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Evaluating the effect of shape on energy absorbing response of structures used in armored vehicles floors

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Abstract. Improvised explosive devices (IEDs) are a major threat to the lives and wellbeing of soldiers transported in armored vehicles. The blast of an IED under vehicle body can cause severe injuries especially to the lower extremities of vehicle occupants. Blast-mitigating structures are developed to absorb as much energy as possible to protect occupants from the effect of blast. These structures are placed on vehicle floor to soften the impact on occupants' lower extremities thus minimizing injuries. Shape plays an important role in determining the amount of energy absorbed in these structures. This paper presents a finite element study where nonlinear finite element (FE) models were used to simulate the motion of vehicle floor due to the blast of an IED. A benchmark structure was developed to mimic Skydex that is a trademark structure. Different shapes were then used and compared with Skydex. The study shows the potential of optimizing shape to maximize the performance of blast-mitigating structures.

Keywords: improvised explosive device, vehicle structure, land mine, blast, protection.

1. Introduction

A typical improvised explosive device (IED) is an explosive material connected with a detonator, buried beneath earth's surface on the route of vehicles. It is preset to explode either remotely or through a trigger mechanism. IEDs are easy to assemble and require no high technological skills, yet they can inflict large human loss and injuries as well as property damage. During the war in Iraq and Afghanistan, more than 50% of all vehicles losses [1] 61.3% of all deaths and 65.5%:77.7% of all injuries [2, 3] were due to IEDs. The majority of injuries were to the lower extremities [4, 5]. IEDs even pose psychological deterrent by the thought that an area may be infested with IEDs; moreover, the sight of injured soldiers affects the morale of their mates [6-9].

Modern armored vehicles have been fitted with different counter IEDs mechanisms; such as V shape protection plates [10], anti-blast seats [11-15] and energy absorbing structures in the form of mats laid on vehicle floors [16-19]. This paper focuses on the latter mechanism.

Skydex is the trade name of an advanced patented structure that was originally developed reduce impact in running shoes but is currently used by the US army to protect army vehicles against IEDs explosions [20-22]. It consists of a twin-hemispheres arranged periodically made of thermoplastic polyurethane. Through its simple and lightweight structure, it absorbs large amount of impact energy at a constant stress. This mechanism reduces loads transferred to the feet of soldiers sitting inside an armored vehicle during an IED explosion [23]. The behavior of Skydex has been studied [24] and modeled [25]. Its design has been parametrized [26] and, it has been shown that filling the hollow microstructure with sand [27] or water [28] improves its performance. However, despite its success in absorbing impact energy and minimizing peak loads transmitted to vehicle floor, it has been shown



that at floor speeds approaching 12 m/s loads can exceed injury threshold (5.4 kN) of the tibia [29]. The performance of energy absorbing floor mats is still far from ideal [30]. The advances in additive manufacturing techniques have been recently shown to produce complex shapes capable of absorbing more energy under compression loads [31].

Despite the importance of shape in affecting the performance of energy-absorbing floor mats, up to the author's knowledge, no previous research has addressed this aspect. In this paper, we attempt to investigate the effect of shape on the performance of energy-absorbing floor mats. Skydex has been used as a base model for comparing the performance of different shapes under the loading effect of under belly explosion of an improvised explosive device.

2. Model development

2.1 CAD development

The computer aided design CAD model shown in figure 1 was developed to represent a single cell of the Skydex structure according to the published data from Ref. [1]. The thickness of its surfaces is 1 mm. The radius of the hemisphere was assumed 16 mm.

