# Hexagonal Cross-Sectional Shape Crash Box Structure for Better Frontal Crash Protection

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**Abstract**

Multi-column and single-column crash-box structures have exhibited considerable advantages in energy absorption with lightweight and have widely used as energy absorber in aerospace, automotive and structural industries. Unlike existing either hollow or foam-filled geometrical column structure, this study will design, evaluate and compare a novel design of Multi-Column Crash-Box Structure with controlled wall thickness and diameter cross-section with Single-column Crash-box along the axial direction to mimic actual crash propagation at the high-velocity impact. According to different studies attain the combinations of wall thickness and geometric shape among single-column and multi-column structure. Thus, four different shapes with average diameters are considered to prove the combination numbers of the axial structure along fix length will have a significant effect on overall Specific Energy Absorption (SEA) and total Deformation at safes state as indicated by New Car Assessment Program (NCAP). The proposed design shows that the Multi-Cell Hexagonal Structure simulated using ANSYS/Explicit Dynamic obtain the most positive counterparts in improvement for the specific energy absorption (SEA) and successfully deformed at the more prolonged time.

**Keywords:** Multi-column Hexagonal, crash box, lightweight

## 1. Introduction

There are two parts of an automotive safety system available in a vehicle which are active safety and passive safety. Active safety features work as a crash preventive tool from occurring or reducing the severity of the inescapable crash. Examples of active safety system are electronic stability control (ESC), electronic brake distribution (EBD) and anti-lock braking systems (ABS). While passive safety features like seatbelts, airbags and crash management system (CMS) are designed to protect the area around passenger and reduce the risk of serious injury at once the accident occurred. To ensure the living space is, as safe as possible passive safety features work as crumple zones, to absorb and distribute crash forces over the crashworthiness structure.

The Crash Management System (CMS) is a structural module mounted in front and rear of a vehicle and each connected to the longitudinal beam front and rear as well. CMS consists of bumper fascia, bumper beam, an energy absorber on both sides and front longitudinal beams which attach to the rest of the vehicle structure to absorb total crash loads (Figure 1). Every level of crash prevention recognise by CMS varies with different vehicle speed when a crash occurs. World Health Organization (WHO) has highlighted few requirements to minimise car incident through enforcing the world to comply at least frontal impact and side impact crashworthiness standard either by UN Regulation 94 or equivalent national standard (World Health Organisation, 2015).

However, designing the crash-box sometimes facing failure when the design does not function as it should be on a thin sheet of selected material with its geometric cross-section. It required additional crash beads on the crash-box wall structure (B, C, & P, 2014; Nakazawa, Tamura, Yoshida, Takagi, & Kano, 2005). In automotive crashworthiness study, the crash energy is primarily absorbed by the front and rear crash management systems (CMS), followed by the deformation of the longitudinal beams. Crash Management System consists of a bumper beam and two crash boxes that are designed to minimise the damage to the vehicle at low-speed impacts and to absorb a maximum of crash energy by deformation at higher speed impacts without affecting the longitudinal beam (Figure 2). Finding an excellent cross-sectional shape of a crash box while keeping it in lightweight are challenging (Lademo et al., 2008).

To prove this relation between single-cell column (Hou, Li, Long, Yang, & Li, 2008) with multi-cell column (Yin, Wen, Hou, & Chen, 2011; Ebrahimi & Vahdatazad, 2015) to have a high strength-weight ratio and exceptional energy absorption capability during crashworthiness analysis. This study was extended to analysed and investigated the maximum energy absorption attain through designing multi-cell hexagonal column crash box, and total displacement occurred on multi-cell hexagonal cross-section with aluminium type material to get light in weight design and high impact absorption.

The comparison is made between single-cell structure as a benchmark with a multi-cell structure. The disadvantages regarding the manufacturing and joining complexity are not discussed because it required more understanding of the manufacturing process with the exceptional cost required due to machine technology.

