchical honeycombs, (Yin, Huang, Scarpa, Wen, Chen & Zhang, 2018). Furthermore, for in out-of-plane direction, it was analyzed the energy absorption capabilities of bio-inspired aluminum honeycomb with horseshoe mesostructured, (Yang, Sun, Yang, & Pan, 2018). The horseshoe shapes were built based on triangle, square, hexagon and kagome honeycomb structures. To compare with typical honeycomb structures the horse-shaped honeycomb obtained the best energy absorption performance. Considering filled materials, the authors of (Liu et al., 2017) evaluated the crushing response of aluminum honeycombs panels filled with expanded polypropylene (EPP) foams. The compression tests were conducted in axial (out of plane) and lateral (in plane) direction. For the axial configuration the EPP foam increased the crashworthiness performance of the structures compared to the empty honeycomb panels in a range of 43 to 120%. Moreover, a better improvement was found for energy absorption in lateral crushing up to 30397%. Finally, the study of crushing of honeycomb structures in-plane and out-of-plane has been extensively reported. However, the study of honeycomb structures under in-plane crushing direction is barely reported.

Thus, the current article studies the effect of the cross-section on the crash-worthiness performance of sandwich structures in-plane crushing direction. For this purpose, several numerical simulations were carried out using Abaqus finite element software. The evaluated cellular cores are based on triangular, square, hexagonal and circular shapes. In all cases, the structures were made with aluminum AA 6063-T5 and using same mass value.

2. MECHANICAL CHARACTERIZATION OF ALUMINUM ALLOY 6063-T5

The use of light materials is one of the most important requirements in the crashworthiness design of vehicles. In order to guarantee an optimal strength/weight ratio of the structural components, the use of aluminum alloys is widely used. AA 6063-T5 exhibited an excellent mechanical behavior and great resistance to corrosion (Zhu, Qin, Wang & Qi, 2011). Thus, all evaluated structures in this study are made with AA6063-T5. The mechanical characterization was carried out following the tensile test ASTM7-E8 for rectangular specimens. An AG-X plus 100kN Shimadzu universal test machine with a quasi-static velocity of 2 mm/min was used for the tensile tests. Details of the tensile specimens are depicted in Figure 1.

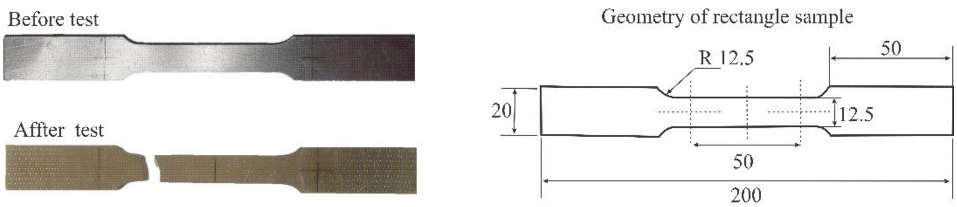


Fig. 1. Tensile sample for ASTM7-E8 (units in mm)

The mechanical response of the specimen is shown in Figure 2. From this curve, the mechanical characterization of AA6063-T5 was carried out. The parameters used in Abaqus models are listed in Table 1, which are consistent with previous works, (Wang, Li & Zhang, 2016). Due to quasi-static nature of the tensile test besides of small strain rate sensitivity of 6063-T5 alloy in a range of 10^{-4} to 10^{3} s^{-1}, the strain rate effects were neglected, (Smerd, Winkler, Salisbury, Worswick, Lloyd & Finn, 2005).

