



Energy Absorption Characteristics of Aluminum Egg-box Structure Subjected to Experimental Impact

Maryam Sanaei, Dr. Ayoub Shirvani

Faculty of Science & Technology

Anglia Ruskin University

Bishop Hall Lane, Chelmsford, Essex, CM1 1SQ

United Kingdom

Abstract: Energy absorbing structures have been under investigation for many years. Their importance in engineering applications extends from Impact and explosion protection enclosures to crash safety barriers for automotive and aeronautical industry. Primary focus of interest that encompasses several new engineering challenges is the effective geometrical attributes that could tune the absorbing capacity within specified designed energy dissipation rates. Technologically challenging issues are evaluated and presented in this study. The model under investigation idealizes an egg-box structure with varying geometric attributes that could change the design magnitude and direction to a required absorption rate. Experimental dynamic crash tests have been designed for comparative analyses. Flat and oblique impact loadings have been applied on free-edged single cells cut out from egg-box panels and situated within panels. In addition, experiments have been carried out on flat crushing of entire egg-box panels. The results of the experiments reveal that a single cone loaded obliquely has an average load level which is, approximately, half the same cone loaded normal to the supporting surface. Hence, it is concluded that with more acute loading, the structural strength decreases. The reduced effect of material stretching in flat impacts is realized to be due to the continuity of the cells. Additionally, it is observed that the average load level of an impacted single cone is approximately 10% of that of the entire panel, where lateral movements are restricted.

Keywords: Egg-box, Energy Absorption, Structural Impact, Experimental Crash Test, Energy Absorbing Structure, Dynamic Loading

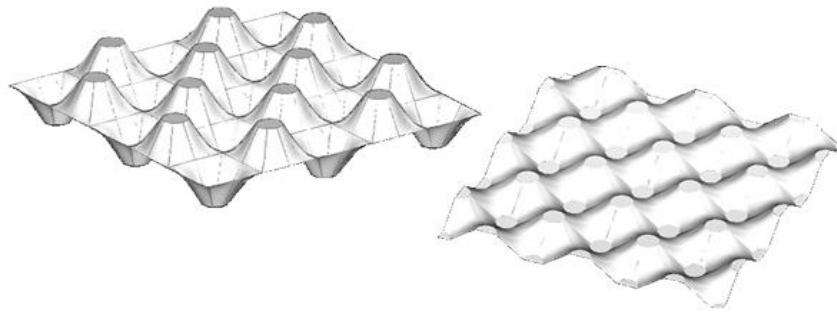
I. Introduction

Severe or fatal traffic accidents are considered to be one of the most threatening dangers in daily life. In a 2001 White Paper on European Transport Policy, the European Commission proposed that the European Union should set itself the target of halving the number of road deaths by 2010. In 2003, the European Union briefed that 1'300'000 accidents a year cause 40'000 deaths and 1'700'000 injuries on the roads with direct and indirect costs of EUR 160 billion [1].

Automotive designers are always looking for more efficient and cost effective absorbers in vehicle interiors to cushion the occupants. One solution is to use cellular solids or structures made up of an interconnected network of cells, which presents the advantage of deforming with comparatively regular force during a compressive impact event. The quality and the relative length of the force-plateau, shown by the absorbers' Load vs. Deformation graph, is one characterizing criteria of a good energy absorber. A new original component, consisting of an array of flat-top frusta, similar to the shape of an egg-box is one such absorber that has the potential to be used in a number of different applications. The egg-box structure shown in Figure 1 is patented and manufactured by Cellbond Composites Ltd under the name of Pressload [2].

Research has briefly looked into the behavior of cellular structures such as egg-box energy absorbers. Deshpande et al. [3] studied the static loading of these structures. Their proposed travelling hinge model and predicted densification strain were in good agreement with the response measured using finite element simulations and experimental tests. A second group of researchers investigated the flat crushing of aluminum egg-box panel structures. The effect of variances of material properties and physical boundaries on the deformation response of these structures was studied. With the aid of FE simulations and experimental testing, they observed that velocity dependence present in the level of structural strength of the egg-box structure is mainly due to the strain-rate sensitivity of the aluminum material from which it has been manufactured [4]. It is concluded in both studies that the energy absorption capacity of aluminum egg-box structures is comparable to that of metallic foams.

