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Structural Optimization of Automobile Bumper Using Honeycomb Structure

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Abstract: ***Bumpers are the primary parts in any vehicle and are used to absorb the crash energy for safety of passengers and minimise the damage of other components. Now a day's automobile manufacturing industries are focusing on minimizing the cost of manufacturing and weight of the vehicle by decreasing the material usage and machining cost. In this process vehicles are failing in safety standards and even for a minor dents service became costly. So in this paper, honeycomb structured fascia is used as the bumper base and then the performance of bumper is studied by varying the honeycomb cell dimensions. These testing were done according to the RCAR safety standards (i.e., 2.6m/s full frontal & 1.3m/s corner impact) and simulated by using ANSYS Workbench***

Terminology and nomenclature

HC	Honeycomb
TE	Total energy
KE	Kinetic energy
RCAR	Research Council for Automobile Repair
ABS	Acrylonitrile Butadiene Styrene
PP	Polypropylene
KMPH	Kilometres/Hour
MPH	Miles/Hour
mps	Meters/sec
ms	Milliseconds
s	Seconds
Pa	Pascal
J	Joules
mm	Millimetres
REF	Reference
E	Young's modulus of honeycomb in axial direction
E'	Young's modulus of material
θ	Honeycomb cell angle
D	Honeycomb cell size
t	Honeycomb cell thickness

1. Introduction

At present every auto-making industry is focusing on making of new cars which are cheaper and satisfies all the customer needs. To attain this goal, designers should focus on how to decrease the material usage and manufacturing cost without affecting the performance, safety, aesthetics and other aspects. Optimization plays an extensive role in achieving of this goal. We can reduce the material where ever we require but it leads to the decrease of the vehicle's safety. Even the India's first ever cheapest auto-maker, Tata motors were also made many changes to its basic design of Tata Nano to achieve better safety, aesthetics and a bit of aerodynamic shape which satisfied many customers in India and also in other countries. There were several advanced materials and structural shapes that fulfil the designer need to attain the goal.

Bumper is the foremost and rearmost component of an automobile and its primary need is to absorb the impact energy at the time of low speed collisions for the protection of occupants and also to avoid damage to the equipment like fog lights, headlights, taillights and other parts like fenders, hoods, cooling and exhaust system which are a bit costly to repair. Poor bumper design may lead to damage of these parts, even in low speed collisions. Bumpers are also meant for the safety of pedestrians under low velocity collisions. Since, these day's accidents became like a common thing on roads.

Several materials are available in the market, but in them only few materials are suitable for manufacturing the bumpers. In past, bumpers were manufactured with a rigid metal structure. Those are good for safety but they increase the fuel consumption and cost of automobile. So to minimize this issue, they started using polymers. From the available list of polymers, only few are suitable based on the properties that a bumper should have. Those few materials are Polypropylene, Polycarbonates and ABS etc.

Today, most of the bumpers which are in market are manufactured by using these three polymers, because their mechanical properties will satisfy the bumper design requirements. Now a day's, researches were happening to substitute these polymers with a new set of materials known as, Composite materials. The composite materials which are presently in use are Glass fibre reinforcement plastics (GFRP) & Carbon fibre reinforcement plastic (CFRP). These composites are used in sports vehicles and high-end vehicles to reduce the overall body mass and to improve the vehicle performance in different aspects.

Bumpers which are available in present market are manufactured by using Polypropylenes (PP) because of its mechanical properties & other factors like recycling cost, fraction of recycling and cost of manufacturing. Thickness of bumper fascia is chosen based on the materials used for it. Generally, thickness of polypropylene bumper fascia varies around 3mm. The capability of absorbing energy varies based on its thickness, structural shape and the materials used.

2. Honeycomb Structure

Honeycomb structures were obtained by a series and systematic arrangement of thin edged hexagonal cells. These structures are called as honeycomb structures due it resemblance with honeybee nests. Because of its geometry these honeycombs minimizes the material use and this reduces the both weight and cost. In axial direction, these honeycombs show high shear & compression properties with less density. Because of their great specific stiffness,

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aerospace industries began to utilize these honeycomb structures since from 1950's. Honeycombs which are made from aluminium, fibre glass and advanced composites were used in aerospace. Due to its high specific stiffness, H.C structures are utilized in almost every engineering work. In most cases laminated honeycomb structures are used to improve their performance. Strength of these laminated honeycombs depends upon size of panel, density of honeycomb cells and material used for facing.

Behaviour of the HC structures is orthotropic; it means that panel reacts differently in different orientation. In out-of plane (T-Direction or axial direction), structure is much stiffer & stronger. Coming to L-direction & W-directions, L-direction is much stiffer and stronger direction. But in case of HC structures made from regular hexagon, the fragile direction is at

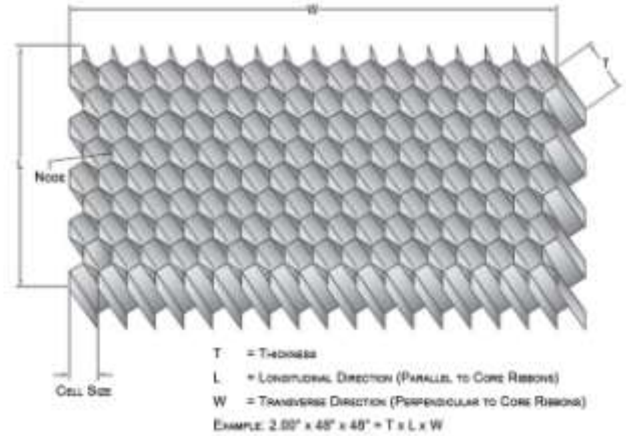

Figure 2.1: Terminology of honeycomb structure

60 degrees from the Longitudinal direction (L) and Transverse direction (W) is the most flexible or yielding direction. Honeycomb sandwich core will also exhibits high compression strength. Elastic modulus for a typical HC structure can be acquired from,

$$E = \frac{[t \times E' \ (1+2\cos\theta)]}{[2D \ \sin\theta(\cos\theta+1)]} \quad \text{eq. (1)}$$

Day by day the usage of honeycomb structures started increasing in automobile industry and already some of the automobile manufacturers like Panther, Jaguar, BMW, Dome, Bluebird and Koenigsegg used laminated honeycomb structures made from Aluminium and carbon fibre in their chassis frames and roof tops.