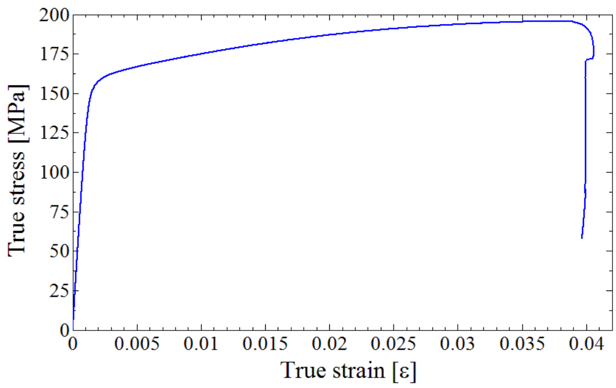


Fig. 2. Force-displacement curve for AA6063-T5

Tab. 1. Mechanical properties for AA6063-T5

Elasticity	Young modulus [MPa]	Poisson coefficient	Density [kg/m^3]
	66940	0.33	2700
Plasticity	Yield stress S_y [MPa]		
	158.79		

3. FIRST NUMERICAL MODEL WITH EXPERIMENTAL VALIDATION

Given that our study is of numerical kind, a first model designated as (S-00) worked out using Abaqus/explicit was conducted. The numerical model was validated through a quasi-static compression test utilizing a universal test machine at 6 mm/min. The discrete model was developed with the assumption that the core of the sandwich panel is obtained from the joint of several single profiles. In this way, the discrete model describes a single square profile subjected to in-plane compression (lateral). The profile was built with AA6063-T5 and height (H) of 38.3 mm, length (L) of 130 mm and thickness (t) of 1.4 mm. The tube was modeled using S4R shell elements with elastoplastic properties described in Table 1. Meanwhile R3D4 elements were used to model the compressed plates as rigid bodies. During the compression test, the structure was set between two rigid plates in lateral direction. A contact interaction with friction coefficient of $\mu = 0.3$ was implemented, (Zhang, Zhang & Wang, 2016). From experimental validation and mesh convergence analysis, an element of 2.5 mm was implemented. Therefore, a total number of 3120 elements were generated. Details of the physical and numerical models are described in Figure 3.

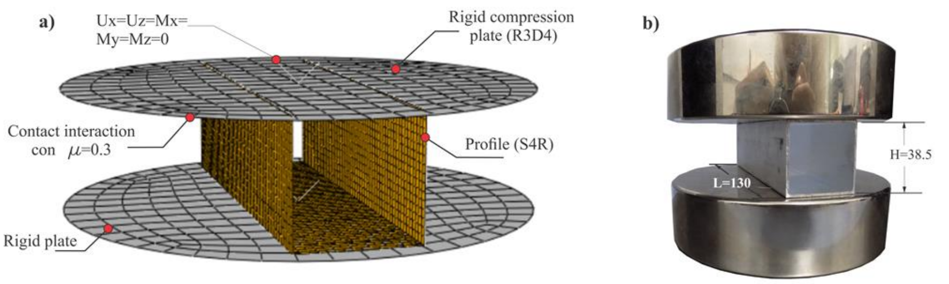


Fig. 3. Lateral compression of S-00 profile: a) discrete model and b) experimental model

The force-displacement curves for both cases were obtained and are compared as shown in Figure 4. In the same plot, the results for the mesh convergence analysis also are presented. In this sense, coarse (5 mm), medium (2.5 mm) and fine (1 mm) meshes were evaluated. Despite of the numerical curves present very little difference, when a zoom on P_{max} region is made a convergence criterion is obtained. A difference close to 2% for fine and medium mesh is obtained. This was not the case for the coarse mesh. Thus, the medium (2.5 mm) element size was validated and the corresponding results are discussed below. As it is observed in Figure 4, the discrete model correctly represents the compression behavior of the structure in quantitative and qualitative way. In this sense, the numerical results predicted a P_{max} value of 46.67 kN and energy absorption of 0.133 kJ, which represents a difference of 1.01% and 3 %, with respect to experimental setup. This discrepancy is associated to the complexity when the plastic deformation involving contact phenomena is captured. In Figure 5 as the compression is carried out the contact area changes from plane to line condition. With regard to the mechanical behavior (see Fig. 4) this is characterized by an increase of compression force until a maximum value of P_{max}~47 kN. Subsequently, the failure of the structure is reached, provoking a drastic drop of the force within the first 2 mm. Afterwards, a smooth decrease is obtained along the compression procedure (20 mm), which is stopped to reach a compression force equal to 5 kN.