Figure 1 Egg-box Structure.



In 2009, Nowpada et al. studied the various stages of collapse and crashworthiness in aluminum egg-box structure under quasi-static compressive loading, concluding that egg-box energy absorbers can play a significant role in improving the crashworthiness of vehicles [5].

Advancements on studying the characteristics of the egg-box structure as an innovative and ideal energy absorber can increase knowledge towards its optimized configuration. Previous scientists have been looking at the performance of the egg-box under static and quasi-static loadings. This study intends to expand the investigation by reviewing the dynamic response of this structure when subjected to flat and oblique loadings, through experimental works.

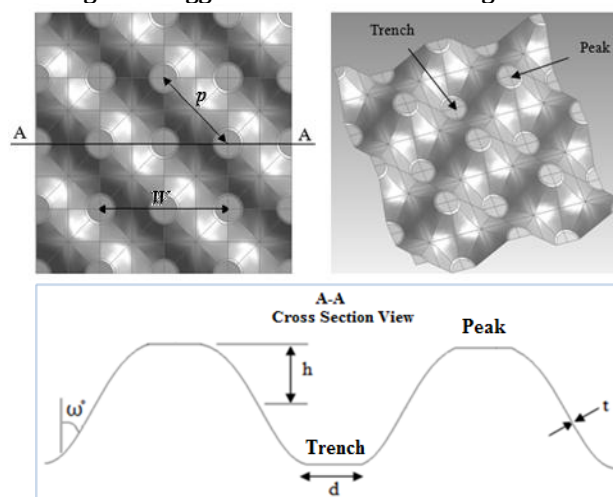
The experiments include axial and oblique impacting of free-edged single cells separated from egg-box panels, axial and oblique impacts of single cells situated within panels and axial impacts of entire egg-box panels. The study covers details on the specimens used, their material properties, preparation procedure, test equipment and the techniques employed. The results of the experiments are presented and analytically explored.

II. Characteristics of Aluminum Egg-box Structure

The egg-box, as suggested by its name, is a structure consisting of a series of conical cells, forming the shape illustrated in Figure 2 with the parameters (p) being the diagonal inter-peak distance and (W) the distance between two consecutive peaks/trenches in lateral direction. This geometrical arrangement of regular flat-top cones is designed to provide axial strength against external forces. In addition, the structure is renowned for its ability to deform in a predictable manner and produce consistent results under various impact angles [6]. Based on the material involved in its production, the egg-box structure can come in relatively low weights and be manufactured to desired geometrical features for specific applications.

The geometrical appearance of the egg-box structure also contributes towards its suitability as an energy absorber. Specific geometrical measures in the structure of an egg-box cell can be adjusted to result in desired levels of energy absorption. Varying the inter-peak length (p), apical angle (ω), cell diameter (d) and/or wall thickness (t), in addition to the material type used and the level of constraints applied to the structure can result in diverse energy absorption characteristics in this structure.

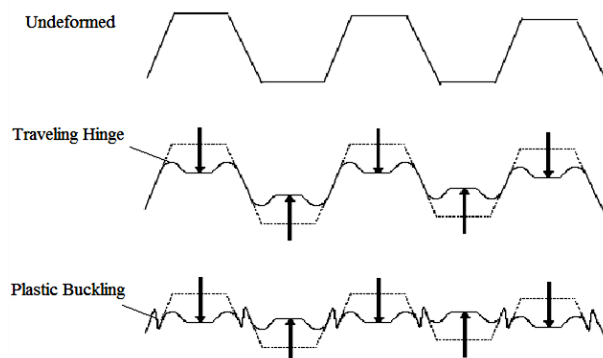
Figure 2 Egg-box Geometrical Configuration



The quality and the relative length of the plateau for the force vs. displacement curve associated with the impact of this structure are characterizing criteria of an efficient energy absorber. The presence of a specific

feature displayed in the deformation process of the egg-box structure, greatly contributes towards its aptness as an energy absorber; with the collapse of the egg-box geometry under impact loads, two main deformation mechanisms can be observed: Travelling Hinge deformation and Plastic Buckling deformation (Figure 3). These two phases need to be investigated more thoroughly for the energy absorption of the egg-box structure to become more predictable and noticeably improved.

