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Design of an Impact Attenuator for High Speed Vehicles

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Abstract **Crashworthiness is a measure of the vehicle structural ability to plastically deform and to protect its occupants in crashes. As per the WHO Global Road Safety Report 2018, road traffic accidents kill an estimated 1.35 million people and injure 50 million people per year globally. The frontal impacts are in the range of 55-60% among the accidents. In high speed automobile collisions, the prime concern is to increase the chance of occupant's survival. An enormous amount of research is going on in the field of crashworthiness of vehicles and impact attenuator (IA) is one of the probable solutions. IA is a structural element placed on the front of a car to decelerate impacting vehicles gradually to stop. In a racing car the driver and frame of the car is protected from injury and further deformation. In Formula Society of Automotive Engineers (FSAE) car the Impact Attenuator is fabricated from DOW IMPAXX 700 foam which is being imported and is very expensive. The aim of this study is to provide a cost effective lightweight reliable substitute of the imported impact attenuator for high speed vehicles. Test Specimens of Aluminium and Thermocol (Polystyrene) combinations in different configurations were modelled and fabricated. These specimens were compressed on a UTM to find out the energy absorption. Similar specimen made up of DOW IMPAXX 700 foam is also tested by the same method. Numerical simulations using Abaqus Explicit 6.13 CAE is also carried out for all four combinations. Experimental and numerical results were compared with specimens of different configuration. It was found that one of the specimens having corrugated aluminum sheet between the Thermocol layers in 0°/90° orientation performed better than existing standard DOW IMPAXX 700 Impact attenuator in terms of energy absorbed per unit volume and per unit displacement of the sample. Thus it may be a possible substitute of the existing attenuator.**

Keywords —Abaqus, Aluminium, Crashworthiness, Energy absorption, High-Speed Vehicles, Impact attenuator

I. INTRODUCTION

Crashworthiness is the ability of a structure to protect its occupants during an impact. It is a measure of the vehicle structural ability to plastically deform and yet maintain a sufficient survival space for its occupants & key components in crashes. Restraint systems and occupant packaging can provide additional protection to reduce severe injuries and fatalities. The crashworthiness of a structure indicates the value of absorbed energy per unit mass. One of indices to measure crashworthiness (C) is given as,

$$C = E_d / M_s$$

Where, E_d is the absorbing energy of structure and M_s is the mass of structure [1].

With rising motorization and expanding road network, travel risks and traffic exposure grow at a much faster rate with day by day increasing traffic density. Today road traffic injuries are one of the leading causes of deaths, disabilities and hospitalization with severe socioeconomic costs across the world. As per the Commission for Global Road Safety report 2018 [2], road traffic accidents kill an estimated 1.35 million people and injure 50 million people per year globally, and global road fatalities are forecast to reach 1.9 million by 2020. The frontal impacts are in the range of 55-60% among the accidents in which the occupants are injured. In high speed automobile collisions, the prime concern is to increase the chance of survival of occupants.

Fig. 1 shows that the rate of death relative to the world's population has remained constant. While taking into account the increasing global population and rapid motorization that has taken place over the same period, one can say that existing road safety efforts may have reduced the situation from getting worse. However, it also indicates that progress to realize Sustainable Development Goal of 50% reduction in the number of road traffic deaths by 2020 – remains far from sufficient.

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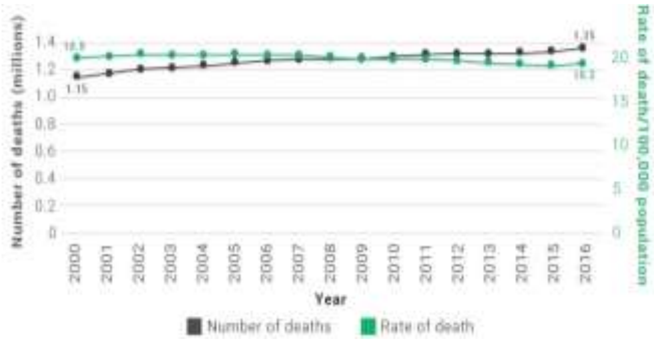

Fig. 1. Number and rate of road traffic death per 100,000 population (GSRRS 2018)