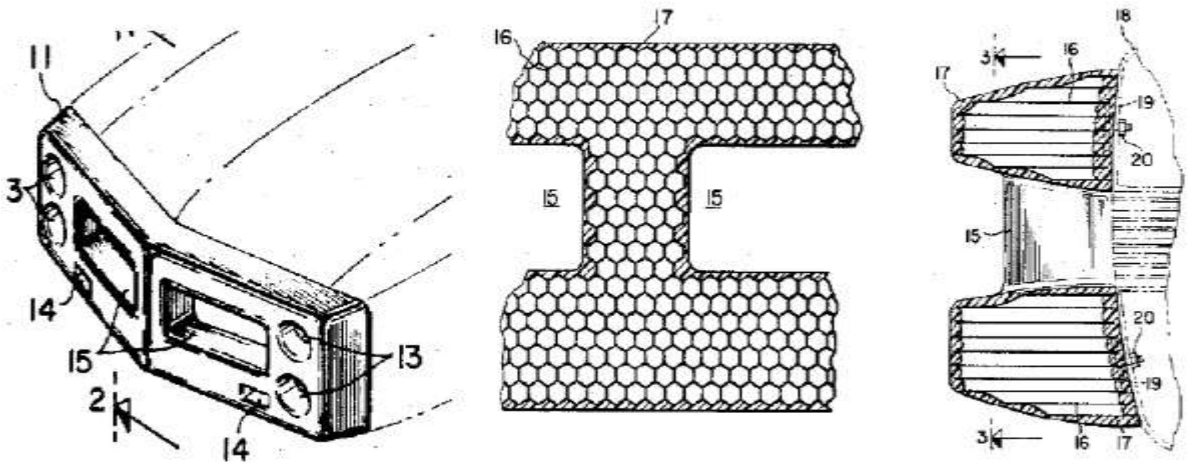

Figure 2.1: Patented Shock absorbing honeycomb bumper

Angelo F. Carbone, Clinton F. Egerton and Emmanuele Fallacaro from United States invented a honeycomb bumper and got patent in 1973 on the name of Shock absorbing honeycomb bumper. In their invention, honeycomb bumper core is made from plastic, metal or paper, and later it is covered by either a rubber, metal or plastic shell which may be coated in silver to make it look as chrome finished bumper. This improves the shock absorbing capacity of the bumper to minimize the damage of the fenders & body of the automobile during slow speed collisions [1]. They stated in their patent copy that, their bumper design is capable of absorbing impact energy under low speed collision excess of 5 MPH (i.e., 8KMPH approx.,).

So it is clear that, the effectiveness of a bumper can be enhanced by using honeycomb structure as core and its performance can be even increased by improving specific strength of HC core. This can be done by choosing suitable cell shape, cell size, wall thickness and material used. This statement is experimentally explained by Jeom Kee Paik, Anil K. Thayamballi, Gyu Sung Kim [2].

Figure 2.2: Honeycomb panels assembled in Audi RS7 (Credit: Audi India)

At present, these honeycomb structures were used in few car bumpers for styling and to reduce the weight at some places. In one word, these honeycomb structured parts are used as a sub-assembly part in whole bumper assembly. This type of bumpers were not yet used as base bumper structure as it's still in research to select the right size and depth of cell based on requirement, which varies from vehicle to vehicle and also the modelling of these honeycomb structured bumpers is a complex task. Even though its complex in design, it reduces cost and weight of the bumper as it requires less material.

3. Virtual modelling of bumper

In this paper Creo 3.0 software is used for the purpose of virtual modelling. We have regenerated the reference model bumper assembly for the purpose of comparison and the reference model which is used for testing is taken from TATA Venture vehicle. For study purpose we have modelled 4 bumper assemblies with varying honeycomb cell wall thickness and cell height. We also modelled the barrier assembly according to Research Council for Automobile Repair (RCAR) safety standards. The 4 bumper assemblies used for study are termed based on their honeycomb configuration (i.e. T_t mm = cell wall thickness_cell height, in millimetres) with cell size 30mm and they are,

- 2_2mm
- 2_3mm
- 3_2mm
- 3_3mm

The each bumper fascia assembly consists of a honeycomb core and left, right & centre panels. In order to minimize errors in the test results, we have modelled a rough bumper beam just to support as the real one. The assembly of bumper fascia with bumper beam makes it as bumper assembly which is suitable for collision test simulation. Before exporting the model into simulating software, this bumper assembly is assembled with barrier assembly to form as master assembly. These were shown in the below figures 3.1, 3.2, 3.3, 3.4, 3.5(a) and 3.5(b).

