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Honeycomb Safety Structure: Design, Analysis and Applications in Safe Road Transport

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Abstract: ***In this research study, honeycomb safety structures was designed, analysed for safe road transport application point of view and the use of materials in these structures were addressed. Honeycomb structure was constructed using honeycomb core, adhesive and aluminium panels and Compression test was performed on it. CAD model of the honeycomb structure was designed using PTC Creo parametric design software. Following which, ANSYS Workbench - Static Structural simulations are carried out on different material grades of aluminium on honeycomb structures. These compression test and simulations are carried out with the aim to compare and understand the impact load capacity on these materials of honeycomb structures. Apart from that, the energy absorption ability of honeycomb structure with the normal block structure has been analysed using ANSYS Workbench- Explicit Dynamics.***

Keywords: Honeycomb structure, Impact attenuator, Crashworthiness, Safety structure

1. Introduction

The main aim of Euro NCAP(European New Car Assessment Programme) is to make cars safer for the buyers. The first important consideration while buying new car is safety. In February 1997, Euro NCAP launched the programme in which they perform crash tests of whole vehicle and then provide safety in terms of star ratings. By considering serious injuries in car crashes, Euro NCAP started progressing with improved safety regulations. 1983 Seat belts wearing law introduced for front seats, 1989 Seat belts wearing law introduced for children in the rear, 1991 Seat belts wearing law introduced for adults in the rear and from 1990s airbags introduced in family cars. Drivers and passengers are still facing injuries after wearing seat belts also. Car structures were unable to withstand the impact energy, deforming during crashes [1].

In the automobile field of engineering, Improvement in crashworthiness of road vehicles is considered as one of the important development point. In recent years, well-designed energy absorbing vehicle structures played important role in the improvement of occupant safety. Therefore, designers are trying to developed advanced design methodologies to improve driver and passenger's safety. Road vehicles crashworthiness can be defined as ability of vehicle structures to absorb impact energy to protect occupants by maintaining enough survivable interior space of the vehicle. To achieve this, materials of the vehicle structures should absorb maximum possible Impact energy in the controlled manner. Pre- crash avoidance systems like Stability control, Blind spit monitors, Driver warning systems and Enhanced brake assist are developed to reduce or prevent the collision but these systems cannot eliminate vehicle crashes. Vehicles crash energy absorbing properties have been enhanced by developing advanced techniques like Structure design, Alternate smart materials and Integration of crush elements. The major aim of these vehicle safety structures is to reduce injuries and eliminate fatalities during accidents. One of the safety features that provides safety for the passengers during the collisions are the impact attenuators [2].

2. Problem Statement

One of the major issues in road safety is crash impact of vehicle accidents on highways and city roads and its impact on human life.

In today's fast paced world the use of automobiles has increased many folds. With more and more jobs moving to the City outskirts, businesses spreading across cities and towns, people migration has lead to heavy usage of automobiles. This has also lead to road accidents leading to occupants and driver's safety as major area of research. World Health Organisation (2017) addresses that around 1.25 million die every year due to road accidents. WHO (2017) also highlight the various risk factors such as human error, speeding, alcohol, non-use of seat belts, distracted driving, reckless driving, unsafe road infrastructure, and many others[3]. There can be events such as natural disasters that lead to collision between vehicles or colliding with other strong objects. One of the major causes identified in India is blatant violation of traffic rules by vehicle users especially the two-wheeler riders on Indian roads. E.g. – Roads in our major industrialized cities such as Pune, Bengaluru etc.

3. Literature Review

3.1 Impact Attenuator

According to Singhal & Subramanium (2013), impact attenuator is energy absorbing equipment that iscommonly deployed in the front head of the vehicles with the ability to engross energy with the ultimate aim to secure the driver from the sudden impact caused due to collision[4]. An impact attenuator is also referred as a safety structure that is widely used for the purpose of decelerating the collided vehicles in a gradual manner to halt [5]. This safety feature is considered to be paramount for race car where the accidents and collisions are common; the impact attenuator in the race car plays an important role in reducing the overall speed of the vehicle gradually with the sole aim of protecting the driver from any fatal injuries. The huge amount of impact energy that is generated during the collision is transferred through the impact attenuator structure thus allowing the drivers of the vehicles to be safe from the accidents. These impact attenuators are commonly placed in front of the vehicles and also in the road barriers with the intention to engross impact energy to save the lives of the drivers and other passengers. Impact attenuator also known as a crumple zone is safety structure which protect and preserve the passengers life by performing following functions,

1) In the event of collision, it absorbs kinetic energy.
2) Across the impact members, it helps to distribute forces evenly.
3) It helps to reduce magnitude of deceleration.
4) The aim is to minimize repair costs of the vehicle, when running below 15kmph.
5) The main goal is to protect passengers from injury, when travelling in between 15 to 40kmph.
6) For speed above 40kmph, the main aim should be pedestrian's protection guarantee, as occupant's injury and car damage is unavoidable.