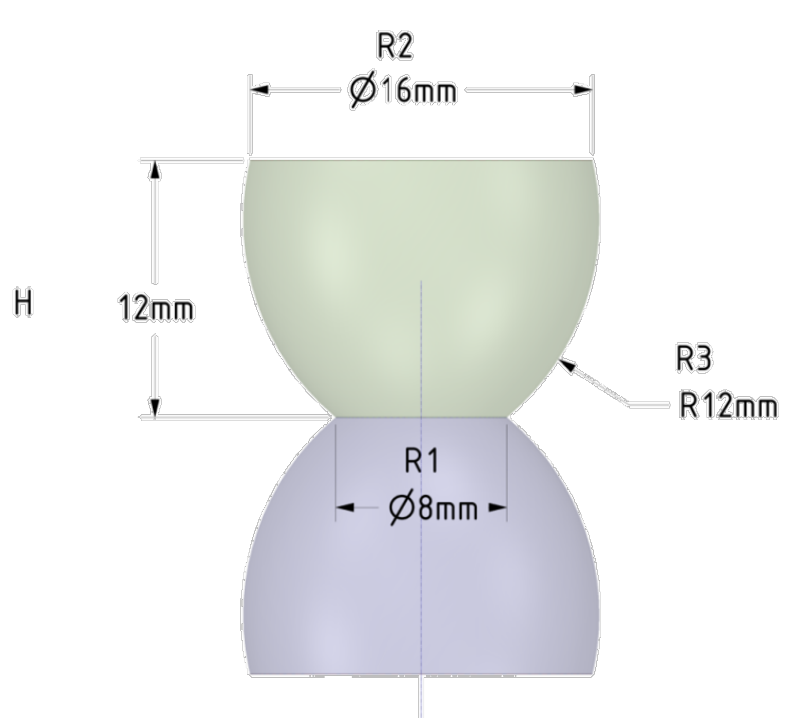


Figure 1.View of the cad model.

2.2 Load determination

For load calculation, the worst case was assumed when an occupant hits the floor with his full body weight landing on his feet. This occurs when a blast is large enough to propel the vehicle upwards after which it slams down to the ground under gravity effect. This scenario involves the effect of the occupant's feet hitting the rigid floor at a 10.8 m/s. This specific speed is within range of values that had been recorded in field [2, 3]. It is also enough to inflict a 10% risk of foot/ankle fracture, which accounts for an abbreviated injury scale of two (AIS 2+) as level recommended by the NATO/RTO HFM-090/TG-25 group in their publicly released report [4].

Considering a mid-size male weighing 78 kg [5] and measuring the surface area of the military boot of the author ~300 cm². The load on one cell is then 0.616 kg. The FE model was developed in ANSYS, which is an efficient finite element package. As shown in figure 2, a rigid steel plate that

weighs 0.616 kg hits the cell from downwards at 10.8 m/s. The time duration was selected as 1.5 ms. This time was calculated to allow the cell to deform to more than half (16 mm) its height moving at full speed of the impactor (10.8 m/s). In reality, the speed decreases due to the resistance of the cell to movement, thus this time was enough to capture the physical phenomenon as evident in the deformed shapes in figure 4.

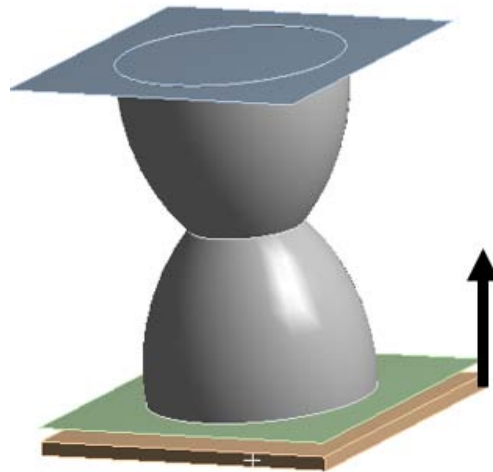


Figure 2. View of the FE model.

2.3 FE model development

A finite element model was developed using the CAD model in ANSYS. The SHELL163 element type was selected due to its accuracy and efficiency. To determine the optimum element size, a mesh sensitivity analysis was conducted and it converged at an element size of 0.5 mm. For material, Skydex is made of thermoplastic polyurethane according to Ref. [6]. The Cowper-Symonds material model [7] was selected to model its strain rate sensitivity in ANSYS. Material properties are given in Table 1.

Table 1. Material properties of Skydex.