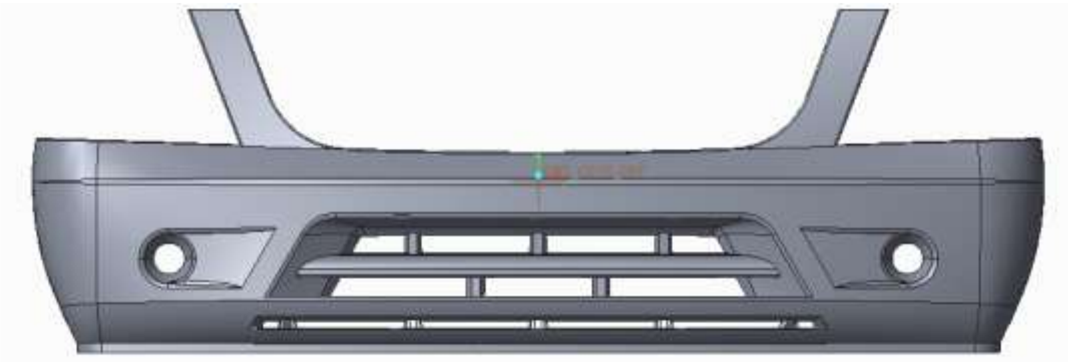

Figure 3.1: Fascia of reference model (TATA Venture)

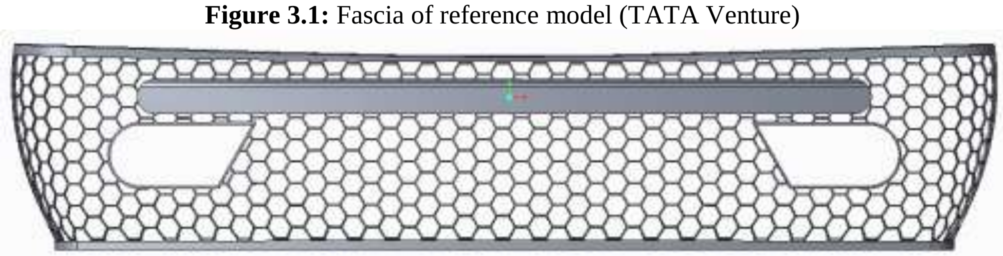

Figure 3.2: Honeycomb base structure

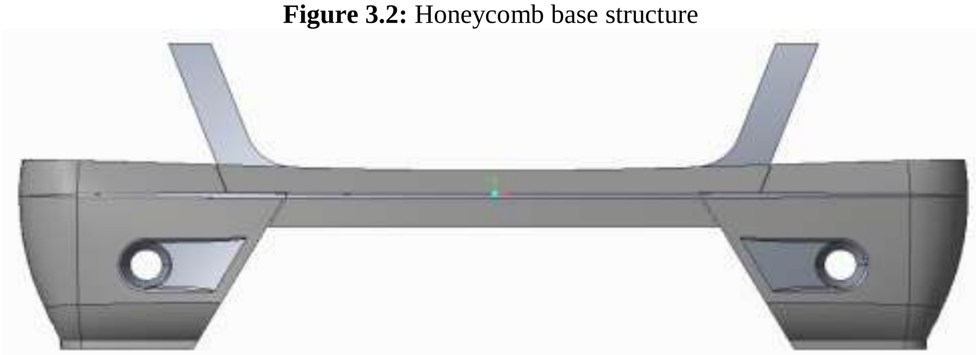

Figure 3.3: Left, Right & Centre panel assembly (Panel assembly)

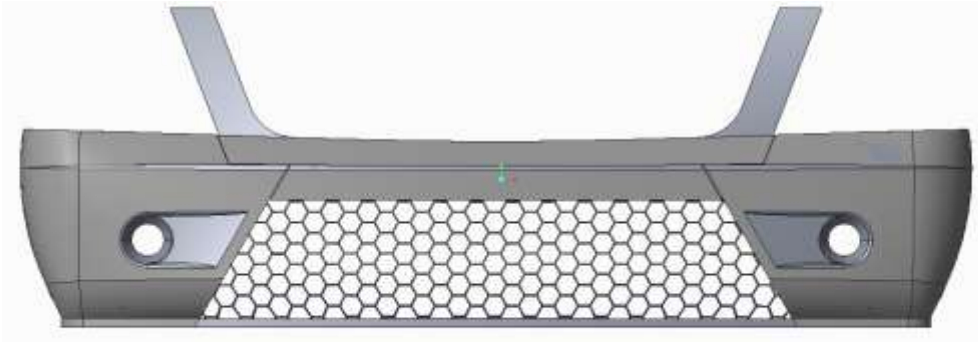

Figure 3.4: Honeycomb base and Panel assembly (Fascia assembly)