II. LITERATURE REVIEW

Large number of literature is available in different aspects of the crashworthiness. *Dennis.*[3] and *Rosenthal et al.* [4] have summarized the principles of crashworthiness by the acronym CREEP, C – Container, R – Restraint, E - Energy absorption, E - Environment (local), and P – Post-crash factor. The Container is the occupiable portion of the vehicle. It should be designed in a way to prevent penetration of external objects into occupied spaces during a crash, thus, maintaining a protective shell around all occupants. Restraints (multi-bag, airbag systems etc.) are used to avoid ejection of the occupant or protecting them from striking injurious objects. For Energy absorption, Crumple Zones are mainly used in automobiles to absorb the energy from the impact during a collision by controlled deformation. The purpose of crumple zones is to decelerate the collision and to absorb energy to reduce the difference in speeds between the vehicle and its occupants. A person's local environment refers to the space that any portion of his body may occupy during dynamic crash conditions. To avoid Post-Crash factors, approach may be either to control the hazard at the source or to provide for more rapid egress (leaving the damaged vehicle) or a combination of both. *Ziliukas and Griskeviciusl* [5] gave the mechanisms used for energy absorption viz. elastic system, dissipation system and restraint system. In elastic system steel plates or steel springs were used to absorb energy and required about 583 kg of steel for energy absorption of collision at 80 kph for an automobile of 1350 kg. Dissipation system allows the energy to be dissipated during or after storage so that the vehicle would not rebound as violently as it approached. It still requires nearly 544 kg of steel for energy absorption of collision at 80 kph for an automobile of 1350 kg. For high speed collisions, any energy absorbing system is likely to be damaged immediately. So the prime concern should be to increase the chance of survival of occupants [6]. This involves restraining the occupants using components such as seat belts head restraint, collapsible steering wheel, air bags etc. to avoid injuries.

Paul and Clifford [1] have summarized the requirements for crashworthiness as: Front structure must be deformable, yet stiff, with crumple zones to absorb the crash kinetic energy by plastic deformation and should prevent intrusion into the occupant compartment; Rear structure should also be deformable to maintain integrity of the rear passenger compartment and protect the fuel tank. Side structures should be properly designed to minimize intrusion in side impact and for rollover protection roof structure should be strong. Finally, vehicle should have properly designed restraint systems that work in harmony with the vehicle structure to provide the occupant with protection in different interior spaces. *Mohammed et al.* [7] have performed experimental as well as numerical simulations for metallic frusta prepared from 6063 extruded annealed solid aluminium rod, with linearly varying wall thickness. Further they have tested the specimen under quasi-static compression and have studied the effect of changing frusta angle on deformed mass efficiency. *Mohammed et al.* [8] have also conducted experimental and numerical analysis of the axial crushing of frusta tubes made up of glass fiber reinforced polymer (GFRP). They have studied the effect of frusta angle and its composition on the crashworthiness performance of the tubes. *Mohammed et al.* [9] have also performed buckling analysis of thin cylindrical carbon fiber reinforced polymer (CFRP) composite shell with oval cutout. The effects of three types of variables viz. layup orientation, element type and cutout orientation are analyzed numerically. *Mohammed et al.* [10] have studied different aspects of energy absorption and have suggested the energy absorption parameter during the plastic deformation process and have also performed numerical simulations on FEM package Abaqus 6.14 explicit solver to perform simulations on thin aluminium frusta with linearly varying wall-thickness. Their study have presented experimental and numerical results for the mechanical response of thin-linearly variable wall-thickness frusta subjected to axial crush under quasi-static conditions. *Zhang and Zhang* [11] have investigated the crashworthiness performance of conical tubes with various thickness distributions and have also analyzed the influences of tube shrinking and thickness distribution on response of the tubes. Both thickness increase and material hardening during tube shrinking shows up to 120% increase in energy absorption with even less structural mass. Although the peak force of tubes is increased after shrinking, the load uniformity is still improved due to larger increase in mean crushing force. *Alavi et al.* [12] have done the quasi-static compression testing of triangular, square, hexagonal and octagonal sections using simple and multi-cell for studying the mechanical behavior of thin-walled aluminum structures and have verified the experimental results by performing the numerical simulations on LS-DYNA. Similarly *Chen et al.* [13] have calculated the force displacement curve for obtaining the energy absorbed by the steel plates of different thicknesses used in a splitting-bending absorber and verified the result by numerical simulations. *Alavi et al.* [14] have investigated both experimentally and numerically the deformations and

