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Aluminium Foam-filled Honeycomb Crash Absorbers

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Abstract. Honeycomb structures are frequently used as energy absorption devices in the automotive and aerospace industry. Many studies have been conducted to optimise these structures and improve crashworthiness behaviour. This paper attempts to improve the crashworthiness behaviour of a honeycomb crash box by filling the cells with open-cell aluminium foams. Experimental tests were conducted to develop the honeycomb and aluminium foam material model and, also, to validate the finite element model by experimental data. Foam-filling the crash box allows the control of the densification zone for different impact energies using open-cell aluminium foam, which shows the main novelty of this research. In the end, the optimised structure is presented concerning the optimum number of foam-filled cells and, also, to the aluminium foam's density that best fits this application.

Introduction

Passive safety is one of the main concerns for the automotive industry, meaning that more than developing faster cars, car manufacturers are investing in safer cars. Therefore, road safety equipment is also being improved and for this reason, many researchers have investigated energy absorption capabilities of devices. Aluminium honeycomb structures are the preferred ones due to their attractive behaviour against impact in the out-of-plane direction. Also, aluminium foams offer an interesting behaviour during compression and, therefore, this paper aims to combine these two attractive structures and perform the optimised structure against impact loading conditions. The main criterion that evaluates the behaviour of an energy-absorbing device is the specific energy absorption. As a result, several combinations of foam-filled cells can be performed to evaluate which one is the best structure under the specific energy absorption criterion [1 – 3]. Moreover, it is necessary to limit the maximum forces, and, in this field, the foam-filled structures have a big influence, since the number of aluminium foams acts as a controlling device for the maximum force. Numerical optimisation methods are one of the most advanced techniques to find an optimum solution for a design process. Thus, it is important to reach an accurate and effective optimisation loop through a local search by using a cost function to meet the defined criterion. Even though several pieces of research have already been made to model the impact behaviour of empty honeycomb structures, single foam-filled tubes, and optimisation loops. There are no significant previous studies that combine all these factors. This study seeks to develop the optimum aluminium foam-filled honeycomb crash box with the most representative studies concerning honeycomb structures, single foam-filled tubes, and optimisation loops. The crashworthiness parameters, namely specific energy absorption (SEA) and crush force efficiency (CFE), depend on the variation of these parameters. The energy absorption capacity improves with the increase of the cell's thickness or, in the opposite direction, with the decrease of the cell size. On the other hand, the CFE decreases with the cell's thickness and side size increase. However, none of these researchers has studied the filling of open-cell aluminium foams in an aluminium honeycomb structure and, also, used an optimisation loop to find the best number of foam-

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filled cells. In this research paper, not only the above topics will be investigated but also ABAQUS/Scripting will be used to reach the optimum solution by modifying the geometry dimensions and implementing the desired cost function that will access the validity of the solution.

Experimental Tests

In order to develop material models for both aluminium honeycomb and foam, tensile and compressive tests were performed, respectively. Empty and foam-filled aluminium honeycomb specimens were dynamically tested to validate the developed finite element model.

Aluminium Foam

A356.2 aluminium alloy was used to vacuum-infiltrating cast 610 mm height hexagonal bars, having smallest hexagon width of 40 mm, of open-cell aluminium foams using water-soluble template balls, made from NaCl particles combined with an inorganic binder, with the size in the range 4.1 – 4.4 mm as a space holder. After leaching in water, the hexagonal aluminium foams were cut into specimens with 80 mm in length and T6 heat treated using the solution treatment at 540˚C for 8 hrs and the aging treatment at 152˚C for 5 hrs. The compression tests on the aluminium foam specimens were performed under BS ISO 13314:2011 [4 - 6] using a Shimadzu AGX-V Universal Testing Machine with a strain rate of 0.003 s^{-1}. Table 1 shows the physical properties and mass of each of the five specimens tested.

Table 1. Physical properties of hexagonal open-cell aluminium foam specimens having pores in the size range 4.1 – 4.4 mm.

	Specimen 1	**Specimen 2**	**Specimen 3**	**Specimen 4**	**Specimen 5**
Density [kg/m^3]	970	900	860	870	950
Porosity [%]	64	66	68	67	65
Mass [g]	107	100	94	96	105

Honeycomb Specimens

Two honeycomb structures: empty and foam-filled, as shown for example in Figure 1, each of 4 specimens were tested. The 8 empty honeycomb specimens were provided by Bangkok Expressway and Metro Public Company Limited, while the 250 mm-height hexagonal bars of A356.2 T6 open-cell aluminium foam were produced as described in the previous section. Each foam-filled specimens contained 4 aluminium foams, which were filled into the honeycomb cells without bonding.