Property	Value
Young's modulus of elasticity [MPa]	60
Tangent modulus [MPa]	50
Yield stress (A) [MPa]	8.6
Strain hardening coefficient (B)	50
Strain hardening exponent (n)	1
Strain rate hardening coefficients (D and q)	15 and 3
Poisson's ratio	0.49
Density [kg/m^3]	1100

3. Cellular structures

Different shapes were modeled and simulated under the aforementioned loading conditions. The model was set as shown in figure 3. The cellular structures were developed such that each structure fits inside the same cell surface area of the original Skydex structure. The thickness of each structure is adjusted to achieve the same mass as the original Skydex structure. This is accomplished in order to isolate the effect of mass and area and include only the effect of cellular shape. However, thickness also influences the response and it will be the focus of future work.

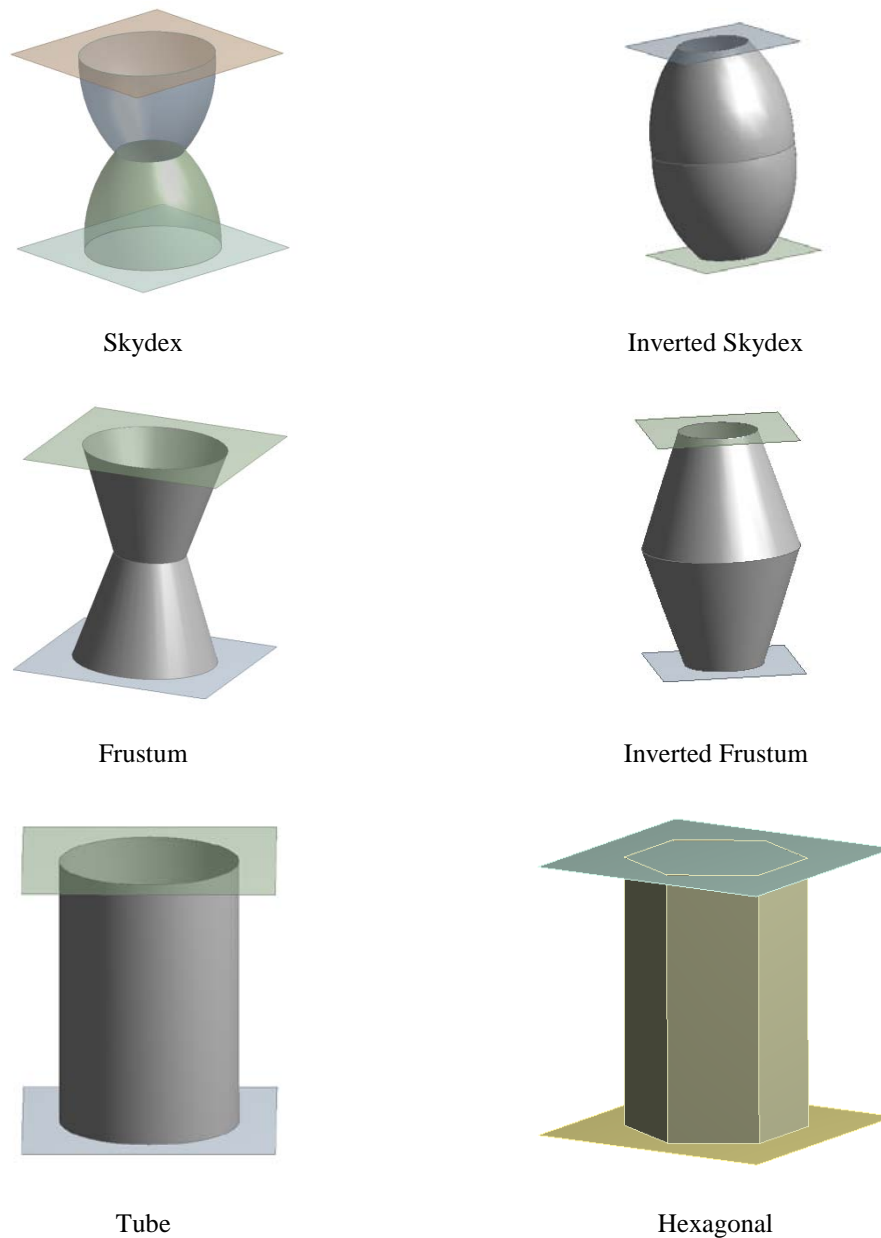


Figure 3. Views of the different CAD geometries.