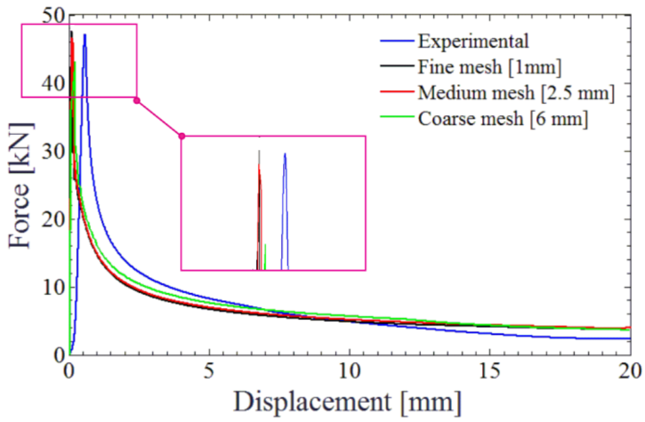


Fig. 4. Comparison of force displacement-curves for first discrete model (S-00)

The final deformation state is presented in Figure 5. The discrete model captured correctly the experimental collapsing mode of the structure. Considering the cross-section, the plastic deformation initiated with the formation of a hinge-line along the length of the profile at middle height. After that, a rolling inside effect on vertical edges was noticed. As the rolling effect increased, the top edge suffers a concave plastic deformation. Opposite deformation occurred at the bottom edge.

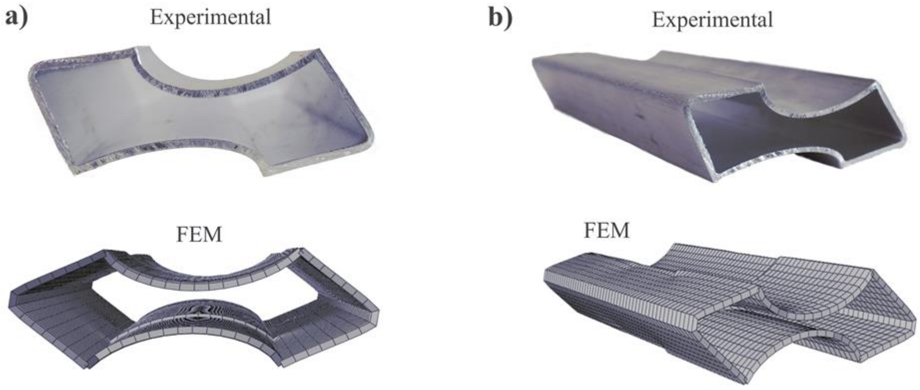


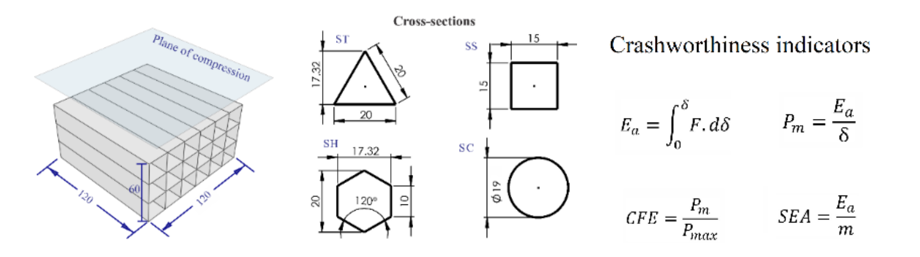
Fig. 5. Final deformation state: a) is the cross-section and b) the isometric view

Lastly, according to Figure 4 and 5 the numerical model describes the mechanical behavior of the profile in the quantitative and qualitative way. Hence, the discrete model is validated, and we can continue with the study of the effect of the cross-section on crashworthiness performance of sandwich structures under lateral load.