Figure 3 Egg-box Deformation Procedure



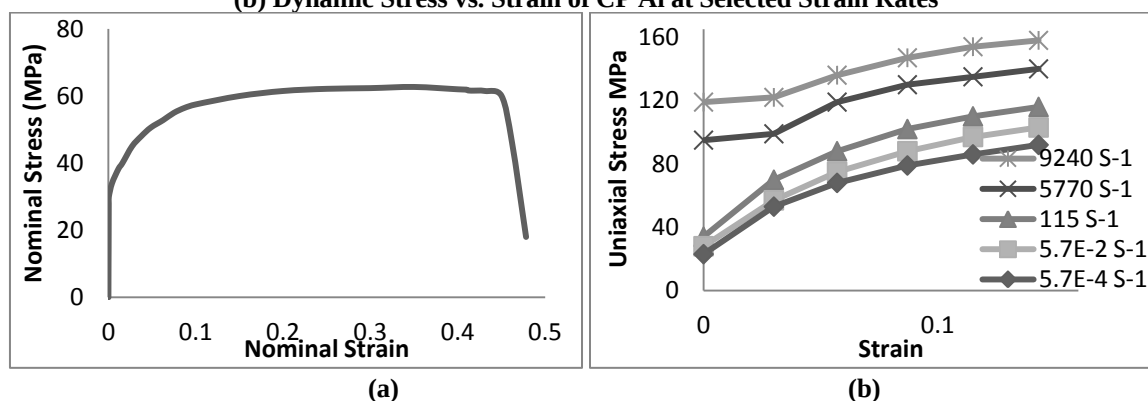
Currently aluminum parts are employed in the automotive industry, most importantly due to their significant weight saving features. To maintain the characteristics of an ideal absorber and as a most commonly used material in this industry, aluminum alloys are selected in this study for the production of egg-box structures.

Experimental testing is used in this work as the main logical method of evaluating the effect of geometric characteristics in the performance of a structure and its energy absorption capacity.

III. Material Properties and Specimen Preparation

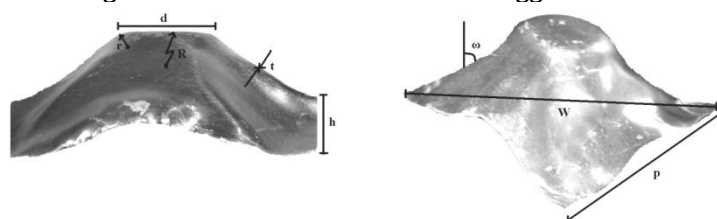
In this study two geometrically different egg-box samples are impacted. The samples were fabricated from aluminum sheet metals. Commercially Pure (CP) annealed 1050 H111 aluminum sheets, consisting of 99% aluminum, with thicknesses of 0.5 and 0.8mm were used in the production of specimens.

**Figure 4 (a) Measured Tensile Behavior of Al 1050 H111 Sheets
(b) Dynamic Stress vs. Strain of CP Al at Selected Strain Rates**



Al1050 is a grade of aluminum used for general sheet metal work where moderate strength is required. The material properties of the alloy are provided in Figure 4(a). Figure 4(b) shows the stress-strain curves of this material for a range of strain rates.

Figure 5 Geometrical Dimensions of Egg-box Cells



The sheets were cold-pressed between lubricated closed dies into egg-box shaped sheets, then cut to panels with overall cross dimensions of $300 \times 300 \text{ mm}^2$. The dimensions and geometrical details of the two sample sets

are presented in Table 1 in accordance to the factors shown in Fig. 5. Factors (R) and (r) are approximate measures.