## 2. Crashworthiness

Crashworthiness is a measurement of the ability of a vehicle to absorb excess energy during a collision to plastically deform and secure the maximum possibility of passenger survival Bois et al., (2004). The objective of crashworthiness is to optimise the structure that can absorb the crash energy by controlled component deformations. To compromise that requirement, research council for automobile repairs (RCAR), has highlighted several tests to encounter from low to high-speed impact.

The front CMS is a structural module where the individual elements fulfil carefully balanced functions. At low or medium speed, the impact energy will absorb by bumper beam elastically deflection until it exceeds the load which can be absorbed. However, if the collision happened at medium or higher speed, the energy absorbing elements will transfer to the crash boxes plastically deformed, and only if the energy absorption capacity of the crash box is exhausted, plastic deformation of the front longitudinal occurs. During a frontal collision, they help in absorbing part of the amount of impact energy, and more importantly, they reduce the impact forces transmitted to the occupants.

### 2.1 Crash Box

The crash box is designated to absorb energy by progressively folding and bending locally as the column walls collapse. As in Figure 3, an individual feature of such deformation mechanism is that the rate of energy dissipation is propagated along each level from low, medium and high-velocity impact over relatively narrow zones. The crashworthiness of the crash box is expressed regarding its energy absorption (E), specific energy absorption (SEA) and total deformation (δ).

### 2.2 Crash Test Evaluation

Surviving a crash is how to overcome the high kinetic energy evolved just at the moment of the impact occur. According to the European Aluminium Association, (2013) and NCAP test crash (Tobergte 2013), protection priorities vary with the speed of the car up to 3 levels of crashing testing. According to Table 1 presented the typical percentage of energy absorption for individual components at CMS taken from Crash Management System, 2011. Firstly, speeds up to 15 km/h, the primary goal is to minimise repair costs, then, speeds between 15 and 40 km/h, the first aim is to protect pedestrians and lastly at speeds over 40 to 60 km/h, the most critical concern is to rescue the car occupants in real-world situations. The crash test will be designed to hit a barrier (Figure 4) either full frontal crash or offset frontal crash with speed according to country NCAP testing regulation (Niyazi Tanlak 2015).
Improving vehicle safety conventionally will put higher investment, and it is a challenge towards automotive industries. Often the simulations are satisfactory when the models which do not adequately capture all aspects of crushing damage observed experimentally. However, in the design process with all accessories needed and setup time are too long, computer simulation is the best tools, and the results are equivalent to the actual test. Therefore, with the advance of computer technology, simulation software from nonlinear to dynamic crashworthiness analysis able to ease down many constraints that automotive industries have faced over the past decades. Since crash tests are extremely expensive and technology development has sped up very fast. Therefore, software simulations have been used to assist many in crashworthiness design and analysis to achieve the same goal as an actual crash test. The main reason for using engineering simulation software is that the researcher will be able to study and predict the behaviour of the proposed design before fabricating in the real condition. In automotive design simulation, most of the researcher commonly used CATIA V5 for CAD design and LS-DYNA as crash simulation (Lei, 2011; Li, 2009) but there is also another design analysis used such as HYPERMESH, ABAQUS (G. Biradar 2014) and ANSYS (Zonghua Zhang 2011).

## 3. Modelling Assumption

Hexagonal cross-sectional geometries are considered in this study with single and multi-cell crash box. Referring to Figure 5 and 6 are the illustration of a single cell, and multi-cell crash box design with designation symbol use to each parameter according to Table 2. The simulation is intended to study crash box performance in the full-frontal

impact crash tests. The crash box is modelled in ANSYS/SpaceClaim using the parameter with a model assumption as in Figure 7.
The behaviour of the crash-box is simulated for the loading conditions in a standard high-speed crash test, because of the difficulty in modelling to simulate the whole car will cause long computational times. Thus, a lumped mass parameter vehicle model is developed from the energy equation that accounts for the structural behaviour. While other attach part nearby bumper system and longitudinal beam are not discussed.