3.2 Energy absorption in impact attenuators

Jain &Kalia (2014) addresses the working of impact attenuators that is widely accepted and considered as an effective mechanism to prevent damages to vehicles and save lives of the drivers during collisions[6]. The mechanism of the impact attenuator is based on "energy conservation" principle that clearly reflects "Energy can neither be created nor be destroyed but can be transferred from one form to another" [7]. In the scenario of impact attenuators, the kinetic energy that is present in the vehicle gets transformed into strain energy of attenuator and that leads to deceleration of the vehicle leading to zero velocity [8].These attenuators are also referred as crash cushion or cowboy cushion that are designed and developed with the aim to eliminate the damage to vehicle structures, and also reduce the motor vehicle impact on the drivers. When the vehicle hit the crash cushions, there are few that will catch the rogue vehicle, few others will redirect them [9]. The significance of impact attenuators in terms of its ability is to engross the kinetic energy produced during vehicle collision. The impact attenuators are very important for the safety of not only the drivers but also the passengers and others around them. Other than in vehicles, these impact attenuators are also fixed in highway stands, crash obstacles and other barricades. These are commonly used during the construction projects in the cities.

3.3 Honeycomb structures

Lande& Patil (2015) provides a clear view about the structure of honeycomb addressing it as a sandwich between two upper and lower face sheets. Two different materials can be used for these two sheets and this structure is mainly rely on the geometric of the core that includes but not limited to cell size, shape, height, thickness of foil, and others.

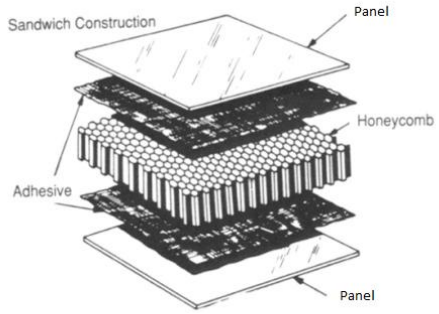


Figure 1: Honeycomb structure (J Kindinger, 1999)

The geometry of honeycomb structure can be designed and manufactured exactly similar to the honeycomb as shown in figure 1, which allows the minimum usage of material. Ultimately, minimum material cost and weight can be achieved with honeycomb structure[10]. Even though honeycomb structures geometry vary according to application, these all structures follows same feature of construction which is, in-between thin vertical walls an array of hollow cells are situated [11]. To achieve tensile strength of honeycomb structural material, a layer of honeycomb material is placed in between two thin layers which results in plate type assembly. Honeycomb structure geometry consists of closely packed bunch of polyhedral or higher dimensional cells to avoid gaps in between cells. Applications of honeycomb structure are in Structural applications, in flat surfaces, in curved surfaces and in the applications where high strength is major concern.One of their major advantages when compared with other impact attenuators is their light weight; honeycomb structures are low weight that comprises of enormous structural strength. Honeycomb structures have been analysed and found that they exhibit strong anti-shock properties when compared with other impact attenuators. This anti-shock property has great demand over automobile industry and sport shoe manufacturing industry. Apart from these strengths, honeycomb also have strong load bearing capability and high tensile strength [12]. Amongst all energy absorbing materials available in the market, Aluminum honeycomb core is an ideal one and it is having following distinctive advantages than other.

1) High crush strength to weight ratio
2) Linear force curve with a constant load
3) Absorbs energy over a long stroke
4) Cells buckle and collapse by themselves
5) With the use of different foil thicknesses, alloys, cell sizes and cell shapes predictable load can be modified.

These honeycomb structures are considered to have excellent characteristics that match with the requirements in the automobile industry; these honeycomb structures can be deployed in the vehicle bumpers to absorb shocks and energy during major collisions. In recent years, these honeycomb structures gained a lot of attention and interest from several researchers where the experiments were carried out to compare their abilities with the impact attenuators. Honeycomb structures are having high structural strength. Therefore, they are widely used in manufacturing vehicles such as aircrafts, high-speed trains, air missiles and satellites. The basic principle behind the energy absorption of the honeycomb structure is to absorb the vehicle's kinetic energy and convert them into internal energy. In major collision expected situations and environments, the aluminium honeycomb is used with the intention to absorb the large amount of kinetic energy. According to requirement these structure can be designed into various shapes and combinations. In energy analysis, geometry of the attenuator is considered as important factor.Aluminium has been used in honeycomb structure for their special characteristics that includes but not limited to their ability to withstand compression, and resistance towards rust and deterioration [13]. Aluminium has been recognised as a material with several outstanding mechanical abilities such as lightweight and also they have a strong ability to resist fire. Their stiffness and flatness mechanical properties also considered to be few of the reasons for choosing aluminium in honeycomb structure. Aluminium honeycomb has a great range of applications; they are widely deployed in tool machines, lightweight panels, automatic machines, etc. They are commonly used as a deflector and energy absorber in vehicles. Aluminium honeycomb have recently achieved a great amount of interest and recognised for their ability to absorb kinetic energy and this allows them to play an important role in vehicle safety [14].

