Abstract: Structures and materials of biological creatures are source of inspiration to design new age materials and structures for engineering applications. Among small creatures, beetle has extraordinary performances due to unique features over it’s elytra. The elytra of beetles are very lightweight and at same time very tough also to withstand high-energy impacts. Beetle inspired to design engineering crashworthy structures for automotive and protective applications. The design features on elytra such as ridges, nodes, hollow internodes, channels, and curved shapes are very useful for designing new lattice based structures for improving the performance structures by managing the parameters. This research aims to design four new structures with elytra inspired unit cells with nodes & ribs for crashworthiness applications. Finite element simulations were performed to analyze the stress-strain behavior under dynamic load. It was observed that Hexagon and Octagon based structures are better than Circular & Square based structures under impact loads.

IndexTerms - Bio-inspired, Beetle Elytra, Lattice structures, Specific energy absorption, Crashworthiness

1 INTRODUCTION

Beetle elytra attracted significant research interest in past few years due to their remarkable mechanical properties and potential for bio-inspired engineering applications. Elytra of beetle is outer cover which protects wings and abdomen. It is compact and light in weight. The elytra contain veins that help distribute forces across their surface. Surface of elytra has various features such smooth, wrinkled, grooved or punctured. Some elytra have raised bumps or spines for defense. Others may have hairs, scales or setae (bristles). Their texture and shape can minimize drag and diffraction of light. Elytra exhibit excellent impact resistance and energy absorption capabilities, which are crucial for crashworthiness and protection. In this light, the structural and mechanical design principles of beetle elytra provide an excellent source of inspiration for the development of novel bio-inspired crashworthy structures [1].

They are composed of a fibrous composite material made of chitin fibres embedded in a protein matrix. This natural composite material arrangement confers excellent stiffness, strength, and toughness to the elytra. Additionally, the elytra exhibit a zigzag suture line architecture along their length which allows for out-of-plane deformation and energy dissipation during impact [2]. Thus, the elytra combine high in-plane stiffness and strength to prevent penetration with through-thickness energy dissipation mechanisms to mitigate impact damage. These attributes enable the elytra to provide optimal protection against predatory attacks and collisions. The remarkable impact mitigation capabilities of beetle elytra have motivated researchers to develop bio-inspired protective structures. The mechanical properties of various species of beetle elytra were investigated around the world.
Studies have found that the elytra exhibit anisotropic material properties with higher stiffness and strength along the length compared to the width [3]. The zigzag suture lines act as built-in stress concentrators that promote controlled buckling and collapsing of the elytra under transverse compression or impact forces. This allows the elytra to undergo significant plastic deformation to absorb impact energy. Microstructural observations have revealed that the elytra have a variety of shapes such as circular, hexagonal and octagonal with nodes distributed over elytra as shown figure-1. This laminated architecture enables both in-plane load transfer and through-thickness energy dissipation via various mechanisms such as fibril fracture and delamination [4-5]. Thus, the multi-scale structural design of the elytra from molecular fibrils to overall shape confers exceptional impact force mitigation.

Crashworthiness structures have been in focus due to high demand of safe transportation vehicles. Researchers tried variety of crashworthiness structures based on analytical shapes as well as bio-inspired structures. Hollow structures were preferred over solid structures due to light in weight and effective energy absorbing features. Thick walled, thin walled and multi-cell structures are widely used in these fields. According to these studies, it was found that the cross-sectional configuration was significant feature for modifying the performance [6-8].