Applied Energy equation of the vehicle, $E = \frac{1}{2} mv^2$ ----------- (1)

A Vehicle mass took with two passengers condition, 1200kg at the full-frontal crash box with a distribution at-end mass of 600kg for each crash-box on both sides left and right and travelling at a speed of 15.56 m/s (56km/h) strikes a barrier as mentioned in Figure 4. According to NCAP crash regulation, general assumption total load occurs for each crash box during a collision according to types of an impact. To prevent penetration due to excessive deformation, a frictionless self-contact condition has been specified for the element surfaces. All crash-box models are made of AL6061-T6 which widely used in the automotive industry. Excellent for skin sheet on achieving a good balance of formability, strength, impact energy absorption and high surface quality after extrusion or pressing (Ghassemieh, 2011).

For Full frontal vehicle impact:

Energy created from a vehicle, $E = \frac{1}{2} \times (600 \text{ kg}) \times (15.56 \text{ m/s})^2$

$E = 72.634 \text{ kJ}$

Assumption of constant barrier mass = 2.5875kg

Energy created for Lumped mass, $72.634 \text{ kJ} = \frac{1}{2} \times (2.5875) \times v^2$

**$v \approx 237$ m/s**

Thus, the modelling parameter is set the velocity of 237 m/s for square and hexagonal each with single and multi-column at a cut-off time of 0.7ms. Where the outer thickness was set to 1.5mm and inner thickness for multi-column is 1.0mm. The overall length for all model was set constant at 250mm and average diameter at 80mm.

### 3.1 Design Analysis

The proposed design of a single structure of honeycomb sandwich cylindrical column will be simulated in a full nonlinear transient dynamic finite element analysis using ANSYS/Explicit Dynamic Version 18 Academic. All simulation and matrixes are built to make sure every element have been tested as with a complete justification according to the SEA, Total Deformation and Time (s). If the simulated design does not satisfy the requirement as stated by NCAP. The process will return to design the proposed crash-box process.

## 4. Design Evaluation

The allowable displacement of the crash box is compared between all four cross-sectional design. The research was found that the Hexagonal with single and multiple columns including square shape have more consistent load compared to square multi-column cross-section resulted in more inconsistent energy absorption by time (Figure 8a). After removing the square multi-column (Figure 8b) the simulated data shown that Hexagonal multi-column produces more reliable data distribution for every deformation. At 90mm of deformation shown that Hexagonal multi-column obtains the highest energy absorption.

To verify the acceptance of energy according to its weight resulted from its deformation trough time. Figure 9 was illustrated base on the Specific Energy Absorption (SEA) according to its crash box mass. Therefore, its supported earlier finding showed that Hexagonal multi-column does produce higher energy absorption by time followed by Hexagonal single-column, Square multi-column and the weakest shape was Square single-column.

To support more on the design acceptance, the analysis was evaluated on the crushing forces created due to normal stresses on crush deformation. Thus, Hexagonal multi-column again showed positive value given the highest energy created by deformation. Furthermore, to prove this finding looking at Figure 11 showed that at 120mm of deformation its required about 0.6ms to absorb that high energy. Meaning that, during crushing over time to reduce the severity of the accident is to have a longer time, shorter deformation but maximum impact absorption.

Figure 12a and 12b showed the simulation of Ansys/ExplicitDynamic at a cut-off time of 0.6ms. Seen that Hexagonal multi-column have a smoother crushing wall. Therefore, by increasing the number of vertical edges, the smoother crushing zone will be created. The folding mechanism also is folded evenly throughout the crushing zone. All square shape give a bad folding mechanism, and these answered the behaviour seen in Figure 8a where square multi-column have an inconsistent folding mechanism.