4. Methodology

4.1 Construction of Honeycomb structure

Honeycomb core, Araldite, Aluminium panel materials are needed for the construction of honeycomb structure. In this structure lightweight honeycomb core is sandwiched between two aluminium panels using 2-pack epoxy adhesive. Honeycomb structure is cut into 12 pieces of size $50 \times 50 \times 24.2mm^3$ and one of them is shown in figure 2.

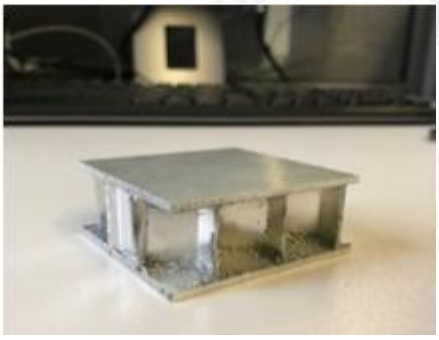


Figure 2: Specimen of honeycomb structure

4.2 Dimensions of honeycomb structure

Two aluminium panels of size $220 \times 160 \times 2.1\ mm^3$are machined in workshop and Overall honeycomb core dimensions are $300 \times 200 \times 20\ mm^3$. Other dimensions of the core dimensions are measured using vernier calliper

1) Cell size: 19.9 mm
2) Single layer Sidewall thickness: 0.05
3) Double layer sidewall thickness: 0.15
4) Size of sidewall: 11.5 mm

4.3 Design of honeycomb in PTC Creo

By referring the measured dimensions, CAD model of honeycomb structure was designed in PTC Creo software as shown in Figure 3 and exported as step file. Similarly CAD model of honeycomb structure was designed for 13.9mm and 26mm cell sizes.

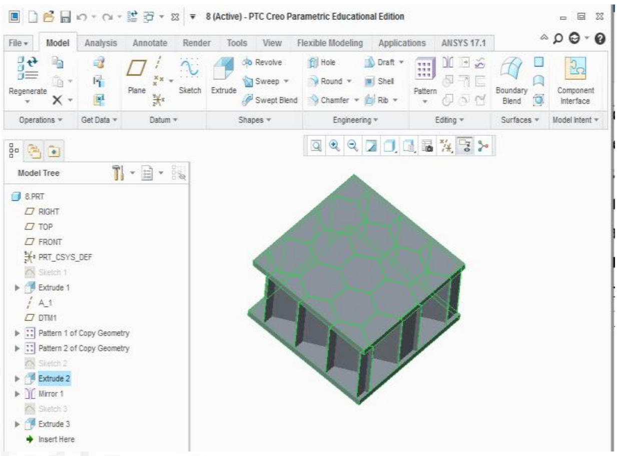


Figure 3: Honeycomb structure designed in PTC Creo CAD software

4.4 Experimental analysis

4.4.1 Static analysis: 30k Universal Testing Machine - "Lloyd"

Compression test is performed on the honeycomb structure and experimental procedure explained as follows

1) Test specimen is properly placed on the flat surface of fixture and Main switch of UTM machine was turned ON.
2) Total thickness of the specimen is measured using Vernier calliper and found to be 24.2mm.
3) Specimen is tested for the 60% deflection of thickness. Therefore, input value of 14.52mm is given through LCD display.
4) Constant load with Ramp speed of 1mm/sec is applied on top surface of the specimen. Load machine will automatically stop applying load till it reaches to the given deflection value of 14.52mm.
5) Then corresponding load at 60% of deflection is recorded and found to be 948.78 N.
6) Similar procedure was followed for remaining five specimens.

Figure 4: 30k Universal Testing Machine - "Lloyd"

4.4.2 Results and calculations

Analysis carried out for 60% of total thickness of honeycomb structure.

1) Total thickness of the honeycomb structure= 24.2
2) 60% of deflection= 24.2*0.6= 14.52mm

Table 1: Deformation and Load for six specimens

	Deformation(mm)	*Load(N)*
1	14.52	948.78
2	14.52	691.48
3	14.52	722.86
4	14.52	819.27
5	14.52	713.31
6	14.52	449.08

Table 1 shows, deformation and load of six specimen for 60% of total thickness of honeycomb structure. Average load of six specimens for 14.52 mm deflection was calculated by following equation,

$$\textit{Average Load} = \frac{948.78 + 691.48 + 722.86 + 819.27 + 713.31 + 449.08}{6}$$

$$= 724.13N$$

4.5 ANSYS simulation

4.5.1 Static analysis

1) Same simulation procedure is followed for three different materials as shown in figure 5.