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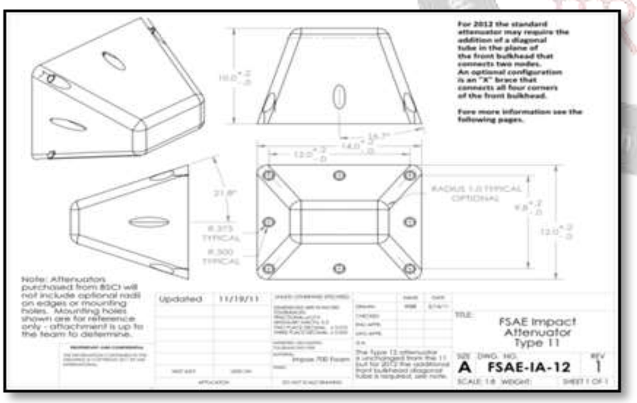
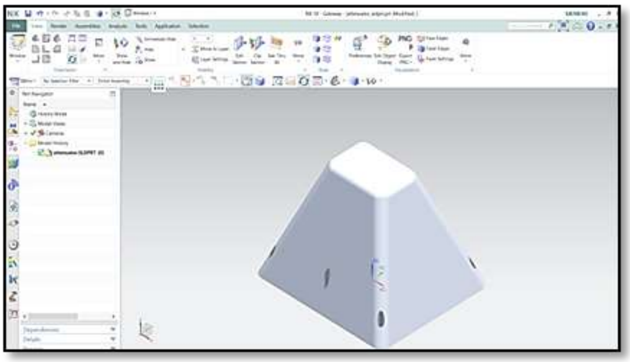
energy absorption capacity of various section shapes viz. circular, square, rectangular, hexagonal, triangular, pyramidal and conical sections and the results show that the section geometry has considerable effect on the energy absorption.

III. Proposed Idea For Improving Crashworthiness

The current design of impact attenuator of FSAE is a standard Dow Impaxx 700 impact attenuator. Considering its specifications and the Formula Student competition rules, three IA having combinations of Thermocol + Aluminium sheet, Thermocol + Aluminium corrugation and Aluminium corrugation + Aluminium sheet, are designed and fabricated as shown in Fig.4. Energy Absorption of all models are evaluated by performing compression tests on a Servo-mechanical Universal Testing Machine by placing the specimen between its rigid jaws and applying a gradually increasing compressive load at a speed of 2 mm/min and the results are evaluated by performing numerical simulation on Abaqus Explicit 6.13 CAE . For performing the simulations, first the 3D CAD models were constructed in SolidWorks for the three proposed specimens and a specimen of Standard Dow Impaxx 700 Foam and then the models are imported in the Abaqus Explicit 6.13 CAE. Finally, the models were numerically simulated by applying similar loads and boundary conditions to validate the experimental results. The specifications and CAD model of standard IA are shown in Fig. 2. The IA is mounted on the front bulkhead of Formula Student (FS) vehicle chassis as shown in Fig. 3.



(a)



(b)

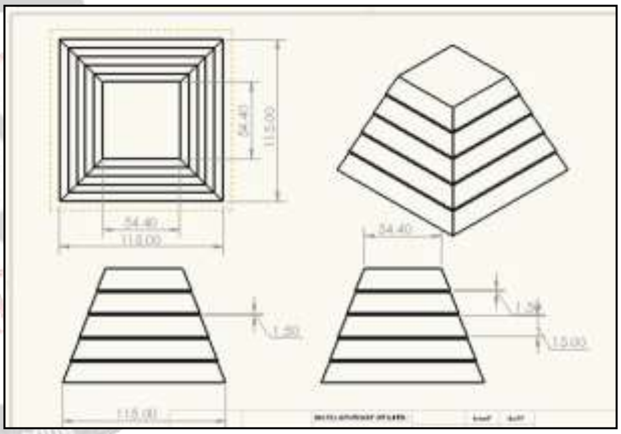
Fig 2: Standard Impact Attenuator (FSAE)