## 5. Conclusion and Recommendation

Under the present study on the crash box cross-section design which tested under crash impact which almost similar to LS-Dyna Finite Element simulation as highlighted in NCAP requirement. The cross-sectional shape, length, thickness and materials do effect the design optimization. Even though this study does not propose any design optimization variables. Still, the crash box can be modelled as a deformable structure in any crash condition. To reduce the computational time, the design was replaced with the FE model and loading condition to reflect the actual crush system occurred in the actual accident to predict a full car model. The resulting optimum shape design is depending highly on the formulated lumped mass for each variable and related data range control. Therefore, the best cross-sectional shape obtained by this study shows that Hexagonal multi-column has the best crushing folding and higher specific energy absorption at maximum impact set by NCAP at 56km/h. The Hexagonal multi-column is successfully achieved the highest energy absorption at shorter time deformation. Even though Hexagonal multi-column has the highest weight, but it is the best design to promote excellent energy absorption among the other three design. The limitation of this design simulation is it does not consider any negative impact toward crushing activity in actual accident example the bumper, tyre friction and road condition. For further investigation study towards best crash box design is to consider another relevant obstacle that should be calculated into the FE model. So that the result obtained correctly reflect the actual crush impact condition.

**REFERENCES**

B, U. D., C, V. K., & P, M. S. (2014). Design Simulation of Crash Box in Car. *International Journal of Engineering Research & Technology (IJERT)*, *3*(1), 978–982.

Bois, P. D., Chou, C. C., Fileta, B. B., King, A. I., & Mahmood, H. F. (2004). *Vehicle crashworthiness and occupant protection. American Iron and Steel Institute*.

Ebrahimi, S., & Vahdatazad, N. (2015). Multiobjective optimization and sensitivity analysis of honeycomb sandwich cylindrical columns under axial crushing loads. *Thin-Walled Structures*, *88*, 90–104. https://doi.org/10.1016/j.tws.2014.12.004

European Aluminium Association. (2013a). Car body – Crash Management Systems. *The Aluminium Automotive Manual*, 1–26. Retrieved from http://www.alueurope.eu/wp-content/uploads/2011/12/4_AAM_Crash-management-systems1.pdf

European Aluminium Association. (2013b). Car body – Crash Management Systems. *The Aluminium Automotive Manual*, 1–26. Retrieved from http://www.alueurope.eu/wp-content/uploads/2011/12/4_AAM_Crash-management-systems1.pdf

Ghassemieh, E. (2011). Materials in Automotive Application, State of the Art and Prospects. *New Trends and Developments in Automotive Industry*, 365–394. https://doi.org/10.5772/1821

Hou, S., Li, Q., Long, S., Yang, X., & Li, W. (2008). Multiobjective optimization of multi-cell sections for the crashworthiness design. *International Journal of Impact Engineering*, *35*(11), 1355–1367. https://doi.org/10.1016/j.ijimpeng.2007.09.003

Kiran Cheni, R., Sinha, A., & Narayan, S. (2013). Enhanced Light Weight Frontal Crash Box Design for Low Speed and Insurance Tests. *Symposium on International Automotive Technology 2013*, *SAE*

*Intern*(1), 1–5. https://doi.org/10.4271/2015-01-1500.Abstract

Lademo, O. G., Berstad, T., Eriksson, M., Tryland, T., Furu, T., Hopperstad, O. S., & Langseth, M. (2008). A model for process-based crash simulation. *International Journal of Impact Engineering*, *35*(5), 376–388. https://doi.org/10.1016/j.ijimpeng.2007.03.004

Nakazawa, Y., Tamura, K., Yoshida, M., Takagi, K., & Kano, M. (2005). Development of crash-box for passenger car with high capability for energy absorption. *VIII International Conference on Computational Plasticity*.

Systems, C. M., Aspects, D., Conditions, D. B., Analysis, V., Cms, S., & Penetration, M. (2011). Design – Case study : Crash Management Systems ( CMS ) 5 Case study : Crash Management Systems ( CMS ). *The Aluminam Automotive Manual*, 1–24.