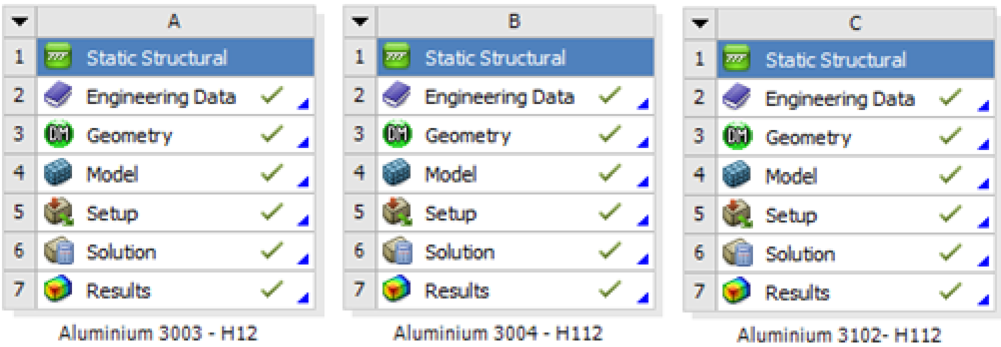


Figure 5: Simulation Procedure

1) In geometry section, step file of honeycomb structure is imported which was previously designed in PTC Creo CAD software.
2) Following material properties was assigned to the model,
   - Material: Aluminium 3003 - H12
   - Density: 2730 kg/m^3
   - Poisson's Ratio: 0.33
   - Young's modulus: 68.9 Gpa
   - Tensile Yield strength: 131 Mpa
   - Compressive Yield strength: 124 Mpa
   - Tensile ultimate Strength: 124 Mpa
3) Meshing: Proper meshing is given to the structure in order to improve results.
4) Boundary conditions: Fixed support was given to one face of the structure while initially 1N of force was applied on other face. In order to get 60% of deflection i.e. 14.52mm of thickness, 1N load is applied as guess value in the initial stage of the simulation.
5) Deflection of 0.0146586mm was obtained for a load of 1 N.
6) Load for a 60% (14.52mm) deflection was calculated Using linear relationship

Load	*Deflection*
1 N	0.014686 mm
X N	14.52 mm

$$X = \frac{14.52}{0.014686} = 988.7N$$

7) In final stage of simulation load applied was changed to 988.7 N and simulation was solved again to get exact 60% of deformation.
8) Now, 14.52mm of deflection was obtained at 988.7N force. Which is exactly 60% of deflection of thickness 24.2mm.

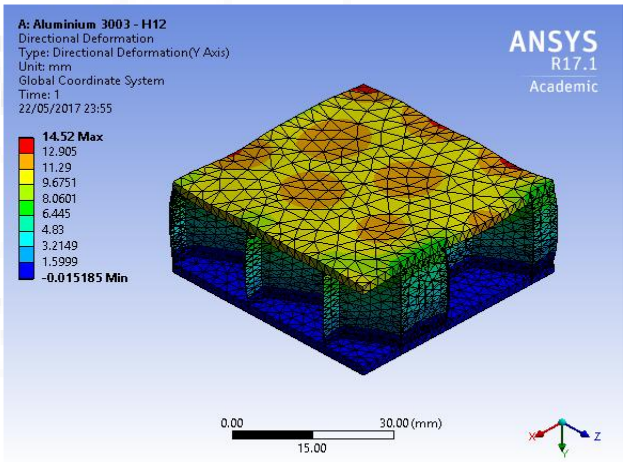


Figure 6: Deflection for 988.7N load

9) Similarly, 14.52mm of deflection was obtained for Aluminium 3004 - H112 at load of 1009.6 N and for Aluminium 3102 - H112 at a load of 1205 N.

4.5.2 Dynamic analysis

1) Geometry: Step file of the honeycomb structure is imported into the geometry section. Solid block of $70 \times 70 \times 30mm$ is designed by sketching $70 \times 70\ mm$ square and extruded to 30mm.