(a) 2D model [15] (b) 3D model on Siemens NX-CAD

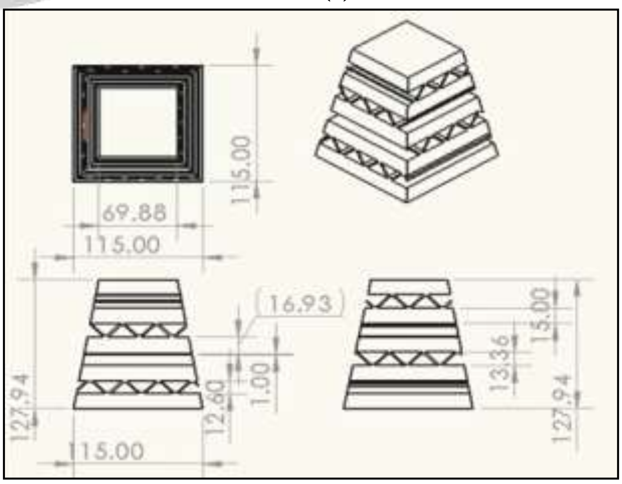
Fig 3: IA mounted on the front bulkhead of FS vehicle chassis

IV. Experimental Work

Specimens of various combinations were modelled in SolidWorks / NX-CAD. The 2D drawings and 3D CAD models having specification as mentioned earlier are shown in Fig. 4 & 5. Based on these specifications four specimens are fabricated and subsequently tested under compression on UTM and load displacement data is recorded with the help of a load cell and an optical encoder.



(a)



(b)

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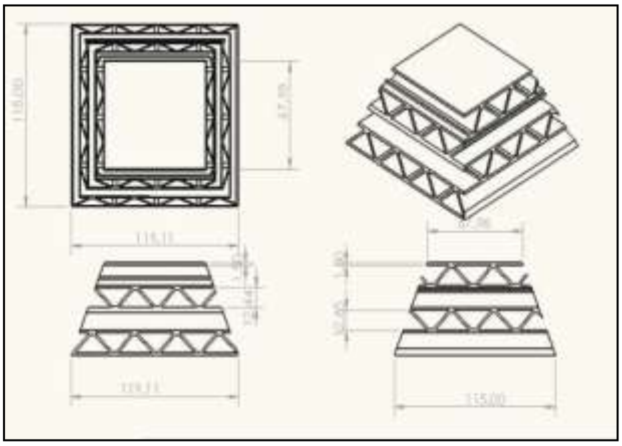

(c)

Fig. 4: 2D CAD model of the specimen (a) Thermocol+Al sheet (b) Thermocol+Al corrugation (c) Al corrugation-Al sheet

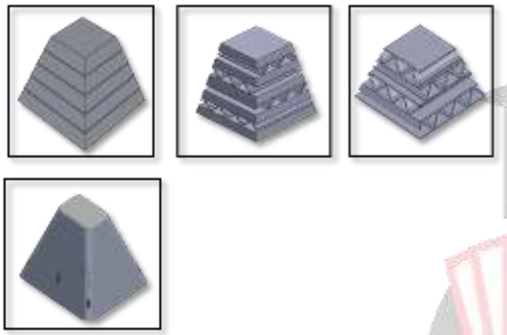

Fig. 5: 3D CAD model of three fabricated specimens and Dow Impaxx 700 IA

A. Model Fabrication

Four specimens are made similar in dimensions to the DOW IMPAXX 700 impact attenuator. First specimen is made by placing layers of commercially pure 1.2mm thick Aluminium 6063, between two layers of Thermocol of 15 mm thickness. The specimen is having five thermocol layers. Second specimen is made by placing layers of corrugated sheets made from 1.2 mm thick Aluminium sheet between two thermocol layers. The corrugated sheets are placed in 0°/90° orientation. Each corrugated aluminium sheet has a height of approximately 10 mm and the specimen contains five thermocol layers. Third specimen is made by placing corrugated Aluminium sheet of 1.2 mm thickness alternatively at 0°/90° orientation between two Aluminium sheets with each corrugation having a height of approximately 10 mm. The final specimen is having five sheets of Aluminium. The fourth specimen is prepared from the standard Dow Impaxx 700 foam as rectangular trapezoid.

To evaluate the energy absorption characteristics of various models, the specimens were subjected to compression test on a Servo-mechanical Universal Testing Machine at 2 mm/min by placing the specimen between two rigid plates and applying compressive load gradually to the upper jaw. The four fabricated specimen after compression are shown in Fig.6. Load deformation data is recorded with the help of load cell and optical encoder.