World Health Organisation. (2015). Safer Vehicles and Roads. *Global Status Report on Road Safety*, 46. https://doi.org/10.1016/B978-0-12-385185-7/00054-8

Yin, H., Wen, G., Hou, S., & Chen, K. (2011). Crushing analysis and multiobjective crashworthiness optimization of honeycomb-filled single and bitubular polygonal tubes. *Materials and Design*, *32*(8–9), 4449–4460. https://doi.org/10.1016/j.matdes.2011.03.060

**Appendix**

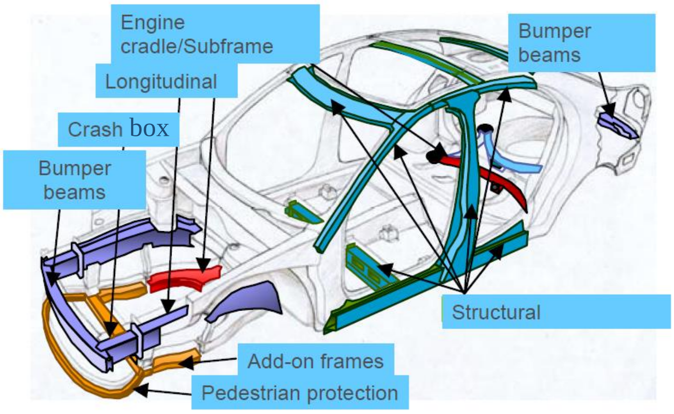



Figure 1: Crash Management System (CMS) (European Aluminium Association, 2011)

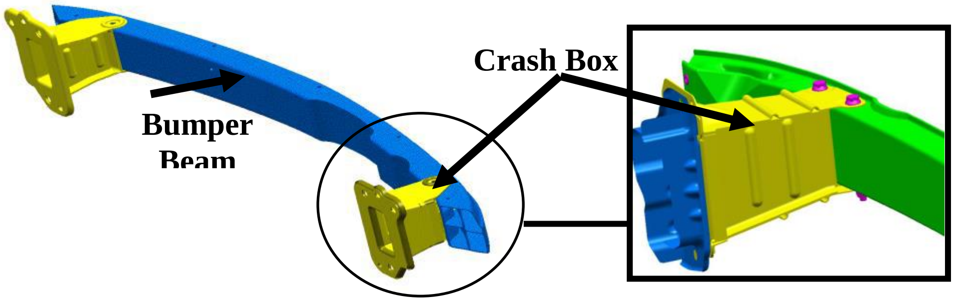



Figure 2: Crash Management System (CMS), Bumper beam and crash box, (European Aluminium Association, 2013b)

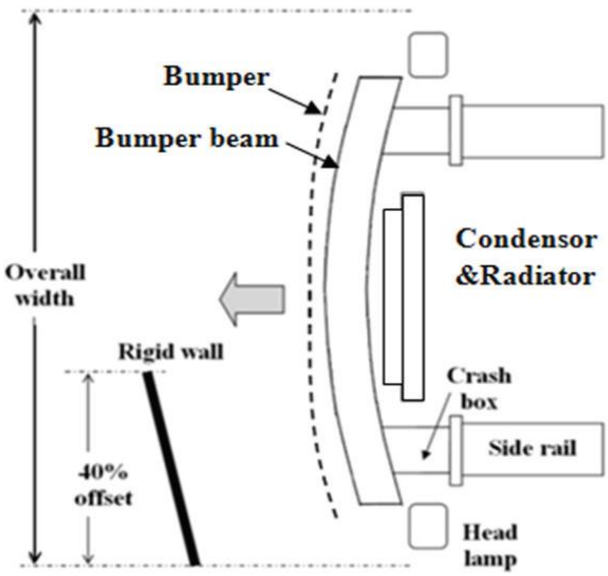



Figure 3: Layout of Frontal Crash Management System with Engine, Condenser and Electrical System, (Kiran Cheni, Sinha, & Narayan, 2013)