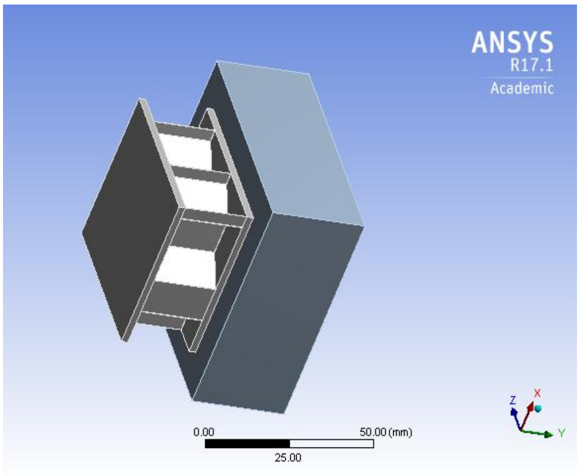


Figure 7: Geometry

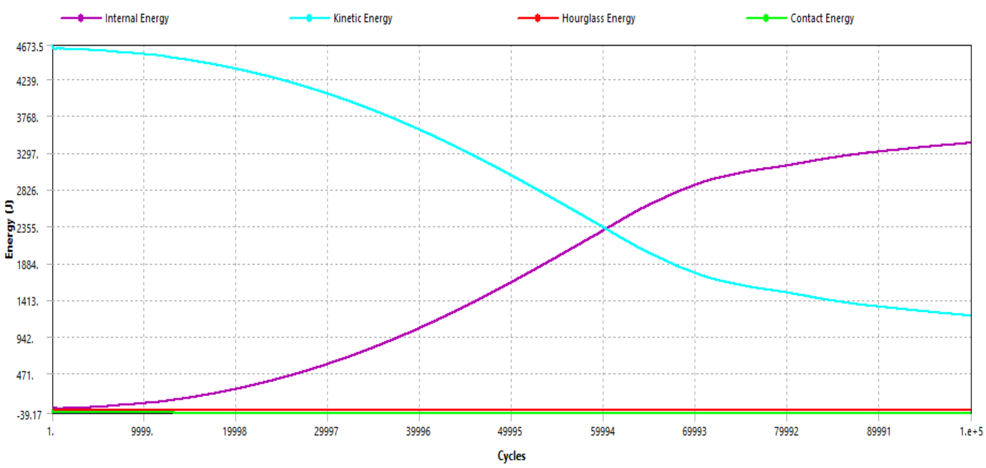
2) Aluminium alloy Material was assigned to the model and its properties are listed below,
   - Density: 2770 kg/m^3
   - Poisson's Ratio: 0.33
   - Young's modulus: 71 Gpa
   - Tensile Yield strength: 280 Mpa
   - Compressive Yield strength: 280 Mpa
   - Tensile ultimate Strength: 310 Mpa
3) Proper meshing was given to the structure in order to improve solution.
4) Boundary conditions: One end of the honeycomb structure is fixed and to other end frictionless connection is given with moving object. 90000mm/sec velocity is given to the moving object,

Table 2: Distance and time relationship

Distance (mm)	*Time (sec)*
90000	1
14.52	T

$$t = \frac{14.52}{90000} = 1.61e - 4\ sec$$

5) Graph 1 shows, Energy summary obtained from Explicit Dynamic ANSYS simulation for honeycomb structureand maximum internal energy absorbed by honeycomb is 3400J.



Graph 1: Energy summary of Honeycomb structure

6) To understand the energy absorption ability of honeycomb structure with the aluminium solid block structure. Same dimension as honeycomb structure,$70 \times 70 \times 30$ mm of solid block structure was designed in CAD software. In figure 8 Grey colour block denotes Aluminium solid block structure.

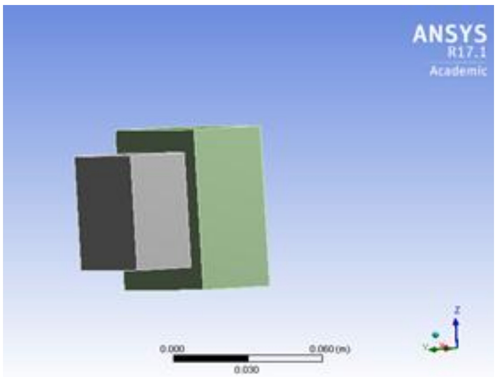


Figure 8: CAD model of Aluminium solid block structure

7) To understand how cell size of the honeycomb core affects internal energy absorption capacity of honeycomb structure, dynamic simulations carried out for two different cell sizes of 13.9 mm and 26 mm. CAD model of honeycomb structure was designed in PTC Creo. Boundary conditions, velocity and all other parameters remains same in each of the simulations. Similarly, Maximum internal Energy absorbed was found to be 940J for 13.9mm cell size, 1160J for 26mm cell size and 2400J for Aluminium solid block structure.

5. Discussion

To investigate best material for honeycomb structure, design and analysis was carried out for all three materials of different aluminium grade. Analysis of the honeycomb structure was carried out by ANSYS simulation and laboratory compression test. CAD model of honeycomb structure was designed in PTC Creo software. Designed CAD model was imported in ANSYS software for analysis.