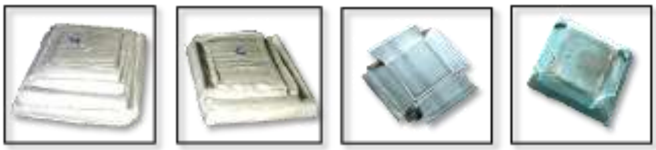

Fig 6: Specimens after compression

B. Test Results

The data obtained from the Quasi-static test is plotted as load v/s displacement curves for the specimens are shown in Fig. 7. It has been observed that the load increases with increase in displacement for all specimens. The rate of increase however is different for different combination as shown in Fig. 7. Then the energy absorbed by each sample is calculated by evaluating the area under the load-displacement curve. Volume Scaling is used to compare the experimental values of energy absorption of each designed specimen with the value of standard Dow Impaxx 700 foam. Volume scale is calculated as the ratio of volume of specimen to the volume of Standard Dow Impaxx 700 foam. Finally, energy absorbed/unit volume and energy absorbed/unit displacement was calculated using the volume and total displacement of top surface of each specimen. Results have been tabulated in Table 1.

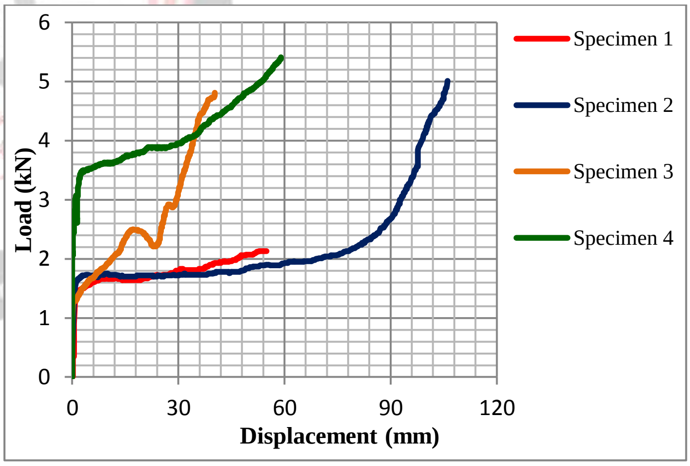

Fig 7: Load Displacement curves for four specimens

Table 1: Energy Absorption of Different Combinations of Impact Attenuator

	Specimen 1	Specimen 2	Specimen 3	Specimen 4
Energy absorbed by specimen (J)	158.40	350.50	107.21	243.15
Volume of Specimen (mm^3) x10^4	60.35	111.68	41.88	138.50
Volume of Std. Impact Attenuator (mm^3)x10^4	1379.15			
Volume Scale	22.85	12.35	32.93	9.95

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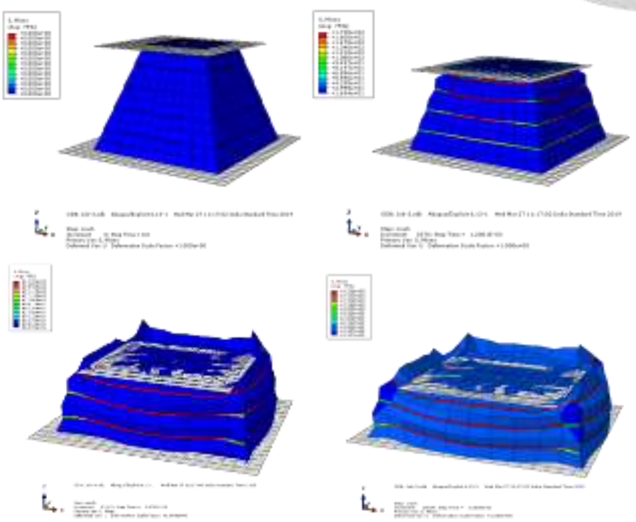
Energy absorbed by Full Scale model (J)	3619.4	4328.7	3530.4	2419.3
Displacement of sample (mm)	53	95	40	60
Energy absorbed per unit volume (J/mm^3)$x10^{-4}$	2.62	3.14	2.56	1.75
Energy absorbed/unit displacement (J/mm)	2.99	3.69	2.68	4.05

V. Numerical Simulation

Specimen 1	Al sheet + thermocol
Specimen 2	Al corrugation + thermocol
Specimen 3	Al corrugation + Al sheet
Specimen 4	Standard DOW IMPAXX 700 I.A.