Table 1: Typical percentage of energy absorption for individual components at CMS (Systems et al., 2011).

| **Typical % of Energy Absorption for Individual Component** | | | |
|---|---|---|---|
| | **Low Speed (2.5 – 8 km/h)** | **Medium Speed (15 – 16 km/h)** | **High Speed (about 60 km/h)** |
| Bumper Beam | 30 – 100 % | 10 – 100 % | 2 – 4 % |
| Foam | 20 – 60 % | 5 – 20 % | 2 – 3 % |
| Energy Absorber | 2 % | 20 – 75 % | 4 – 6 % |
| Compliance of surrounding structures | NA | 20 % | 89 – 95 % |

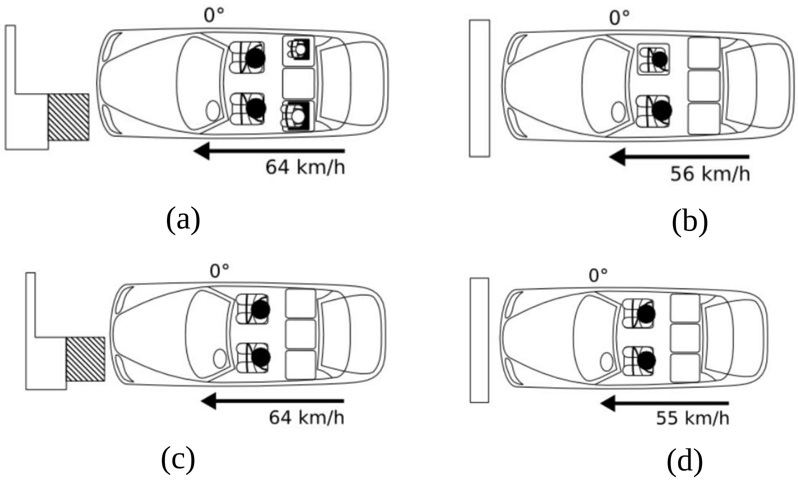



Figure 4: Low-velocity frontal test, (a) NCAP Europe front offset test, (b) NCAP USA front test, (c) NCAP Japan front offset test, (d) NCAP Japan front test, (Crash Tests 2015)

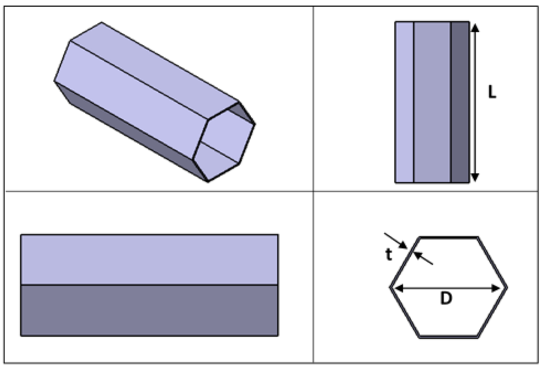



Figure 5: Single-cell Crash-box geometry using ANSYS/Design Modeler Geometry

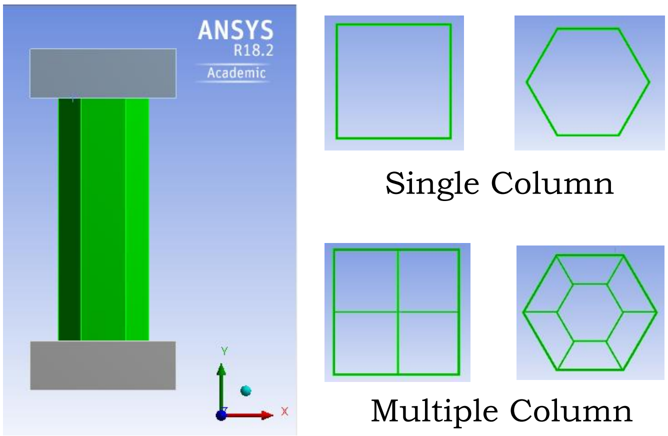



Figure 6: Multi-cell column Crash box cross-sectional view ANSYS/SpaceClaim

Table 2: Geometrical parameters used for Hexagonal Crash-Box Structure.