4. NUMERICAL SIMULATIONS

The main contribution of this paper was to analyze the effect of the cross-section of sandwich structures when are subjected to quasi-static lateral compression. For this purpose, numerous simulations were carried out. The analyzed cross-sections included triangular, square, hexagonal and circular shapes. In order to get a reliable comparison, all sandwich arrangements presented same mass (0.369 kg) and were made with an aluminum 6063-T5 alloy. The assessment of the structures was carried out by dimensional and dimensionless crashworthiness parameters. The most important are as follows: the peak load (P_{max}), the energy absorption (E_a), the mean crush force (P_m), the crush force efficiency (CFE) and the specific energy absorption (SEA). Where F is the compression force, δ the displacement and m the mass. The E_a was obtained by integration of the area under force vs displacement curves, using an integration method known as trapezium rule. Regarding the CFE, optimal performance of the structure is obtained when CFE equals to 1. Details of the evaluated specimens and crashworthiness parameters are shown in Table 2.

Tab. 2. Numerical setup (dimensions in mm)

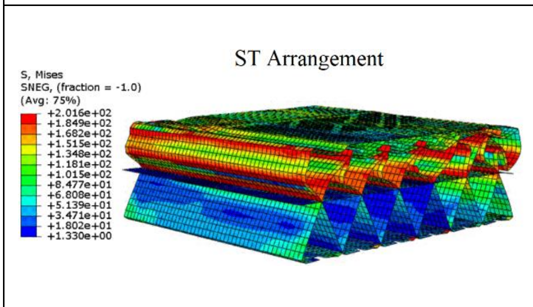
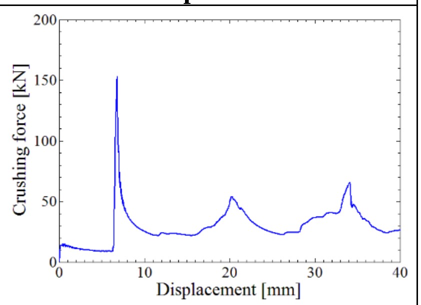


Specimen code	Shape base	Thickness [mm]	Mass [kg]
ST	Triangular	0.884	0.369
SS	Square	1	0.369
SH	Hexagonal	1.395	0.369
SC	Circular	0.915	0.369