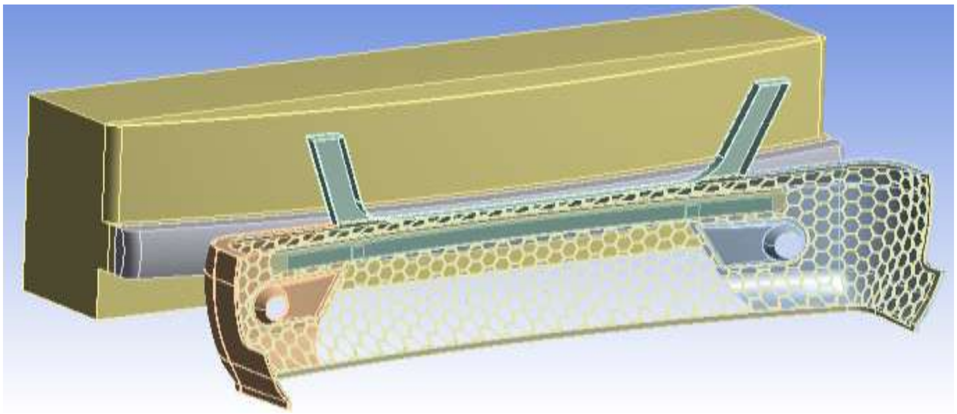

Figure 3.5 (a): Assembly for full frontal impact test

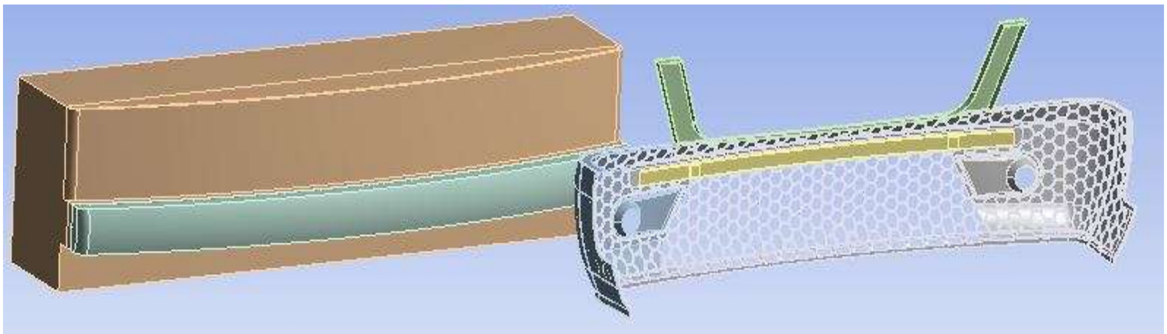

Figure 3.5 (b): Assembly for corner impact test (15% overlap from edge)

4. Results and Discussions

To obtain the test results, we have used Ansys workbench for simulating the collision test. For the purpose of comparison, the obtained test results were plotted into graphs. In order to study the performance of bumper we need to observe,

- Total energy (Fascia assembly),
- Kinetic energy (Barrier assembly),
- Total deformation (Honeycomb base structure),
- Equivalent elastic strain (Fascia assembly) and
- Equivalent stress (Fascia assembly).

Total energy plot gives us the information about impact energy absorbing capacity of the bumper. If the bumper displays high total energy value, then that bumper is said to good. Kinetic energy observations of barrier were taken to study the rate of deceleration of barrier and how fast energy is being absorbed by the bumper system. Total deformation values were observed to understand the deformation property of bumper. The reason behind observing the Total deformation of honeycomb base structure alone is, the damage of body parts like headlights, radiator, engine etc., will depend on the deformation of honeycomb base structure only. The stress and strain values were observed to study the strength of bumper assembly. If a bumper displays less stress and strain values, then it said to have good strength.

As discussed previously, this simulation is done according to RCAR safety standards. These safety standards were used to test the performance of bumper under low speeds and it consists of two tests. The velocity value and respective test name is listed in below table 4.1. For the purpose of reducing the errors, velocity is applied to the barrier instead of bumper assembly due to their weight difference. The constraints were applied to the barrier assembly in such a way that, it moves in prescribed velocity and parallel to the ground. Mass of the barrier used for this is, 1341.0232Kg.

Table 4.1: Velocities of barrier

S. No	Impact test name	Velocity of barrier (m/sec)
1	Full frontal impact	2.6
2	Corner impact	1.3

Material used for honeycomb configured bumpers is same as that of reference model (i.e. Polypropylene) and the material properties of barrier assembly and bumper beam were also listed in below table 4.2. Polypropylene is used for fascia assembly and also for absorber cover used in barrier assembly. The medium carbon steel is used for bumper beam and barrier structure.

Table 4.2: Material Properties

S. No	Material	Density (kg/m^3)	Young's modulus (MPa)	Poisson ratio	Yield strength (MPa)
1	Polypropylene	900	1300	0.45	35
2	Medium Carbon Steel	7888	2.1e5	0.3	250

4.1. Full frontal collision test

As discussed previously, in full frontal collision barrier is set to collide with the bumper assembly at a speed of 2.6m/s and test is conducted for 0.005sec. In this collision, barrier vertical centre plane coincides with the bumpers vertical centre plane. This is the main test to be concentrated, as total impact energy from barrier will be acting on the bumper due to aligning the centre of gravities of both bodies on same line. In general, major property damage will occur in full frontal collision than the corner collision.

Best design configuration can be picked from the available 4 configurations only after comparing their values with reference model. For this, the plots related to new designs & reference model should be combined in single plot. As discussed previously, bumper should have good energy absorption ability and should possess less deformation, stress and strain values. The model which satisfies above requirements is said to be the best out of 4 configurations. The related plots were shown as below in figures 4.1 to 4.5.

From below total energy plot 4.1, it's clear that energy absorbed by reference model is very less when compared to that of honeycomb configurations. So it's clear that honeycomb bumpers are absorbing more crash energy compared to that of reference or existing model. It can be even improved by altering the remaining dimensions & shape of the HC structure. In this thesis only 4 honeycomb configurations were examined & in them 2_2mm configuration is absorbing the highest amount of impact energy (i.e. 31.28J) and is followed by 3_2mm, 3_3mm and 2_3mm. Best configuration can be chosen only after observing the remaining plots related to total deformation, stress & strain.