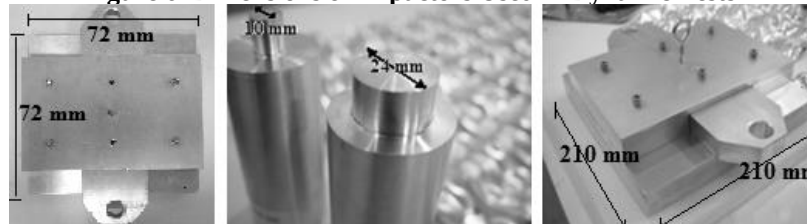
Table 1 Egg-box Cell Dimensions

Geometrical Factors	W (mm)	d (mm)	p (mm)	h (mm)	t (mm)	R (mm)	r (mm)	ω (deg)
Sample 1	75	24	103	12	0.8	50	2	48
Sample 2	36	10	52	6	1.0	50	2	53

IV. Experimental Setup

The egg-box specimens are impacted by drop masses of 5500g and 225g, for the entire panel and the single cells respectively, as shown in Fig. 6. The weights are directed to free fall at a contact speed of 6ms-1. The samples are prevented against lateral movements.

Figure 6 Dimensions of Impactors Used in Dynamic Tests



The applied force is measured using a universal low profile load cell with $\pm 0.05\%$ accuracy class and the data is recorded through a 1000kg capacity digital interface. A high frequency industrial accelerometer with $\pm 500G$ is placed on the impactor to verify the load and displacement histories in the drop weight tests.

Three sets of tests are performed per sample type including flat impact of the entire panel, flat impact of a single cell within the panel and oblique impact of a single cell within a panel. For sample type 1 two extra sets of tests are conducted including flat impact of a free-edged single cell and oblique impact of a free-edged single cell. Due to the small geometrical features of sample type 2 and the velocity of the impact, the latter test has been omitted for this sample type.

V. Drop Test Results

In the dynamic impact of single cones separated from a panel, as illustrated in Figures 7(a), due to the speed of the loading, the material begins to stretch following initial contact. Signs of low strength displayed by the structure at this stage are due to the friction present between the cell and the supporting surface. With no constraints present at the edges, the trench corners at the edge of the cell begin to curl upwards, slightly increasing the strength level in return. The force level is continuously elevated as the deformation progresses. In a respective order the deformation continues by plastic hinges forming at the peak to trench transition lines, peak curvature flattens and then goes through inversion, the top cone of the cell is plastically deformed and eventually, the force level rises at a steep slope as full compaction occurs.

When a similar free-edged single cone specimen is subjected to an oblique load, the side of the cell which is initially touched by the edge of the impactor starts bending at the contact line. The thin shell structure shows very little resistance to this preliminary load. Due to the presence of the support surface extension acting as a stop at the bottom of the cell, as the deformation progresses, this end begins to curl upwards, causing a slight rise in the force-displacement curve. The impacting surface eventually reaches the peak cone and the entire structure begins to fold, hence the force level begins to increase further. Finally the impactor hits the tilted support surface resulting in a steep rise in the curve. This is shown in Fig. 7(b) for loading at an angle of 45° . As a consequence of the freedom present at the cell edges in the first two test types, the force-displacement curves enter the plastic region at very early stages of deformation.

The resultant curves of the impacts on single cones within the egg-box panel structure at 90° and 45° are shown in Figure 8. A brief review of the force-displacement curves resulted from these tests reveals the effect of the continuity of the egg-box panel. With the adjacent cells partially restricting the lateral stretch of the impacted cell,

the strength level of the cell rises substantially in comparison to the free-edged specimens. Additionally, the entire deformation behavior of the cone would be different.