4. Results and discussions

Finite element simulation is conducted for each cellular structure and the modes of deformation under impact is recorded and are shown in figure 4. The amount of energy absorbed (EA) in each structure during impact and the average transferred load (ATL) are recorded which and are summarized in Table 2Error! Reference source not found.. It should be noted here that these are the two important metrics for the design of efficient floor mats. A good design must ensure the maximum amount of EA at minimum ATL. This means that the structure protects the occupant's feet by absorbing as much impact energy as possible while transmitting as little energy as possible. Figure 5 shows the general behavior of a structure under impact. It shows the amount of EA as it increases as the structure deforms with time (figure 5-a) and the variation of transmitted load with time as shown in figure 5-

b. The average values of the transmitted load are calculated for each structure and are summarized in Table 2.

It is clear from figure 4 that in general shape has a profound effect on the modes of deformation. For example, inverting the shape of Skydex alters the mode of deformation and the structure starts to crumple from the tighter ends. The frustum shape has sides with no curvatures as in Skydex. Although it appears to deform in the same manner as Skydex, however, a closer look shows that necking in the outer walls of the frustum are developed as shown at onems in figure 4. This raises the transferred reaction force; 30.3 N for frustum versus 26.6 N for Skydex.

For better visualization of results, the values of EA and ATL are normalized with respect to the ones for the original structure –Skydex- and are given in figure 6. Skydex is located at the origin of the plot where other cellular structures are located to its right upper side; this means that other cellular structures absorb higher energies but at the expense of higher transmitted load. We can then conclude that there is a trade-off between EA and ATL as shown in the increasing trend between both values. However, more insight in figure 6 reveals that the trend is not monotonically increasing since an increase in EA does not necessarily mean that ATL will increase at the same percentage. This is obvious if we look at locations of frustum and inverted frustum; they achieve approximately the same values of EA but the frustum transmits 21% less load than the inverted one. This can be further explained if we look at the deformation modes in figure 4 that shows the inefficient and irregular deformation mode of the inverted frustum structure. One can also deduce from Figure 6 that the tube structure is superior to the hexagonal one since it absorbs higher (14%) EA at less (12%) ATL than it. This is evident because the tube is further to the right and below the hexagonal structure, i.e. it absorbs more energy at lower transferred load. Finally, comparing between Skydex and the frustum structure reveals that the curvature of the outer wall play a significant role in the performance of the structure during impact. The frustum structure is simpler than Skydex since there are no curvature in the sidewalls, therefore, it will be easier and cheaper to produce. This observation can be used for developing structures of the simpler and cheaper frustum structure that achieves better 45% increase in energy absorption compared to Skydex. The 34% increase in ATL in case of the frustum structure must then be looked in more details. For example, the structure can be optimized to minimize it.

Table 2. Energy absorbed (EA) and average transferred load to each cellular structure.

	EA (mJ)	ATL (N)
Skydex	398.1	26.6
Inverted Skydex	521.2	30.3
Frustum	605.9	39.6
Inverted Frustum	574.0	41.1
Tube	466.9	33.6
Hexagonal	577.6	35.7

5. Conclusions

It can be concluded that the shape of the cellular structure plays a major role in the performance of energy absorbing structure for the application of vehicle floor mats. Simple shape changes such as the curvature in the sidewalls will significantly alter the performance of the structure. It was revealed that there is a strong trade-off between the amount of energy absorbed and the transmitted load, which are the two most important performance measures. In addition, we found that some structures perform more efficiently than others do. This means that optimization can be applied to find the shape that achieves the best/optimum balance between energy absorption and transmitted force. It is recommended that this point is suitable for further future research. Finally, this present research focused only on the effect of shape of cellular structure using limited number of shapes while the same material was used for all structures.