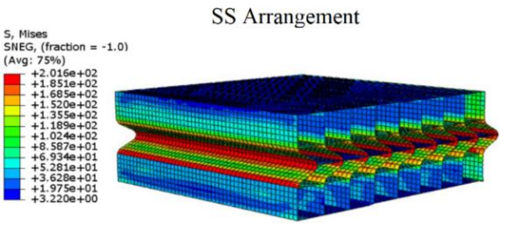
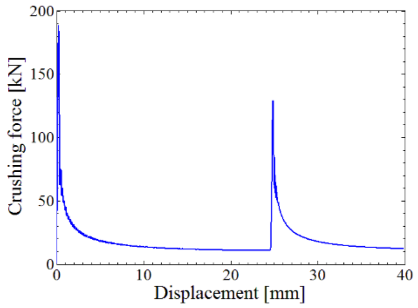
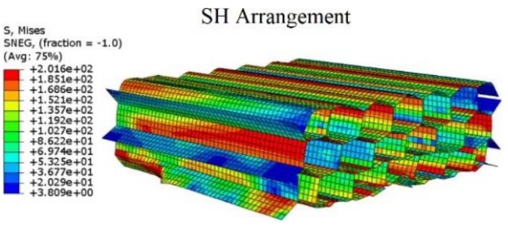
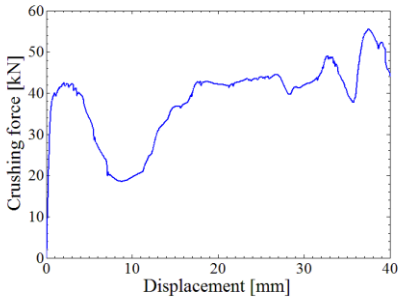
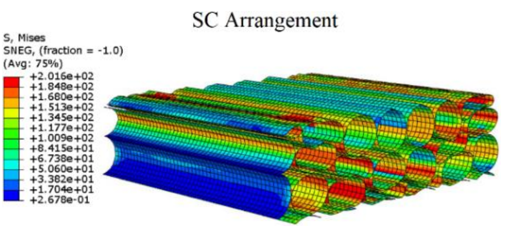
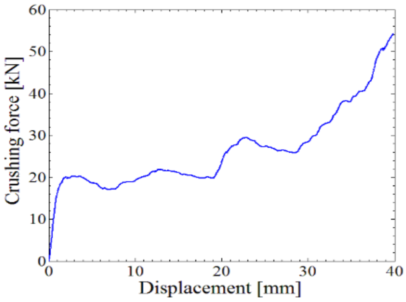
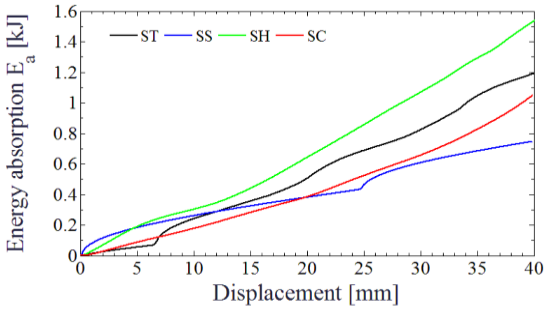
5. RESULTS

The crashworthiness performance of the structures was obtained from the analysis of the crushing force vs. displacement curves. The structures with triangular and square base exhibited a peak load (P_{max}) value followed by a drop of the crushing force. Meanwhile, the structures close to circular shape described a smooth transition between P_{max} and mean crushing force (P_m). Depending on the cross-section, different values of P_{max} in a range of 188 to 53 kN were calculated. The interaction between the walls of the structures modified the typical deformation mode described for the single profiles (Fan, Hong, Sun, Xu & Jin, 2015). Hexagonal and circular profiles presented higher deformation than triangular and square sandwich structures, as can be seen in Table 3 and 4. This was corroborated observing the plot of the energy absorption (E_a) along with the displacement (see Table 4). Hexagonal and circular cross-section, in turn, presented higher stability during the compression test.

Tab. 3. Mechanical behavior of the sandwich structures I

Final deformation at 40 mm	Force vs. displacement curve
	

Tab. 4. Mechanical behavior of the sandwich structures II

Final deformation at 40 mm	Force vs. displacement curve
	
	
	
Energy absorption per length unit	
	

A summary of crashworthiness results of the whole evaluated sandwich arrangements is compiled in Table 5. The energy absorption (E_a) performance of the structures was directly influenced by the cross-section. The best E_a was obtained for hexagonal structures (SH) with 1.553 kJ, which represents an increase of 108.17% respect to the lowest E_a value for the HS profile. (0.746 kJ). This behavior was verified by calculating the maximum mean crush force (P_m) and specific energy absorption (SEA) equal to 38.82 kN and 4.20 J/gr, respectively. On the other hand, the poorest crashworthiness performance was achieved for the triangular sandwich structure (ST). This condition is associated to small deformation besides of the apparition of the buckling phenomena.

Tab. 5. Mechanical behavior of the honeycomb structures

Code	P_{max} [kN]	P_m [kN]	E_a [kJ]	*SEA* [J/gr]
ST	153.33	29.82	1.193	3.23
SS	188.81	18.65	0.746	2.02
SH	55.44	38.82	1.553	4.20
SC	53.50	25.80	1.049	2.84

A high E_a value does not necessarily represent the best crashworthiness performance. In this way, the crushing force efficiency (CFE) is a more useful parameter. The CFE involves a comparison of the P_m and P_{max} values. An optimal behavior of the profiles is achieved when the CFE value is close to the unit. A comparison of CFE values for all sandwich arrangements is shown in Figure 6.