Material properties are assigned to all materials and proper meshing given. Fixed support was applied to bottom face, as backside of the honeycomb structure can be fixed to vehicles frame while on test face load was applied.

5.1 Comparison of ANSYS and Experimental values

Honeycomb core and aluminium panels was supplied without data for exact material type, so assumptions need to be made. Using reverse engineering same design simulations are carried out for different aluminium grades and found that Aluminium 3003- H12 is having closest value to experimental sustainable load. But there are some other factors like adhesive and design approximations which may affect the similarities in ANSYS and real experimental values.

Table 3: Comparison of ANSYS and Experimental values

	ANSYS values		*Experimental average value*
1	Aluminium 3003-H12	988.7 N	724.13 N
2	Aluminium 3004–H112	1009.5 N	
3	Aluminium 3102–H112	1205 N	

1) Real dimensions of honeycomb structure
   - Single layer Sidewall thickness: 0.05
   - Double layer sidewall thickness: 0.15
2) Design approximations in PTC Creo CAD design software: For both single and double layer sidewall thickness was approximated as average 0.1mm. Because in PTC Creo minimum value of dimensions can be given as 0.1.

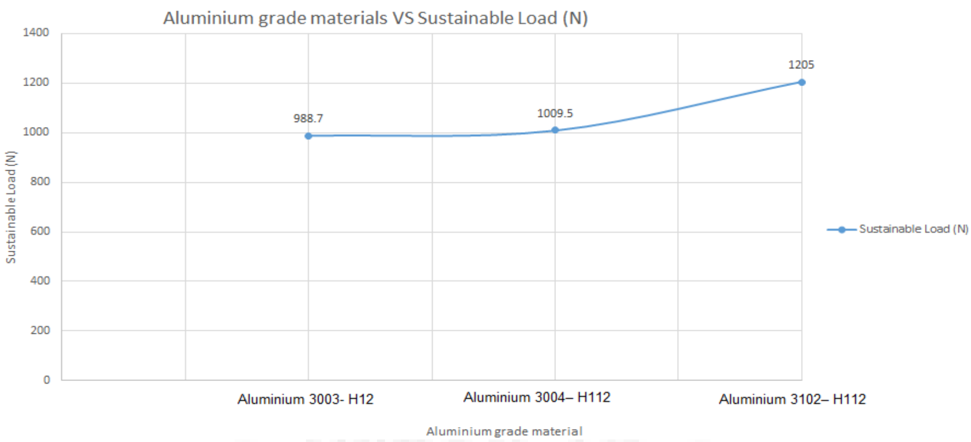
5.2 Sustainable load for 60% of deflection for different materials

Honeycomb structure is tested for three different materials to find out the sustainable load of the honeycomb structure for 60% of deflection. Following table 4 shows the sustainable load achieved by three materials for 14.52mm deflection.

Table 4: Sustainable Load for different aluminium grade material

	Material	*Sustainable Load (N)*
1	Aluminium 3003- H12	988.7
2	Aluminium 3004– H112	1009.5
3	Aluminium 3102– H112	1205

Graph 2, plotted for three different aluminium grade materials against sustainable load capacity of corresponding materials. From results obtained, it is observed that sustainable load is higher for high-grade aluminium material. From graph, it is clear that by increasing grade of aluminium material sustainable load can be increased.



Graph 2: Different aluminium grade materials against sustainable load capacity

5.3 Comparison between honeycomb structure and Solid block structure

To understand the energy absorption capacity of the honeycomb structure, simple block structure was designed by referring same dimensions as honeycomb structure and it is found that honeycomb structure has more energy absorption capacity than simple block structure. From table 5, it is clear that honeycomb structure absorbs more energy compared to simple block structure.

Table 5: Comparison between honeycomb structure and simple block structure

	Structure type	*Maximum energy absorbed by structure in Joules*
1.	Honeycomb structure	3400J
2.	Solid block structure	2400J

5.4 Cell sizes

There is no proper co relationship between cell size and amount of energy absorbed by honeycomb structure. Therefore, designer has to be economical while selecting proper cell size of the hexagonal cell of the honeycomb structure. Area of the honeycomb structure and Number of cells packed in honeycomb structure needs to be considered while finalizing cell size.