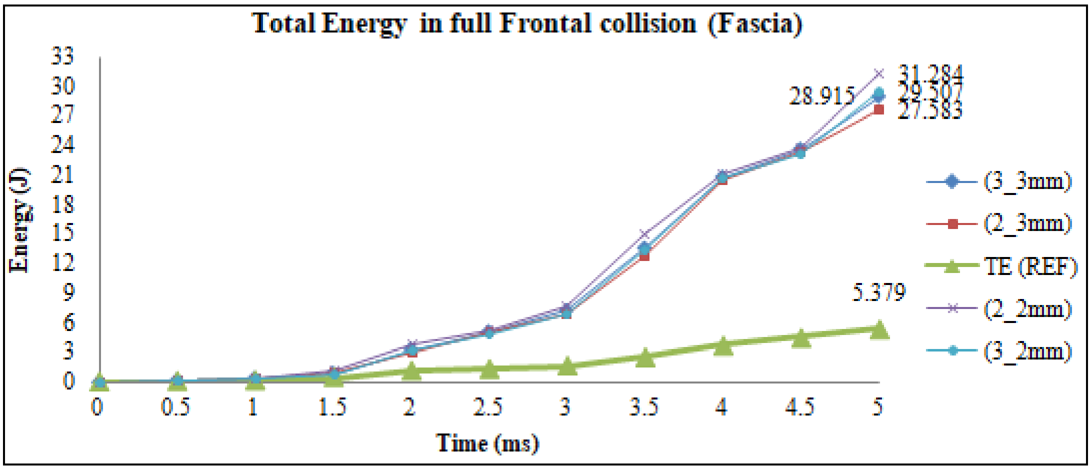

Figure 4.1: Comparison of Total energy

Kinetic energy plot of moving barriers is as shown in the figure 4.2 below and it is observed that, KE of barrier used in reference model has lost more energy when compared to H.C configurations. But as per total energy plot, reference model bumper absorbed very less energy. This means, in reference model the impact energy is transferred to the bumper beam and remaining parts in the vehicle and this leads to a great damage in future. Kinetic energy drop is high for 2_2mm followed by 3_2mm, 3_3mm & 2_3mm.

From below figure 4.3, it can be noticed that deformation of honeycomb (HC) configuration is less than that of reference model. As these are assembled bumpers, deformations of base structure were used for comparison. Because, if deformation of base structure more then it leads to damage of remaining parts due to crushing loads. So from above figure 4.3 it's clear that, HC base configurations performed well and in the order of 3_3mm < 2_2mm < 2_3mm < 3_2mm.

From below figure 4.4 it is observed that, stress values were also recorded less for HC + panel assembly then that of reference model. Even though HC configurations showed peak values at starting but later the slop of curves were recorded very less than that of reference model. The values recorded at simulation end time were also displayed in the figure and they were in the order, 2_3mm < 3_3mm < 2_2mm < 3_2mm.