Based on this work, it is recommended that future study must include: initial floor speed, cell thickness and type of material. In addition, experimental testing must be included to help in verifying FE results.

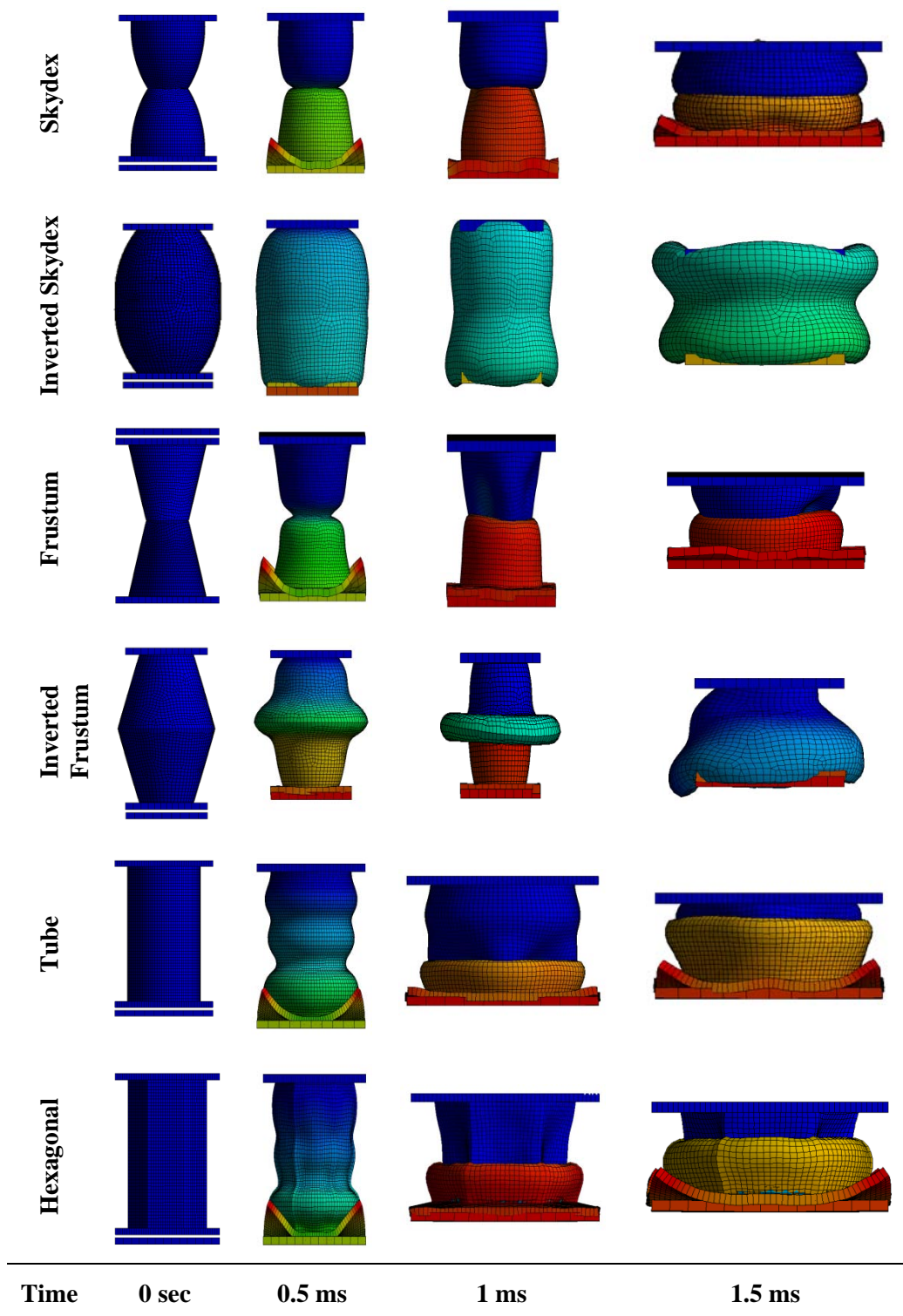
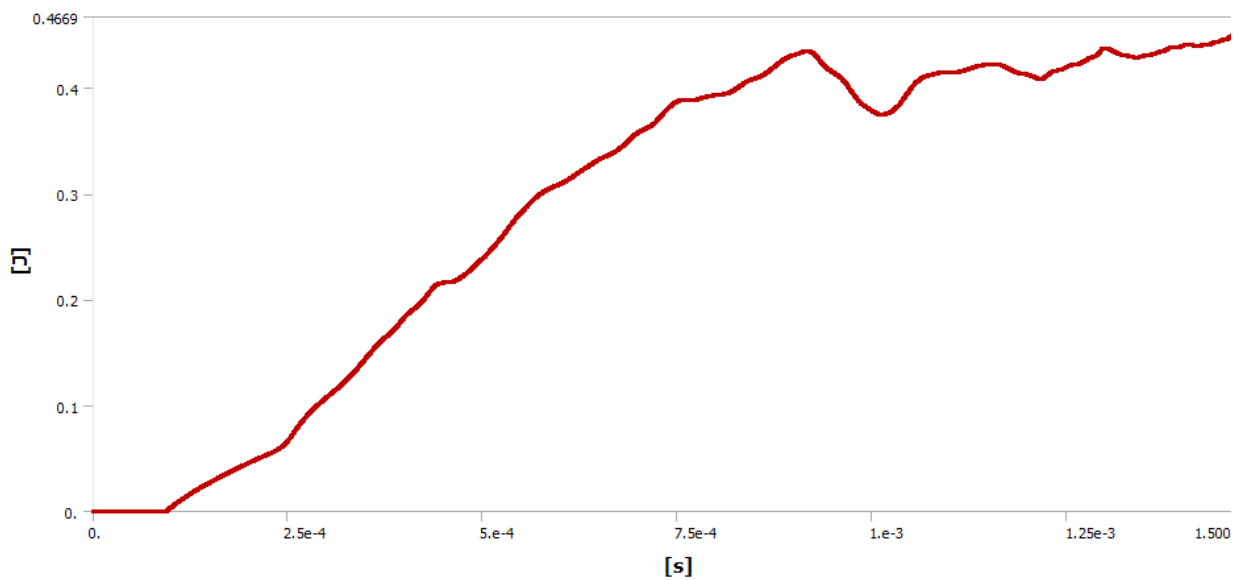
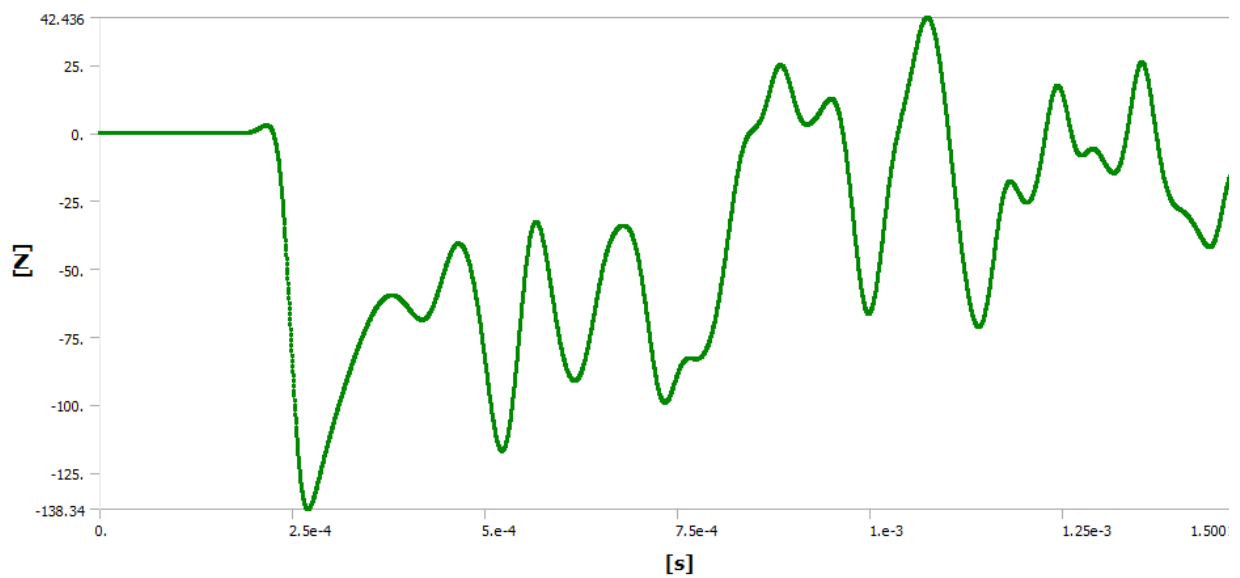