To perform numerical simulation, 3D CAD models were constructed in SolidWorks for specimens and imported in the Abaqus Explicit 6.13 CAE [16] [17]. Two materials i.e. aluminium and thermocol are created with required properties in the property module. Then a solid homogeneous section of the constituent material is selected. Finally by selecting the each layer, section is assigned. For the present analysis 'Dynamic Explicit' condition is chosen. The constraint was used on lower plate for having an interaction of the plate with the assembly. A predefined velocity field of 2.78 m/s is applied for load, on the top plate and boundary conditions used as Bottom plate fixed and top plate movable in Z direction only. Meshing is done using the tetragonal element shape and 'free' mesh technique with global mesh size of 12-15mm is applied. The results obtained are shown in the following figure.

A. Simulation Results of Specimen 1: Thermocol + Aluminium Sheet:



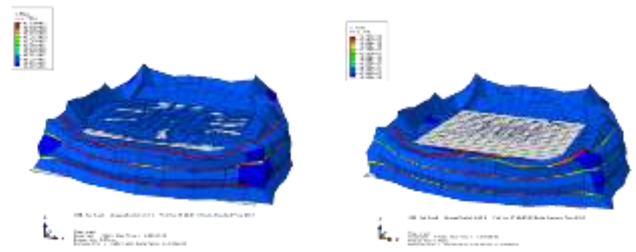


Fig 8: Meshed model at (i) 0% deformation (ii) 20% deformation (iii) 40% deformation (iv) 60% deformation (v) 80% deformation (vi) 100% deformation

B. Simulation Results of Specimen 2: Thermocol + Aluminium Corrugation

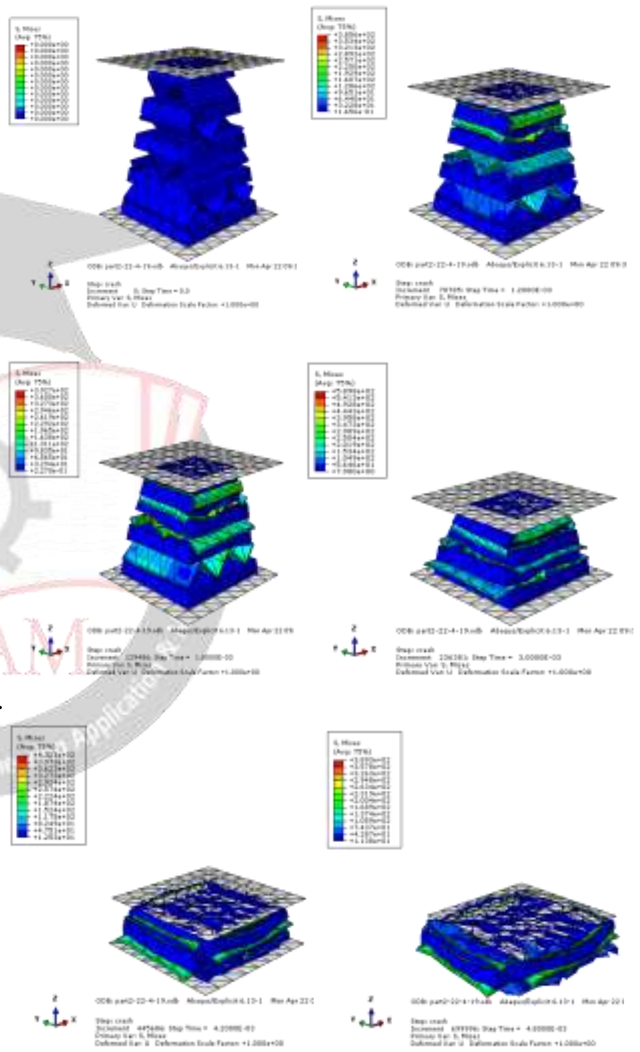


Fig 9: Meshed model at (i) 0% deformation (ii) 20% deformation (iii) 40% deformation (iv) 60% deformation (v) 80% deformation (vi) 100% deformation