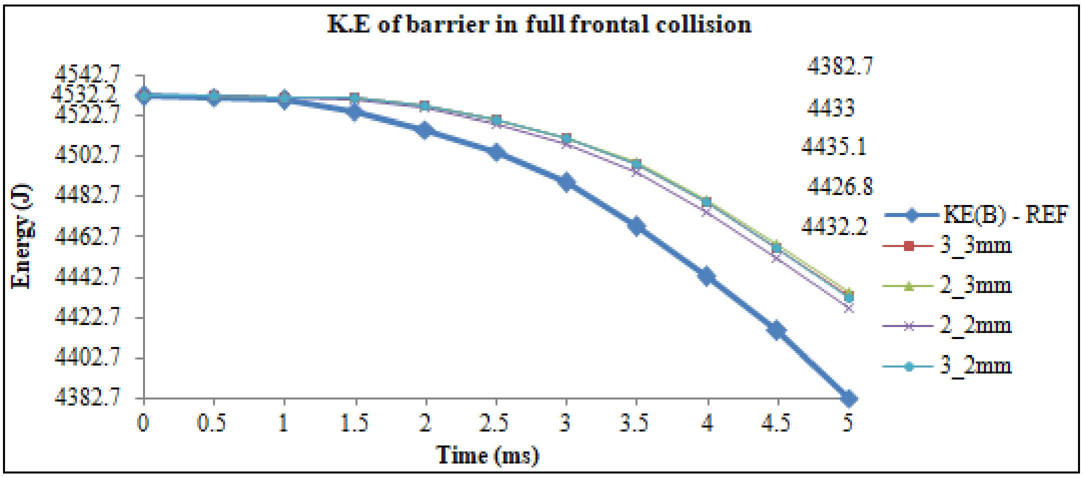

Figure 4.2: Comparison of Kinetic energy

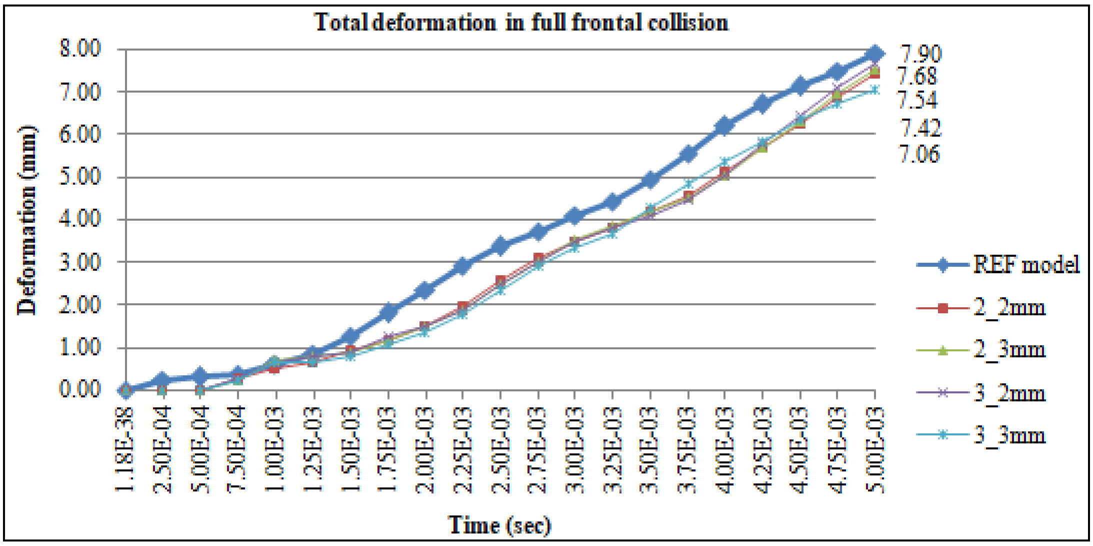

Figure 4.3: Comparison of Total deformation

From below figure 4.5 it is observed that, strain values of HC-configurations were recorded less than the reference model and even though graph has some peaks at beginning later slop dropped at the end of test. When it comes to reference model, slope got increased gradually and at the simulation end time it is recorded as 9.77mm/mm. The strain values of Honeycomb configurations at the end time are in the order 2_3mm < 2_2mm < 3_2mm < 3_3mm.

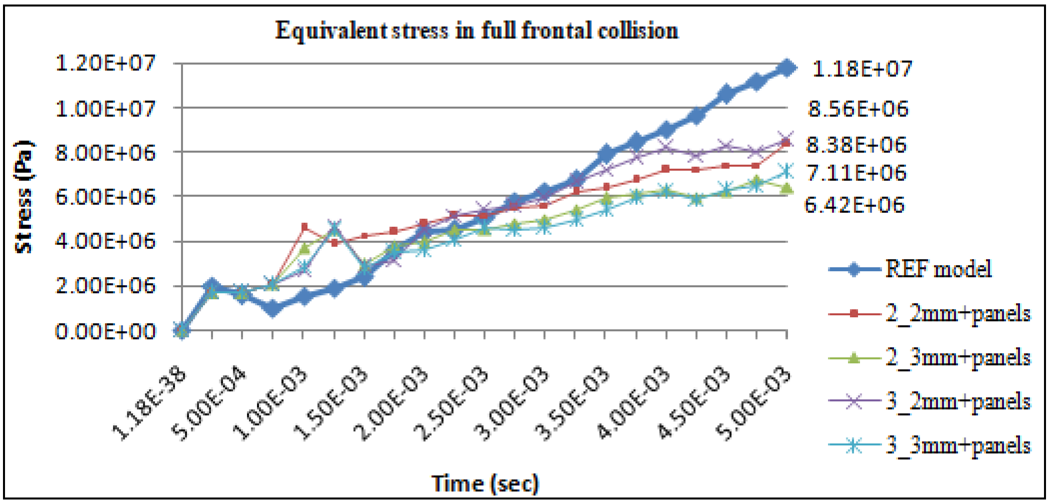

Figure 4.4: Comparison of Equivalent stress values

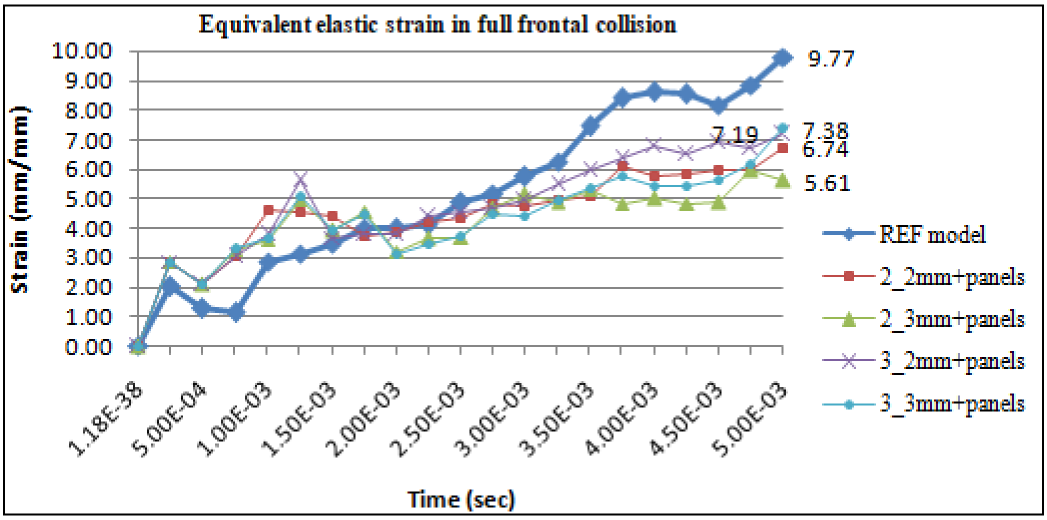

Figure 4.5: Comparison of Eq. Elastic Strain values

4.2. Corner collision test

In this type of collision, barrier is set to crash into the vehicle at a velocity of 1.3m/s with an edge to edge overlap of 15% (as shown in the figure 3.5(b)). This type of testing is done to minimize the damage of parts like headlights, fenders & fog lights etc by providing the good design. Bumper beam is generally not extended to full width of vehicle and this leads to less protection in the corners and leads to damage of equipment. To reduce this damage cost, bumper need to exhibit good impact resisting characteristics in the corners. In reality, after impact the vehicle slides to its side instead of moving in the straight line like that of full frontal impact. KE & Total energy values were not considered in corner collision, because of negligible amount of change in them and not affecting the final output in best bumper selection.