Figure 7 Result Curves for Impacting Free-edge Single Cell of Sample 1
(a) at 90°, (b) at 45°

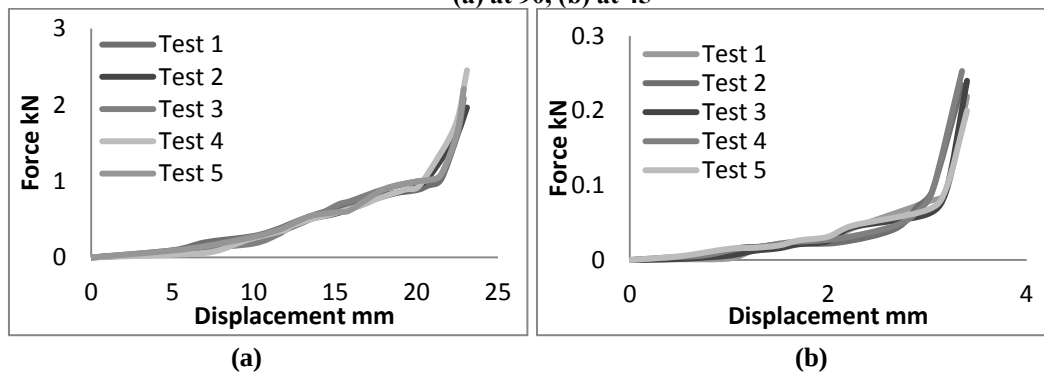
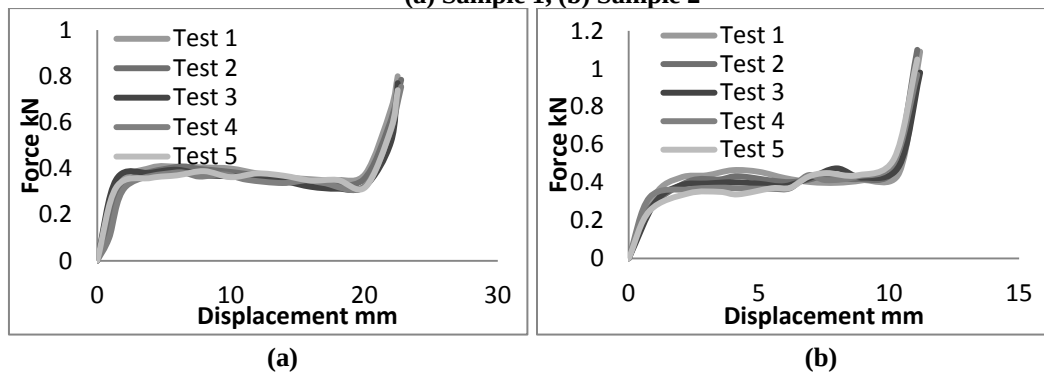


Figure 8 Result Curves for Impacting Single Cone of at 90°
(a) Sample 1, (b) Sample 2



Once the cell is impacted by the cylindrical weight, an inversion process of the peak cone begins with travelling hinges forming at the peak circle circumference. The translation of this occurrence in the curve is the initial steep rise. Simultaneously, the neighboring trench cones show minor signs of deformation in the base curvature region. The procedure will continue until the travelling hinges are no longer present and the inversion of the cone will cease.

In the oblique impact of a single cone situated within an entire egg-box panel, the cylindrical mass, centered with the peak diameter, initially comes into contact with a corner of peak curvature. Meanwhile, the cone is bent over a diameter of the peak circle in line with the impactor edge. The four neighboring cones in this situation will be acting contradictorily; the two cells positioned above the impacted cell, in terms of the impact location, will be stretched in tension while the lower two cells will be slightly compressed as part of the impacted cone tilts in their direction.