Table 6: Energy absorption in different cell sizes

	Cell size (mm)	*Maximum energy absorbed by honeycomb structure (J)*
1	13.9	940
2	19.9	3400
3	26	1160

6. Conclusion

This research study is carried out with the intention to investigate and understand the energy absorbing characteristics of different types of aluminium materials such as Aluminium 3003-H12, Aluminium 3004 - H112 and Aluminium 3102 - H112. In this research both theoretical analysis and also ANSYS experiments have been carried out to understand the energy absorption characteristics of aluminium honeycombs. ANSYS simulation results conclude that during the impact, the honeycomb structure tends to absorb the kinetic energy released from the solid structures. It can also be concluded that the kinetic energy released during the collisions are highly reduced, where there is an amount of internal energy in the honeycomb structures get increased. It is clear from these ANSYS experiments that the aluminium honeycomb structure absorbs the kinetic energy that get released during the collision of the vehicles. Though this research study is mainly aimed to analyse the vehicle impact with others and the energy absorbing during the collisions, it can be applied on several other fields due to its wide range of applications. These experiment results can be applied for the aerospace industries and also in construction field where there is high possibilities of failures in their structures and collisions.

This research also concludes that the selection of material plays a significant role in the design and development of honeycomb structure; this selection is very crucial as it affect the sustainable load capacity of corresponding materials. This study also carried out the experiment to compare the energy absorption capability of the honeycomb structure with the simple block structure using ANSYS experiments. This study also reveals that there is no relationship between the cell size of the structure and the kinetic energy that get absorbed during the collisions, however this research study highlights the importance of considering the area of honeycomb structure and number of cells in the structure for effective absorption of kinetic energy. This research supports the view that it is very important for the structural and fracture engineers to select the right material for the effective and sustainable absorption of kinetic energy during collision or accidents. Vehicle safety can be improved through the right selection of materials for the honeycomb structure, and also it is highly recommended to consider the area and number of cells in the honeycomb structure. This research also recommends that the aluminium structure with lowdensity has great impact on the absorption capability of the honeycomb structures.

7. Proposed solution to overcome stated problem and Future scope

To address the above real life challenges, the main focus of research and development to minimise or eliminate the human injuries or fatalities due to impact after sudden vehicle accidents or collisions. In one of the detailed researches of JP Research India, it has mentioned that accidents due to infrastructure such as crash barriers, road medians (as Object Impact) has accounted for 28% of all the accidents [15].Hence improvement in crashworthiness of road crash barriers and road medians is considered as one of the important safety measures during unexpected accidents and collisions. So well-designed energy absorbing safety structures play important role in this area.

7.1 Solution is targeted at:

1) Developing road crash barriers and road medians as Impact attenuator objects using advanced safety structures to minimise or eliminate collision impact without transferring the impact backlash on the vehicle occupant – Crash Safety Structures. Refer 7.2.1 for illustrative example.
2) Developing honeycomb safety structure (Impact Attenuator) in Vehicle application. Impact attenuator is energy absorbing structure having the ability to absorb energy with the ultimate aim to secure the vehicle occupant from the sudden impact caused due to collision.

7.2 Honeycomb Safety Structure in Road safety transport application

Figure 9shows, honeycomb structure which consists of aluminium core sandwiched between two aluminium plates. This structure was designed in CATIA CAD software

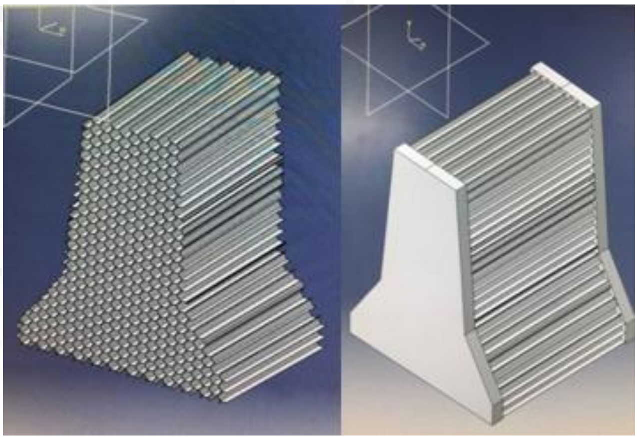


Figure 9: Honeycomb core and honeycomb structure

7.2.1 Below is one of the many simulated examples of Crash Safety Structure

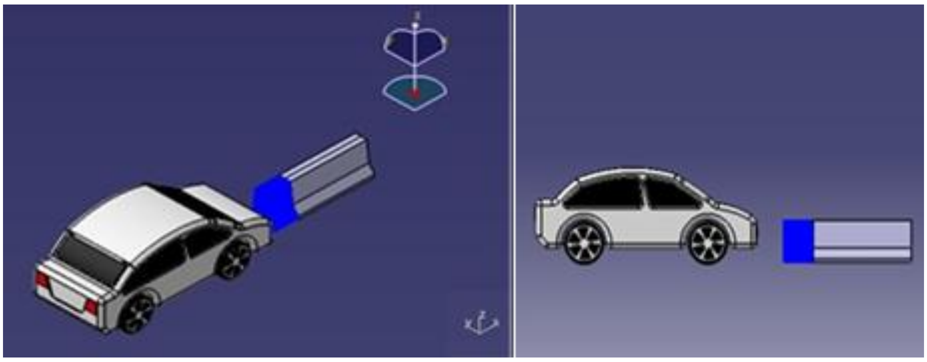


Figure 10: Before impact

Figure 10 shows, Vehicle moving at reasonably high speed crashing against a road crash barrier/median. Safety structure product is installed upon the crash barrier shown in blue colour.