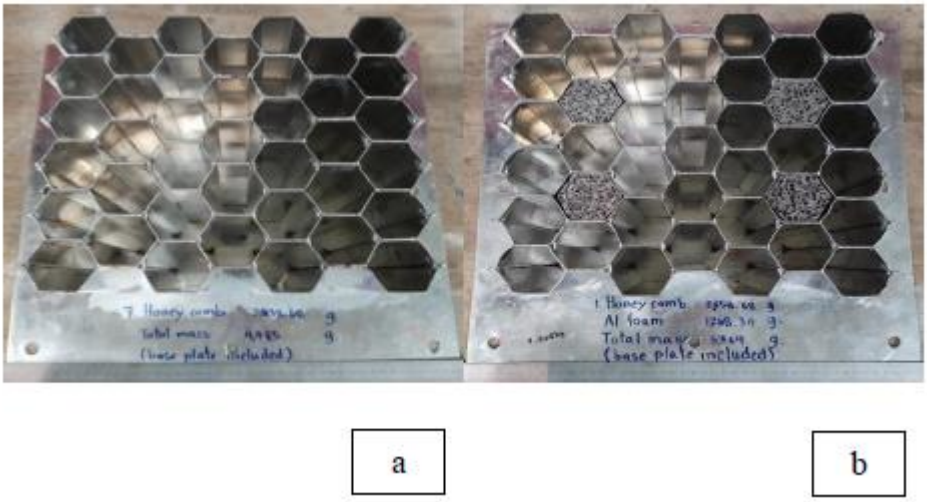


Figure 1. Top view of a) empty and b) foam-filled honeycomb specimens.

Both empty and foam-filled honeycomb specimens were tested under quasi-static conditions to determine the collapse force and to further determine the impact energy that could absorbed in the dynamic tests. Figure 2 shows, for example, a foam-filled specimen after the quasi-static test. It is observed that the aluminium foams did not remain in the correspondent honeycomb cell. The honeycomb cells that were foam-filled were separated in half due to the transverse forces applied by the aluminium foams in the vertical walls of honeycomb cells during compression. Due to this fact, it is also possible to notice the dissociation of the aluminium foams that culminated in the exit of the aluminium foam to the honeycomb structure.

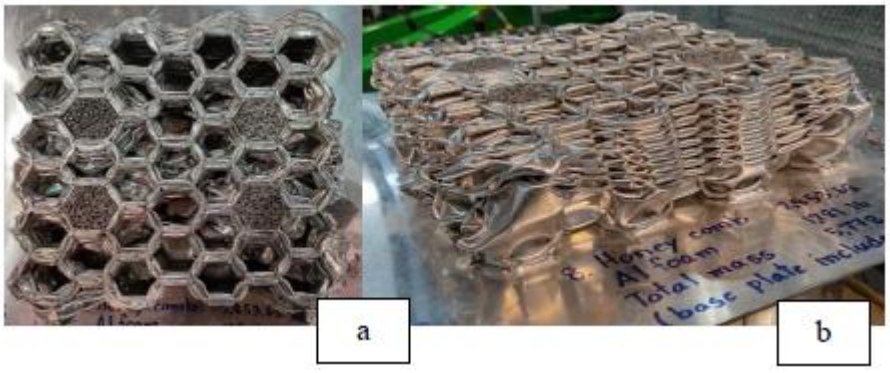


Figure 2. Foam-filled honeycomb specimen after the quasi-static test a) top and b) isometric view.

After quasi-static tests, it was necessary to conduct the dynamic impact tests. As mentioned before, the impact energy was set based on the collapse force, considering that all energy is absorbed by the structure. The empty specimen was impacted by a trolley of 900 kg at an impact speed of 9.3 m/s and the aluminium foam-filled specimen with 900 kg at an impact velocity of 11.2 m/s. These equated to impact energies of 38.9 kJ and 56.5 kJ, respectively.

Figure 3 shows the side view of the dynamic impact test apparatus instants before the impact. The trolley is animated with the impact energy mentioned before and the specimen is attached to a fixed plate in the out-of-plane direction.