Figure 4. Modes of deformation under impact load.



(a) Change of energy absorbed with time



(b) Change of transmitted load with time

Figure 5.A sample of EA and transmitted load during time for Skydex structure.

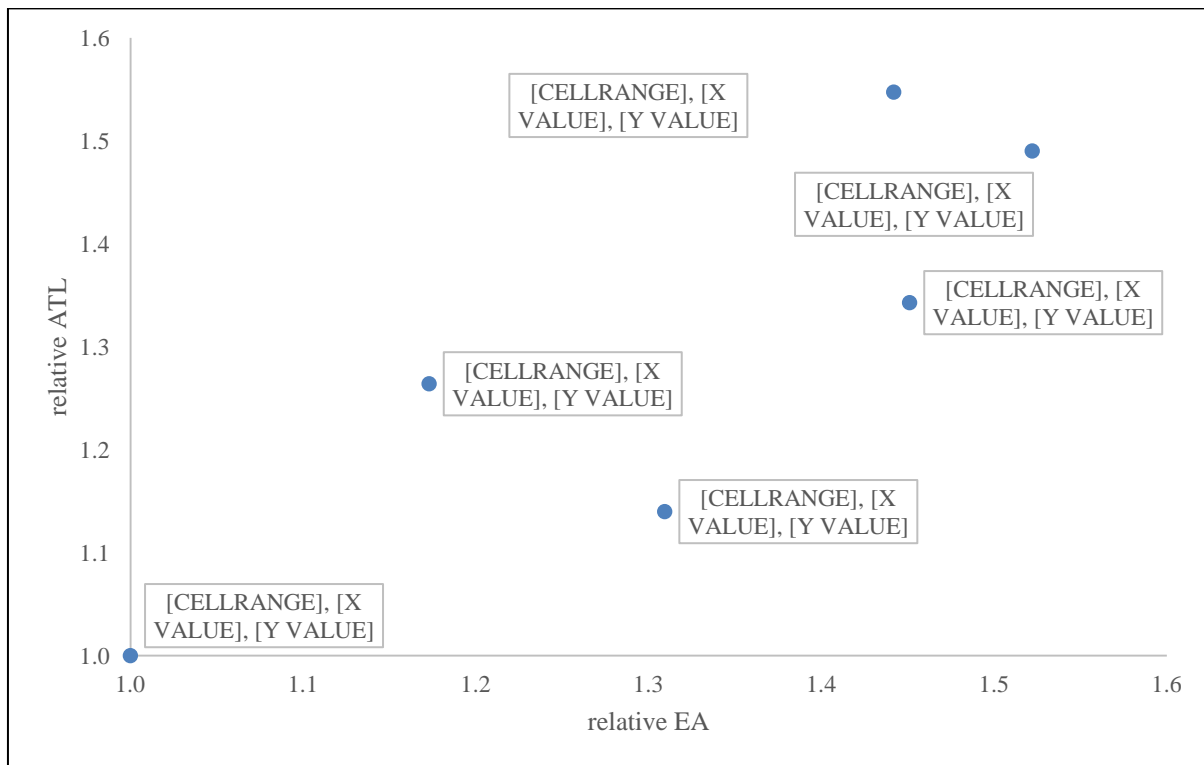


Figure 6. Representation of relative EA and ATL values for the different cellular structures.

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