By observing the below graphs, the best performing bumper can be chosen or placed in ascending order by its overall performance. The plots of total deformation stress & strain where as shown in the figures 4.6, 4.7 and 4.8. The delay in response in total deformation plot is due to 1mm gap between Honeycomb base structure and panel cover assembly and this can be neglected.

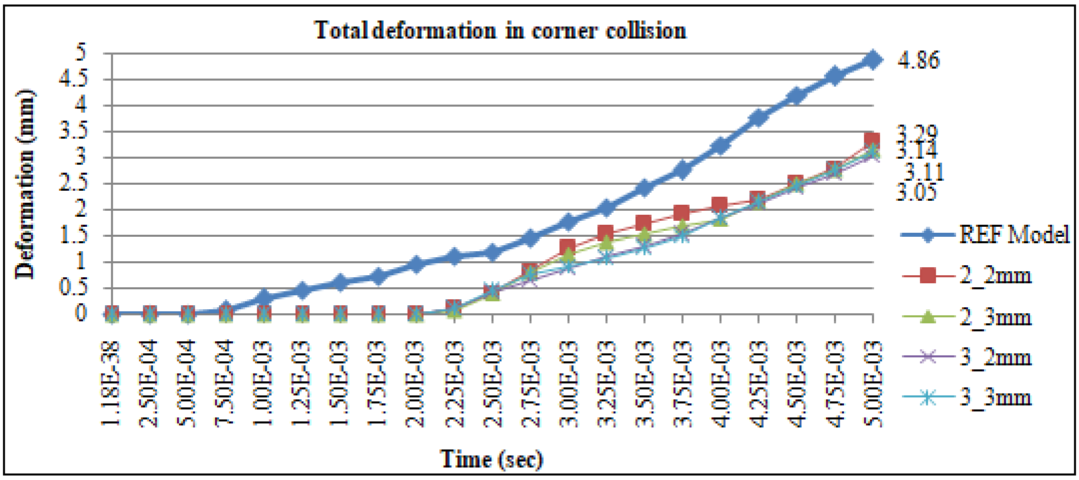

Figure 4.6: Comparison of Total deformation

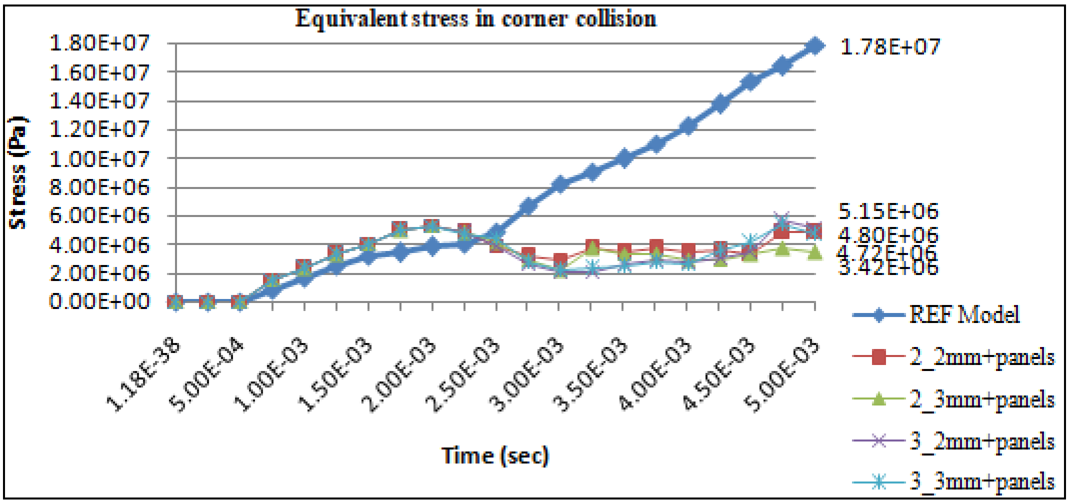

Figure 4.7: Comparison of Equivalent stress values

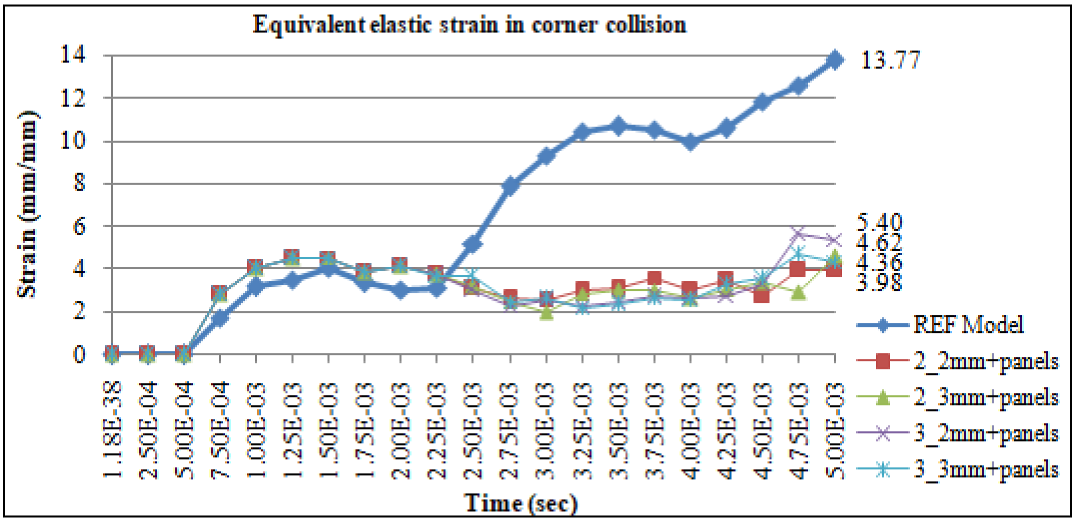

Figure 4.8: Comparison of Eq. Elastic Strain values

By observing the above plots, one thing is very clear that reference model is showing the peak values in all the three cases and a minor difference can be observed in the values related to honeycomb structured bumpers configurations. So, when we place them in the ascending value order, the order looks as seen below.