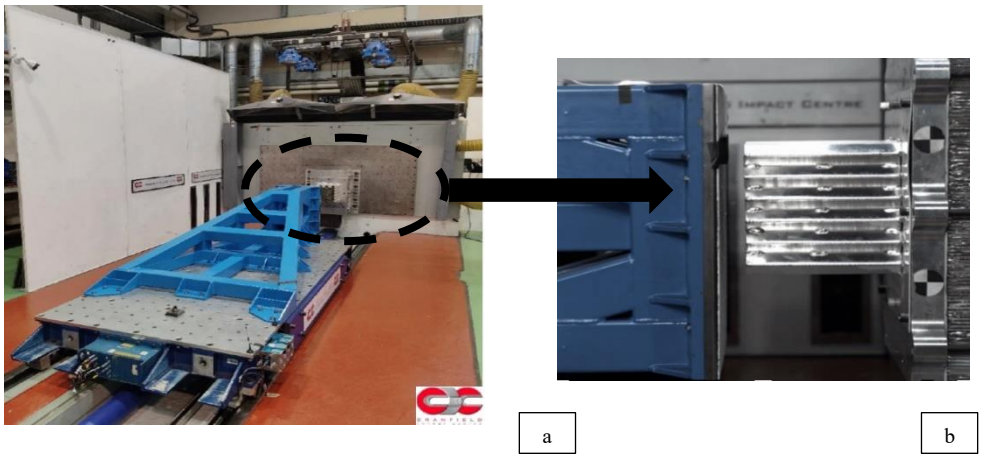


Figure 3. a) Full view and b) side view of dynamic impact test apparatus.

Figure 4 represents the force-displacement curve of the three dynamic impact tests. It is observed an elastic region that is followed by a plateau zone that defines the collapse force. The applied energy was not enough to observe the complete collapse of the structure and, therefore, the densification zone that is developed. However, it is possible to notice that the curve starts to rise in the last stages of the graph, indicating the hypothetic starting point of the densification zone. Also, the collapse mode occurred through the development of folds that started only in the impact end of the specimen. Moreover, the top and bottom cells moved in the vertical axis and, therefore, didn't collapse in the longitudinal axis of impact due to the opening of the welded joints in the lateral part of the structure.

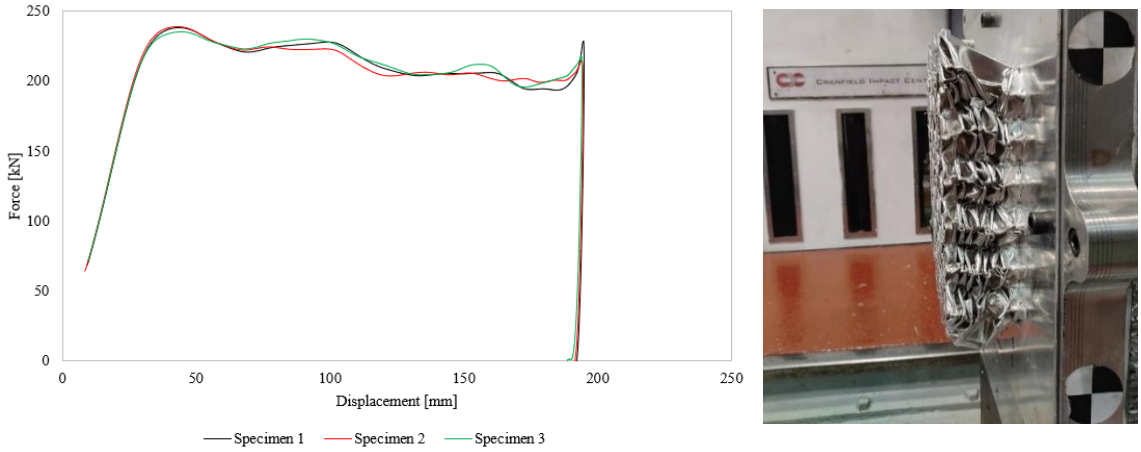


Figure 4. Force-displacement curves of dynamic impact test on empty structures and post-test side view.

Figure 5 shows the force-displacement curve of the three dynamic impact tests performed on the foam-filled specimens. The observed behaviour is like the one noticed for the empty specimens. However, in this case, two different amounts of energy were applied, that is, the first specimens were impacted with the same energy applied to the empty specimens and the two others with the value based on the quasi-static collapse force.