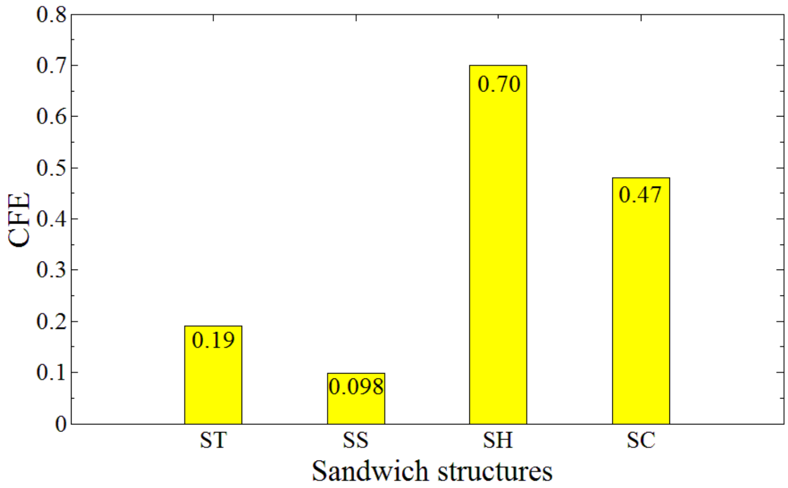


Fig. 6. Comparison of CFE parameter for all evaluated structures

According to Figure 6, cross-sections with many edges or close to the circular shape show a better CFE performance. In this way, two trends were described by the structures. The first is formed by structures ST and SS, which is characterized by low CFE values close to 0.2. This condition was obtained due to a high P_{max} value at the beginning of the crushing process, followed for a drastic drop to the crush force. The opposite case was observed for structures SH and SC where only minor differences between P_{max} and $P_m$were calculated. Therefore, higher CFE values were achieved. The best CFE value of 0.70 was obtained for the sandwich structure with hexagonal base. This means an increase of 700% respect to the lowest CFE value (0.1). The hexagonal cross-section allowed for high resistance to form the plastic hinge lines with a great stability of the arrangement during all crushing process. Thus, profiles with hexagonal cross-section should be considered to the control of lateral impacts.

6. CONCLUSION

A numerical study of the effect of the cross-section on the crashworthiness performance of sandwich structures under lateral load was carried out. According to our study, the following conclusions were obtained:

1. Considering the same mass for all structures (369 g), the energy absorption (E_a) is highly dependent on the arrangement of the single profiles in the cross-section. In second instance, the E_a depends on the geometrical base of these profiles. This condition explains the higher E_a value for the triangle specimen respect to the square sandwich profile.
2. The E_a capabilities can be improved when hexagonal cross-section is implemented. In this way, an increase of 108% was calculated in relation to the lowest value that was calculated for square sandwich structure (0.746 kJ).
3. As the cross-section tends to form a circular shape, a decrease in the peak load (P_{max}) value was computed. The lowest P_{max} value ~53.50 kN was obtained by the sandwich structure with circular base (SC).
4. Regarding to CFE parameter, a better performance is obtained when the cross-section tends to form hexagonal or circular shape. Then, an improvement in a range from 480% to 700 % can be achieved.
5. Square and triangular cross-section are not recommended to design energy absorption systems due to the high P_{max} values and the instability presented during crushing process.
6. Finally, hexagonal honeycomb structure presents the best crashworthiness performance with a CFE value equal to 0.70. This means an excellent stability with a large plastic deformation. This kind of structure can be used to reduce injuries and fatalities during axial impacts.