C. Simulation Results of Specimen 3: Aluminium Sheet + Aluminium Corrugation

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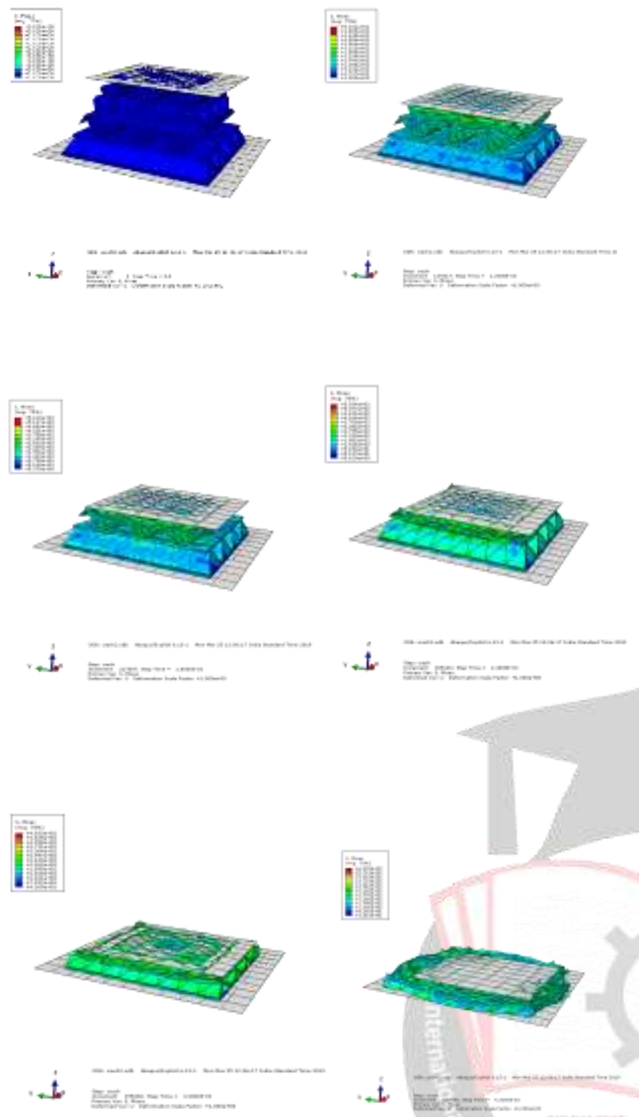
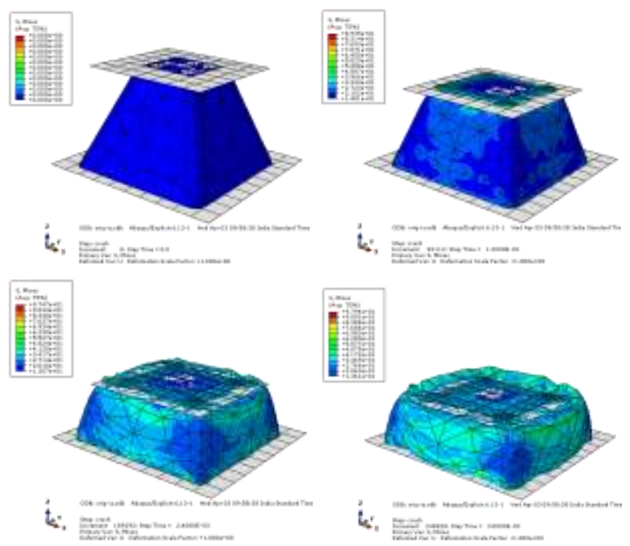


Fig 10: Meshed model at (i) 0% deformation (ii) 20% deformation (iii) 40% deformation (iv) 60% deformation (v) 80% deformation (vi) 100% deformation

D. Simulation Results of Specimen 4: Standard I.A. from Dow Impaxx 700 foam



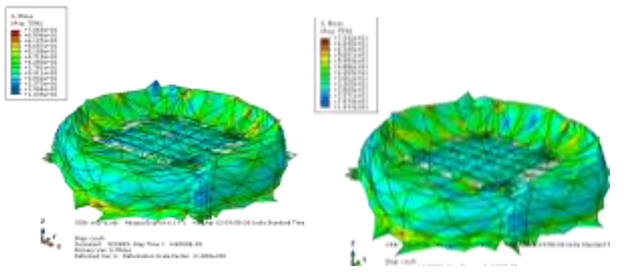


Fig 11: Meshed model at (i) 0% deformation (ii) 20% deformation (iii) 40% deformation (iv) 60% deformation (v) 80% deformation (vi) 100% deformation