| ***Parameter*** | ***Single-column*** | ***Multi-column*** |
|---|---|---|
| *Length, L (mm)* | 250 | |
| *Diameter, D (mm)* | 80 | |
| *Thickness, t (mm)* | 1.5mm, | 1.5mm (outer), 1.0mm (inner) |
| *Impact Angle* $(^{0})$ | $0^{o}$ | |
| *Impact Type* | Full Frontal | |

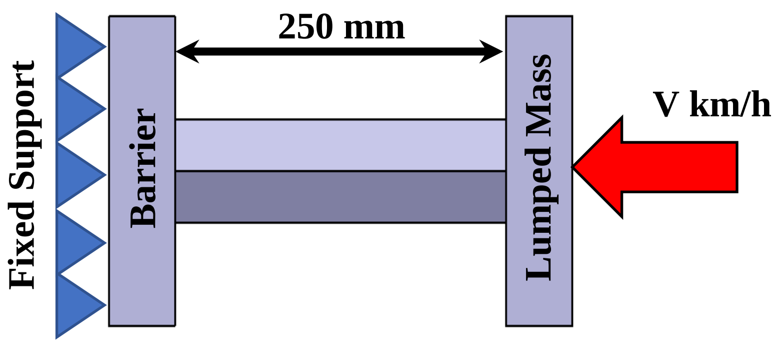
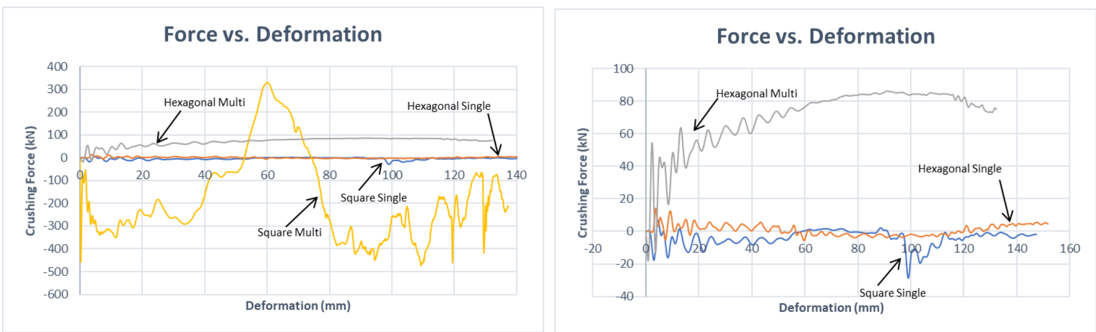



Figure 7: FE Model and loading condition




(a) (b)

Figure 8: Forces created by energy absorption along the deformation.

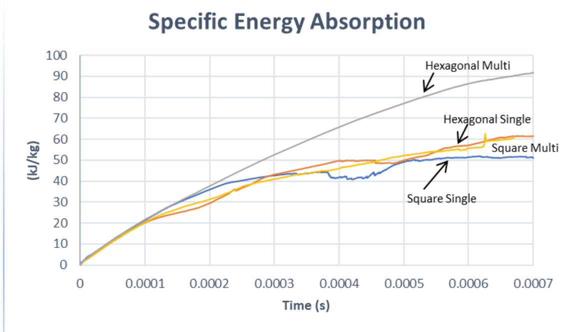



Figure 9: Specific Energy Absorption (SEA) for all four proposed design.