REFERENCES

Crupi, V., Epasto, G., & Guglielmino, E. (2013). Comparison of aluminium sandwiches for lightweight ship structures: Honeycomb vs. foam. *Marine Structures*, *30*, 74–96. doi:10.1016/J.MARSTRUC.2012.11.002

Estrada, Q., Szwedowicz, D., Rodriguez-Mendez, A., Elías-Espinosa, M., Silva-Aceves, J., Bedolla-Hernández, J., & Gómez-Vargas, O. A. (2019). Effect of radial clearance and holes as crush initiators on the crashworthiness performance of bi-tubular profiles. *Thin-Walled Structures*, *140*, 43–59. doi:10.1016/J.TWS.2019.02.039

Fan, H., Hong, W., Sun, F., Xu, Y., & Jin, F. (2015). Lateral compression behaviors of thin-walled equilateral triangular tubes. *International Journal of Steel Structures*, *15*(4), 785–795. doi:10.1007/s13296-015-1202-x.

Goel, M. D. (2015). Deformation, energy absorption and crushing behavior of single-, double- and multi-wall foam filled square and circular tubes. *Thin-Walled Structures*, *90*, 1–11. doi:10.1016/J.TWS.2015.01.004

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. doi:10.1016/J.COMPSTRUCT.2017.04.056

Khan, M. K., Baig, T., & Mirza, S. (2012). Experimental investigation of in-plane and out-of-plane crushing of aluminum honeycomb. *Materials Science and Engineering: A*, *539*, 135–142. doi:10.1016/J.MSEA.2012.01.070

Li, T., & Wang, L. (2017). Bending behavior of sandwich composite structures with tunable 3D-printed core materials. *Composite Structures*, *175*, 46–57. doi:10.1016/J.COMPSTRUCT.2017.05.001

Liu, Q., Fu, J., Wang, J., Ma, J., Chen, H., Li, Q., & Hui, D. (2017). Axial and lateral crushing responses of aluminum honeycombs filled with EPP foam. *Composites Part B: Engineering*, *130*, 236–247. doi:10.1016/J.COMPOSITESB.2017.07.041

Smerd, R., Winkler, S., Salisbury, C., Worswick, M., Lloyd, D., & Finn, M. (2005). High strain rate tensile testing of automotive aluminum alloy sheet. *International Journal of Impact Engineering*, *32*(1–4), 541–560. doi:10.1016/J.IJIMPENG.2005.04.013

Yang, X., Sun, Y., Yang, J., & Pan, Q. (2018). Out-of-plane crashworthiness analysis of bio-inspired aluminum honeycomb patterned with horseshoe mesostructure. *Thin-Walled Structures*, *125*, 1–11. doi:10.1016/J.TWS.2018.01.014

Yin, H., Huang, X., Scarpa, F., Wen, G., Chen, Y., & Zhang, C. (2018). In-plane crashworthiness of bio-inspired hierarchical honeycombs. *Composite Structures*, *192*, 516–527. doi:10.1016/J.COMPSTRUCT.2018.03.050

Wang, Z., Li, Z., & Zhang, X. (2016). Bending resistance of thin-walled multi-cell square tubes. *Thin-Walled Structures*, *107*, 287–299. doi:10.1016/J.TWS.2016.06.017

Zhang, Y., Xu, X., Wang, J., Chen, T., & Wang, C. H. (2018). Crushing analysis for novel bio-inspired hierarchical circular structures subjected to axial load. *International Journal of Mechanical Sciences*, *140*, 407–431. doi:10.1016/J.IJMECSCI.2018.03.015

Zhang, X., Zhang, H., & Wang, Z. (2016). Bending collapse of square tubes with variable thickness. *International Journal of Mechanical Sciences*, *106*, 107–116. doi:10.1016/J.IJMECSCI.2015.12.006

Zhu, H., Qin, C., Wang, J. Q., & Qi, F. J. (2011). Characterization and Simulation of Mechanical Behavior of 6063 Aluminum Alloy Thin-Walled Tubes. *Advanced Materials Research*, *197–198*, 1500–1508. doi:10.4028/www.scientific.net/AMR.197-198.1500