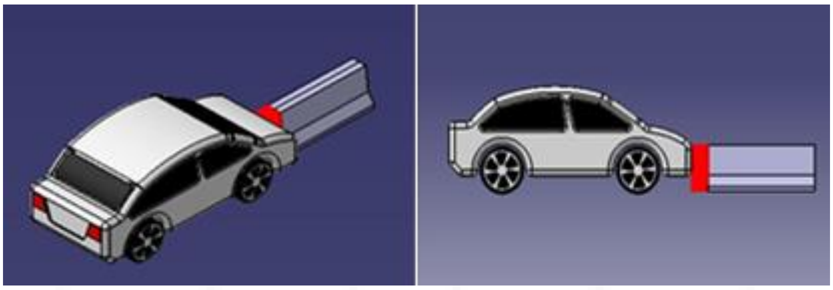


Figure 11: During Impact

Explanation of Figure 11, during vehicle crash, safety structure is absorbing impact energy according to law of conservation. The safety structure has absorbed all the impact energy illustrated by red colour. So this avoids backlash shock energy being transferred back on the vehicle and most importantly the vehicle occupants. This is one of the critical causes of human injuries. The same principle is applicable for two-wheeler/ three-wheeler vehicles.

7.3 Honeycomb Safety structure in vehicle application:

Figure 4, Vehicle moving at 324Kmph reasonably high speed crashing against a stationary object and safety structure product is installed upon the vehicle.
Red colour block: Vehicle
Blue colour block: Stationary object

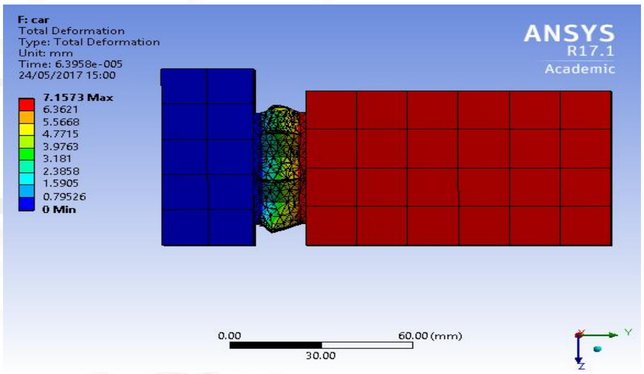
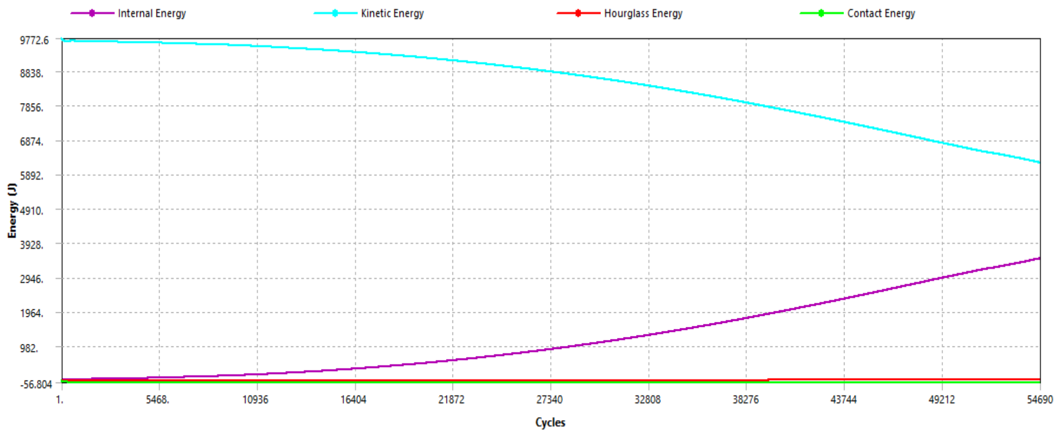


Figure 12: Application of honeycomb structure on vehicle

Graph 3 shows, Energy summary obtained from dynamic ANSYS simulation for honeycomb structure. During impact, Kinetic energy of the vehicle is absorbed by the honeycomb structure. From graph it is clear that, kinetic energy of the vehicle is reduced while internal energy of the honeycomb structure is increased. Kinetic energy of the vehicle is converted into internal energy of the honeycomb structure and maximum internal energy absorbed by honeycomb is 3400J.



Graph 3: Energy summary for honeycomb structure attached to the vehicle

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