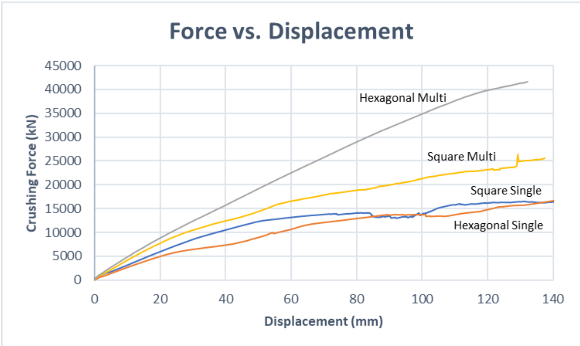



Figure 10: Crushing forces created by time consumption during impact.

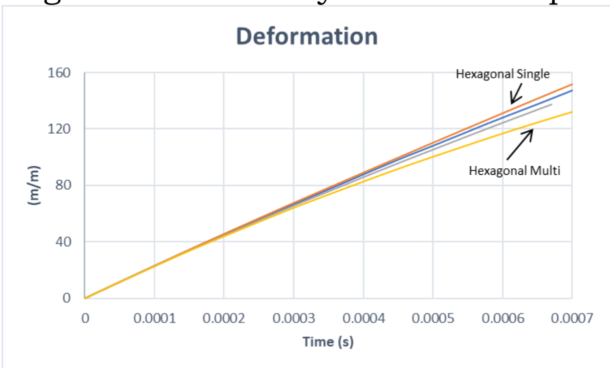
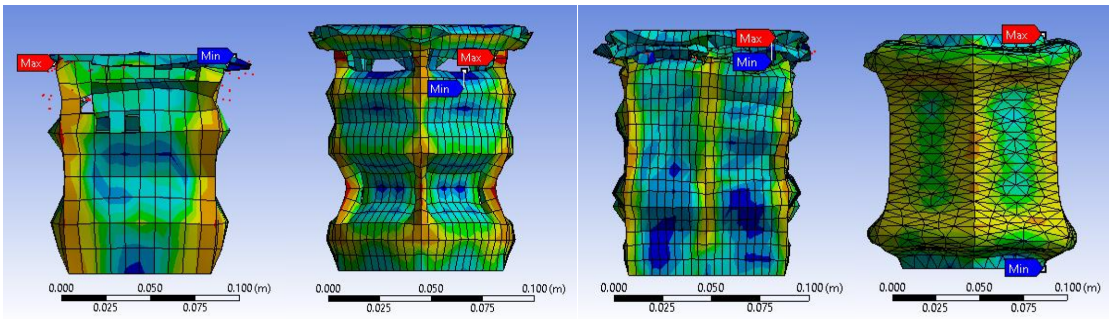
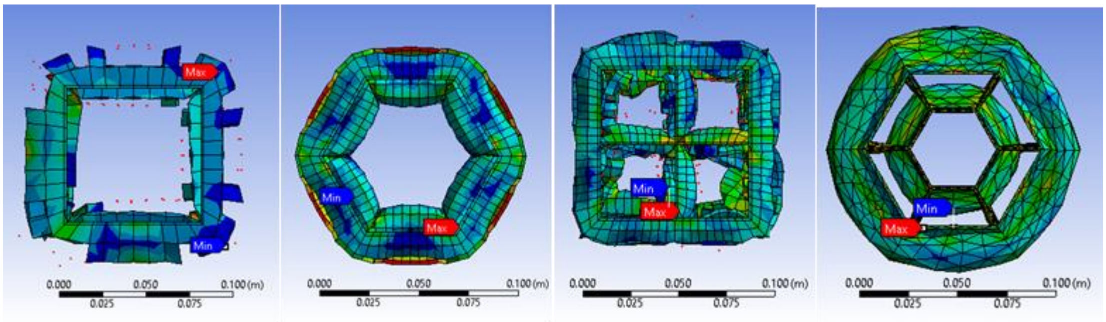



Figure 11: Deformation over crushing time.




(a) Side view crushing at 0.6ms




(b) Top view crushing zone at 0.6ms

Figure 12: Crash box square and hexagonal design single and multi-column.