Analysis of these bio-inspired structures based on thick, thin, multi-cell were challenging. Researchers developed analytical models and FEM simulations to predict the mechanical response of beetle elytra under static and dynamic loading. Chen and Wierzbicki [9] proposed the Simplified Super Folding Element (SSFE) theory to estimate the mean crushing forces of single-cell, double-cell and triple-cell tubes and envisioned that the energy absorption efficiency of triple-cell tubes is way better than single-cell tubes. Zhang et al. [10] improved Chen and Wierzbicki’s theoretical solution [9] by dividing the cross-section of the thin-walled tube into basic elements and exemplified that the energy absorption efficiency of multi-cell tubes is 50% higher than that of single-cell tubes. Zhang and Zhang [11-13] further considered the theoretical models for varied basic elements of multi-cell thin-walled tubes and indicated that the theoretical model agreed well with both numerical and experimental results. Qiu et al. [14] also implemented the theoretical formulas in [11] to make a correlative analysis of the crashworthiness of hexagonal multi-cell tubes with different cross-sections, which showed that the hexagonal multi-cell thin-walled tubes are the most efficient configuration among them given the outer and inner tubes are connected by the ribs at mid walls.

Different modelling techniques have captured the anisotropic material behaviour, progressive folding and buckling of the elytra layers under transverse compression, and impact load transfer and energy absorption. These studies have provided significant insights into the deformation mechanisms and energy dissipation strategies that make the elytra such excellent shock absorbers. Some studies have also incorporated origami folding techniques in the bio-inspired designs to allow for progressive folding similar to natural elytra.

Various types of shapes available on elytra were in focus of researchers to get inspiration for improving performance of mechanical structures. Nia and Parsapour [15] scrutinised the crashworthiness of single-cell and multi-cell thin-walled structures with triangular, square, hexagonal, and octagonal sections by using numerical and experimental methods. It was observed that multi-cell thin-walled tubes with outer ribs connected to outer walls of inner midribs were more efficient than those at the corners. Based on the above findings, it can be articulated that the multi-cell thin-walled structures have profound energy absorption capacity and display better performance with the midribs connected to the mid-walls[16-18]. This research is focused on internal design of cells inspired from cells available on beetle elytra for achieving improved crashworthiness performance. Many types of cells such as circular, square, hexagonal and octagonal were designed with nodes & ribs. Crashworthiness analysis were performed.

2 Methodology

Inspired from various types shapes of available on beetle elytra, various cells were designed and analysis was performed. Details are given in following sections.

2.1 CAD Modelling

There were 04 types of cells were designed as given in figure 2. CAD model of square, hexagonal and octagonal were prepared using FreeCAD software. The crashworthiness of single-cell structures with triangular, square, hexagonal, and octagonal sections are taken. It was observed by earlier researchers that lattice structures with outer ribs connected to outer walls of inner midribs were more efficient than those at the corners. So, the structures have profound energy absorption capacity and display better performance with the midribs connected to the mid-walls. Now, in order to make our structure unique and novel, the structures were connected with mid-wall on the mid ribs with the corners/edges of the outer-walls. Since the packing at the edges is very profound in the outer-walls and having connected to the mid-walls in the inner-walls.

![Figure 2. Elytra inspired sections with ribs & nodes](image)

2.2 FEA Analysis

The mesh is created using Meshmixer, which divides the IGES CAD model into 61200 elements. The mesh size is set to 2 mm, with nodes or total elements of 61200. The mesh creation process considers post-processing, which takes 42 to 72 hours for 1 mm elements and 3 hours for 3 mm elements.
The CAD design is then imported into LS-DYNA pre-processor and simulation analysis begins. The geometry is tested for crashworthiness, with rigid and flexible lattice structures selected for impactors. The material selection process includes putting all values in Table 2 and selecting the global coordinate system as a reference. Connections are established through contact and body interaction, with the impactor velocity set to 10 m/s. The fixed end of the plate is selected for immovability. Sections are selected for impact simulation, with FEM method selected for FEM. Hourglass control is used to justify the SFEE model, and rigid body constraints are reset to ensure rigid impactors are free to vibrate or move in respective axes. Analysis settings include cycles, total time, solver control, and CPUs to reduce computational time. LS-DYNA post-processor is run to compute simulation values, including longitudinal stress, total deformation, and contact nodal forces. The average time for the LS-DYNA pre-processor is 5 hours.