Figure 9 Result Curves for Impacting Single Cone of at 45°
(a) Sample 1, (b) Sample 2

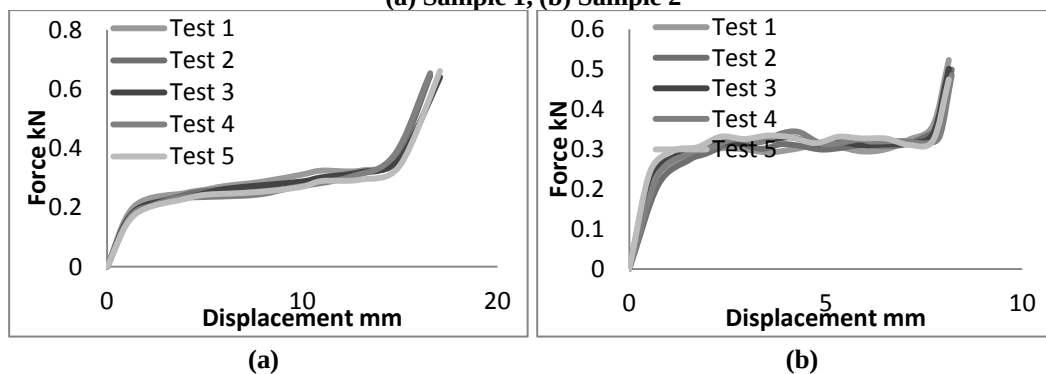


Figure 10 Result Curves for Impacting Single Cone of at 90°

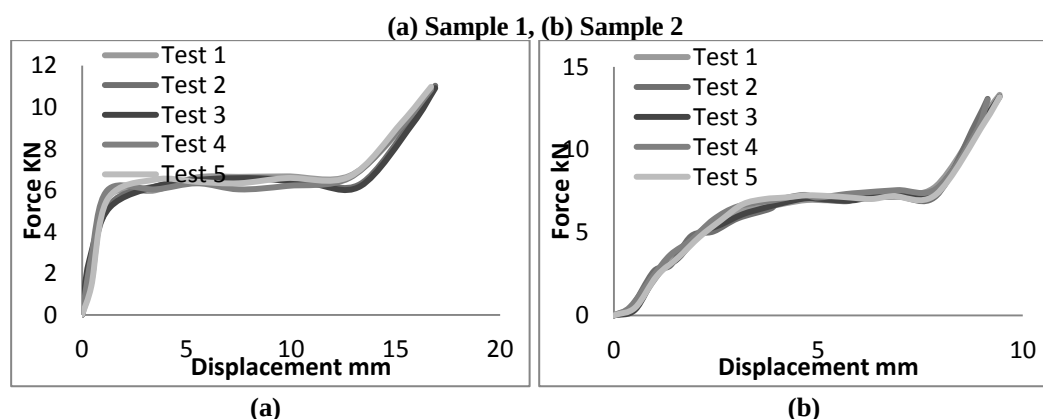
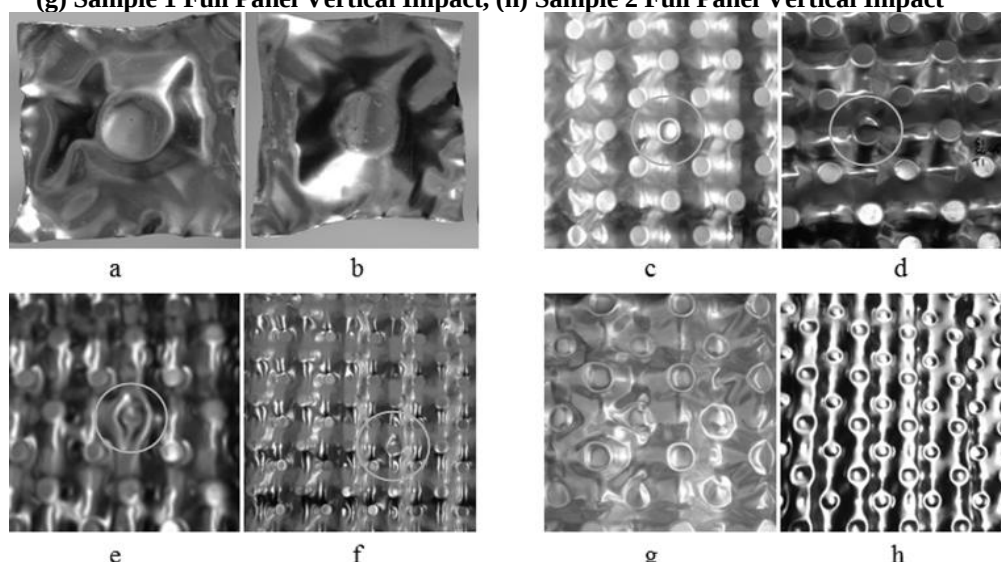