- Total Deformation: 3_2mm < 3_3mm < 2_3mm < 2_2mm.
- Equivalent stress: 2_3mm < 3_3mm < 2_2mm < 3_2mm.
- Equivalent Elastic strain: 2_2mm < 3_3mm < 2_3mm < 3_2mm.

So from above order it's clear that, all the values are changing depending on the dimensions. A minor change in dimension is bringing small change in their performance. So it's clear that, a improved design can be achieved by changing the shape and all the three dimensions of honeycomb structure. Coming to the corner impact test, honeycomb 3_3mm configuration is showing a bit satisfied results.

4.3. Weight comparison

From collected design requirements, it is clear that the bumper need to have low weight to decrease the weight of complete vehicle. This leads to the improvement of overall vehicle performance. So, along with the deformation, stress and strain characteristics weight of the bumper is also needed to be considered in order to select the overall best & improved design. The masses of different configuration bumpers are tabulated in 4.3 below and later placed in ascending order for easy understanding.

From below table it can see that, weight of honeycomb bumpers got reduced than that of reference /actual model. The weight drop is as below,

- 2_2mm + Panels model is 0.9973 Kg less than the reference model.
- 3_2mm + Panels model is 0.9733 Kg less than the reference model.
- 2_3mm + Panels model is 0.8493 Kg less than the reference model.
- 3_3mm + Panels model is 0.8133 Kg less than the reference model.

Finally, 2_2mm < 3_2mm < 2_3mm < 3_3mm < Reference model.

Table 4.3: Weight values of bumpers

S.NO	BUMPER NAME	MASS (Kg)
1	Reference/Actual bumper	2.0533
2	2_2mm + panels	1.056
3	3_2mm + panels	1.08
4	2_3mm + panels	1.204
5	3_3mm + panels	1.24

4.4. Selection of best bumper

After conducting full frontal & corner collision tests, it is clear that all the bumpers were showing the results within the limits. Even though the test is conducted for less time period, by observing the stress and strain plots it can be said that the bumpers won't fail even if the tests were conducted for large time period. So these four new configurations can be considered as safer bumper models and the best one should be sorted out by observing the results of both the tests. The weight of bumper is already reduced between 39 - 49% when compared to that of original model. So any bumper can be chosen when we consider the weight.

Now the best bumper can be selected by observing and comparing the test data related to deformation, stress and strain. All the four configurations showed almost equal results. To simplify this selection process, let's arrange the configurations in descending order based on overall performance in full frontal and corner impacts and the orders were shown below,

- Overall full frontal test: 3_3mm > 2_3mm > 2_2mm > 3_2mm.
- Overall corner impact test: 3_3mm > 2_3mm > 2_2mm > 3_2mm.

From above performance order it is clear that, same order is continued in both the test and it makes us easy to choose the best bumper configuration. Therefore, 3_3mm + Panels model is said to be the best configuration based on its overall performance. Due to this configuration, weight has been reduced up to 39%.

5. Conclusion

This paper is done to improve the overall performance of existing bumper of a vehicle (TATA Venture) by using honeycomb structured bumper without compromising the aesthetics of vehicle. For this purpose, 4 different configurations of honeycomb with fixed cell size is used and tested as per modified RCAR regulations. For the purpose of saving time, the test is performed for 5ms and results were plotted into graphs for easy comparison.

Based on overall comparison of test results, 3_3mm + Panels bumper configuration has come out to be the best performing bumper out of tested configurations and the results greatly improved than the existing model. Even though all the bumpers performed nearly the same, the best is 3_3mm configuration. This model reduces the weight up to 39% and as the less deformation in recorded this improves the protection of remaining body parts.

For the purpose of maintaining the aesthetics and aerodynamics, honeycomb configured base structure is assembled with panels which looks similar to that of existing bumper design. These panels make it effortless to repair/replace the panels when they get damaged. This reduces the overall maintenance charges like denting, repair & replace etc.

Finally it is concluded that, the bumper which is made from honeycomb structure improves the performance of bumper by reducing its weight and also its maintenance charges. This solves the maximum problems which are being faced by the use of ordinary bumpers available in the market.

6. Future Scope of Work

By testing the four different configurations it is clear that, performance of HC structure is changing by changing the dimensions of the honeycomb structure. So in order to improve its performance, lot more configurations were needed to be tested by changing its cell shape, cell size, wall thickness and overall structure thickness.

The performance of bumper can also increased by choosing a different material that is being used of the honeycomb base structure. Currently, several advanced materials were available and can be used for the performance enhancement.

The ability of absorbing energy can even increased by placing the absorbers between honeycomb base structure and the panels that are being used. This also improves the bumpers life.

Use of energy absorbers between bumper & bumper beam will also enhances the ability of absorbing energy and it also improves the pedestrian safety.

Using rubber covered base panel will improve the energy absorbing capacity base structure and reduces the erosion caused by the action of friction.

Aesthetics can even more improved by attaching chrome panels to the bumper in required area. This honeycomb cells makes it even easier to customize the bumper whenever it is needed.

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