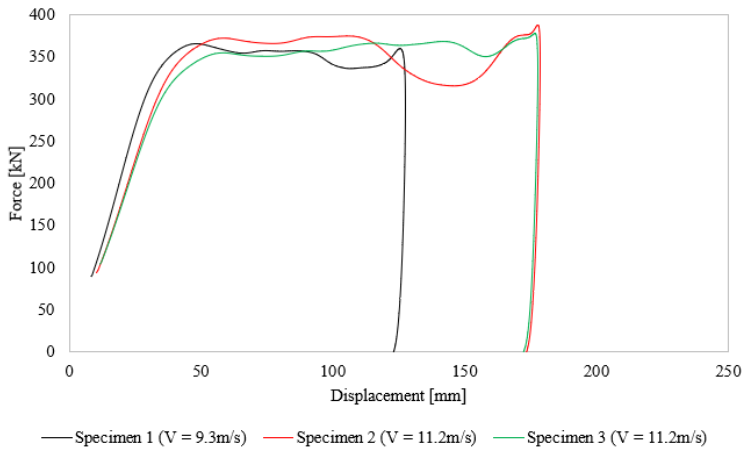


Figure 5. Force-displacement curves of dynamic impact test on foam-filled structures.

Figure 6 shows the structure was able to absorb all the impact energy within 119 mm, approximately, which is a reduction of 36% compared with the empty specimen. The honeycomb cells were separated in half mainly in the foam-filled cells due to the transverse forces applied by the aluminium foam in the honeycomb cells. The corrugated sheets together make the honeycomb structure. Due to manufacturing imperfections, it is not possible to utilise the full potential of the aluminium foam, namely, the densification zone. The aluminium foam on the left was cut in half by the honeycomb cell next to the foam-filled one. This event led to a bad deformation of the aluminium foam since it is noticed that the upper part was compressed while the bottom part remained with the initial aspect. The aluminium foam on the right moved in the transverse direction to the neighbouring honeycomb cell. The bottom part of the aluminium foam showed a brittle behaviour, while the upper part remained the same.

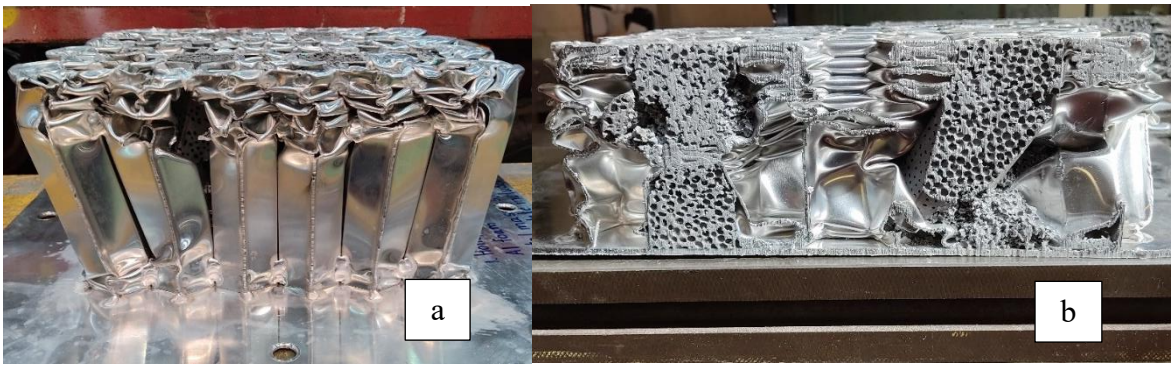


Figure 6. a) Side view and b) view-cut of the foam-filled specimen after dynamic impact test.

Conclusions

Both empty and foam-filled specimens were tested statically and dynamically. Three dynamic impact tests were performed for the two sets of specimens. The calculation of the impact energy was based on the static crushing force without considering the strain rate effects that occur dynamically. The goal was to deform the structure as much as possible without reaching a high value of energy. In this regard, choosing a suitable number of foam-filled cells, aluminium foam mechanical properties or even the optimum number of honeycomb cells was essential in this study. The optimum structure was achieved by filling 18 honeycomb cells with aluminium foam, with a density of 350 kg/m^3. Finally,

foam-filling the crash box allows the control of densification zone by changing the number of foam-filled cells and aluminium foam's density and different impact energies required a different arrangement of foam-filled cells to reach an optimum design.

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