Figure 10 shows the results for the 90° impact test for sample types 1 and 2. It can be seen that both cases follow the same path. The crush response curve shows a primary rise in load in the elastic region with the initiation of deformation corresponding to the bending/flattening of the peak curvature about its circumference. This is followed by a kink and change in the slope of the curve as it enters the plastic region with the appearance of travelling plastic hinges at the top and bottom, and eventually at the mid-point of the cell walls. The crush load remains moderately constant with the progression of deformation, up to the point where the peak and base of the cells reach the same point. The steep rise in the curve emerging past the point of densification illustrates the bottoming phase where no more plastic hinges will appear.

Fig. 11 shows the samples as impacted with regard to each test type. The disfiguration patterns can be linked to the deformation procedures described earlier in this section.

Figure 11 Post-impact Deformed Samples

(a) Free-edged Single Cone Impacted at 90°, (b) Free-edged Single Cone Impacted at 45°, (c) Sample 1 Single Cone within Panel Impacted at 90°, (d) Sample 1 Single Cone within Panel Impacted at 45°, (e) Sample 2 Single Cone within Panel Impacted at 90°, (f) Sample 2 Single Cone within Panel Impacted at 45°, (g) Sample 1 Full Panel Vertical Impact, (h) Sample 2 Full Panel Vertical Impact



VI. Concluding Remarks

From a comparison between curves of Figure 8 with Figure 9 it can be seen that a single cone loaded obliquely has an average load level which is approximately half of that of the same cone loaded vertically. This proves the fact that with the reduction of measure of the angles between the impact direction and the horizon, the strength of the egg-box energy absorbing structure decreases.

On another note, despite different geometrical measurements, both samples are showing similar average force levels. This is due to the larger concentration of cells in sample type 2 in comparison to sample type 1; shorter inter-peak lengths mean higher cell density within constant panel cross-sectional dimensions.

As expected, comparison between the graphs of single cone and entire panel for each sample shows that the average load level of a single cone is approximately 10% of that of the entire panel in cases with restricted boundaries.

The presence of neighboring cells and the assumption of the panel being continuous minimize the effect of material stretching in the deformation process due to flat impact. It can be seen that the densification is occurring at around 75% of the entire height of the panel.

The results obtained from these experimental works can be employed as tools for verifying results of numerical and analytical techniques. Validated models such finite element simulations, can be used in future studies as repetitive and less expensive means for further investigating and optimizing the deformation behavior of egg-box energy absorbing structures.

VI. References

- [1] [1] European Commissions (EC) (2003), Saving 20000 Lives on Our Roads, Office for Official Publications of the European Communities: Luxembourg
- [2] [2] Ashmead, M. (2000), Energy-absorbing structures Int. Patent, Serial No. WO 00/31434
- [3] [3] Deshpande, V. S. and Fleck, N. A. (2003), Energy absorption of an egg-box material, *J. of the Mechanics and Physics of Solids*, vol. 51(1), p. 187–208
- [4] [4] Zupan, M., Chen, C. and Fleck, N. A. (2003), The plastic collapse and energy absorption capacity of egg-box panels, *Int. J. of Mechanical Sciences*, vol. 45(5), p. 851–871
- [5] [5] Nowpada, S., Chirwa, E. C., Myler, P. and Matsika, E. (2010), Aluminium Egg-box panel as an energy absorber for pedestrian protection, *Advanced Engineering Materials*, vol. 12(7), p. 591–595
- [6] [6] Ashmead, M., Bedus, S. and Bradley, S. (2000), *Advanced Materials for Enhanced Automotive Safety*, Automotive Composites and Plastics Conf.

VII. Acknowledgement

The author wishes to thank Cellbond Composites Ltd, Huntingdon, UK for providing aluminum egg-box structures.