VI. RESULTS AND DISCUSSION

The specimens were tested to achieve an energy absorbing capacity of specimen comparable to standard IA. Based on the experimental tests the energy absorbed by specimens are tabulated in Table 1 by calculating the area under the load-displacement curve, of each specimen. As the actual size of the specimens tested are smaller than the standard Dow Impaxx size, Scaling method is applied for the comparison. Multiplying with the scale factor the energy absorbed by the full scaled product is calculated. It was found that the energy absorption of specimen 1, 2 and 3 on full scale is 3619.4 J, 4328.7 J, and 3530.4 J respectively while the sample of actual impact attenuator is having 2419.3 J of energy absorption. As the aim of this study is to find a combination of material to We should achieve the energy absorption greater than or equal to that of the standard impact attenuator. Based on the result we find that Specimen 2 having aluminium corrugation between the thermocol layers is given us better results among all the specimens.

To validate the results of experimental test, numerical simulation is carried out. Different combinations of the specimen were simulated in the Abaqus Explicit 6.13 CAE software whose results have been discussed below. The energy absorption of each specimen was calculated with the help of load displacement curve. The experimental and numerical values of energy absorption are shown in Table 2. All the simulations were done at a loading rate of 2.78 m/s impact speed. Subsequently the effect of varying speed of impact (crash) on the energy absorption of Specimen 2 i.e. combination of the thermocol and aluminium corrugation layers was studied at varying load speed i.e.Impact speed and the results are shown in Table 3 and Fig. 12.

Table 2: Comparison of experimental & simulation results

Specimen	Energy absorbed (Experimental),J	Energy absorbed (Numerical),J
1	158.40	175.42
2	350.50	342.76

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3	107.21	116.47
4	243.15	261.68

Table 3: The Effect of varying speed of crash (impact) on the Energy Absorption of Specimen 2

S.No	Speed (m/s)	Maximum displacem-ent (mm)	Energy absorb-ed (J)	Energy absorb-ed(kJ)	Energy absorbed/displace-ment (J/mm)
1	2.78	20.81	342.76	0.34	16.47
2	8.33	65.99	2489.27	2.49	37.72
3	13.90	78.56	6418.13	6.42	81.69
4	19.44	97.46	11340.5	11.34	116.91
5	30.56	118.60	25241.4	25.24	212.11

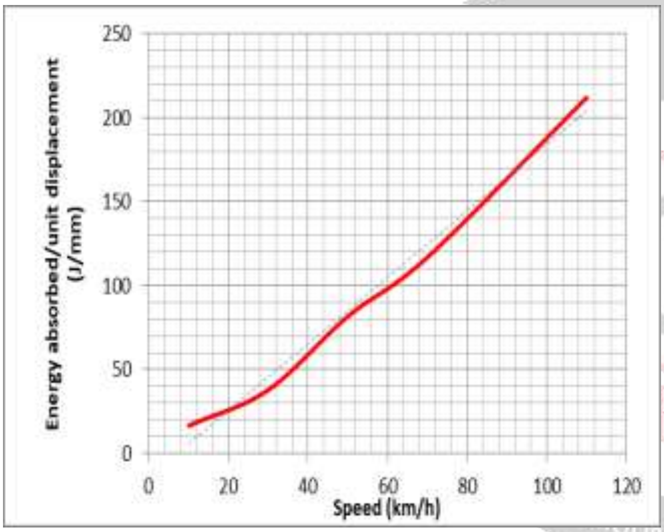

Fig. 12: Effect of impact speed on Energy Absorption of Specimen 2

VII. Conclusion

Three combinations of aluminium and thermocol has been anlysed experimentally as well as numerically to find out an indigenous substitute of imported Dow Impaxx 700 attenuator which is an essential but expensive part of FSAE vehicle. The study shows an encouraging result. It is found that the second model of Aluminium corrugation and thermocol layers combination is providing better energy absorption capacity than the standard IA in terms of energy absorbed per unit volume and energy absorbed per unit displacement. The cost of proposed indigenous impact attenuator is much less than the standard IA.

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