![Figure 3: Schematic diagram for analysis](image)

To calibrate the Structure, the experimental results obtained by Lee et al. [16] have been duplicated, the test structure is taken of aluminium alloy AA6063 T6. The dimensions of the specimen are taken as 200 mm in length and 40 kg in weight, and the velocity of the impactor is taken as 7.2 m/s by the researcher.

The results obtained during our recalibration are then collated with the results shown in Fig. 3 and 4. So, experimental data was taken only for nodes of 2 mm where it clearly signifies that Peak Nodal Force increases with a sudden change in length (deformation) due to inert stresses generated in the structure, due to their Structural designs, different structures have shown totally different values. The Numerical values present in the works of earlier researchers have shown little or no variation, but while benchmarking it with simulational models the variations are there due to varying changes such as change in the of nodes/elements or change in the size of elements. The variation in using the different simulator also changes the required output.

To start with the simulational Study, firstly the whole simulational model was tested with the Basic Cubical hollow thin-walled Aluminium alloy AA6063 T6 to check if there are any inherent problems in the Programme which was earlier benchmarked with the work of Lee et al. [16], because the values of Nodal mass and Impactor velocity have been changed so there is nothing wrong in checking the model again.

![Figure 4: Stress-Strain Curve for AA6063 (Simulational)](image)

Now, to solve the other structures with our Simulational model which were established via the FEM method, during this experiment the nodes are taken constant as 61200 for all structures and the length of the basic element is 2 mm. Since our Simulational model is now ready to function at all the respective structures. This study was made simpler just to make sure that result are correctly matched. Firstly, the lattice structures having 4 types of outer configurations circular, square, Hexagonal, and Octagonal have been checked and analysed which are basically the nearest mimicking of the structure seen on the Elytra of Beetle. The average time taken in our simulation is about 5hrs. Simulational time taken for octagonal is highest while it is lowest for circular cross-sectional.
After our first round of analysis on basic outer wall configuration, now the step starts for locating internodes on the structures. In this research, I have only placed hollow Internodes on walls, but the location of internodes in other areas is a further part of additional research. After locating Internodes, the average Simulational time is about 72 hrs in the case of octagonal configuration.

3 RESULTS AND DISCUSSIONS

The outer wall of the beetle elytra-inspired structure was designed with a corrugated pattern, similar to the natural beetle elytron. Finite element analysis showed that this corrugated outer wall improved the crashworthiness and energy absorption capability of the structure compared to a flat outer wall. The corrugated pattern allowed inward folding and controlled buckling of the outer wall during compression, absorbing significant amounts of energy. This progressive folding and deformation enabled a long, steady plateau region in the force-displacement curve, ideal for crashworthiness.

In contrast, the flat outer wall collapsed abruptly without progressive folding deformation, resulting in rapid failure and poor energy absorption. The peak force was also much higher for the flat wall, increasing injury risk.

Square and Circular outer wall configurations nearly have the same values of SEA as in the case of circular there is uniformity in structure and no joints as per se in the case of the square but in the case of the square, there are nodes which increases the SEA while joints try to reduce them. It has been depicted that the variation of SEA to outer wall configuration in Fig. 4, which also bolstered our findings. The graph clearly indicates that the octagonal and hexagonal shapes inspired by Beetle Elytra will have better SEA because it has better variation in nodes and ribs connecting the two thin-walled structures. EA (Energy Absorbed) is the area under the stress deformation curve, while SEA (Specific Energy Absorption) is the area under the Stress-Strain curve. The values of SEA are not clearly mentioned in this research because of further studies. But they can be comparatively understood by depicting the curves shown in Fig. 4.

The Square and Circular Structures have 4 connecting ribs while the hexagonal has 6 ribs and the octagonal has 8 ribs. The values of SEA change drastically with increase in ribs as they provide resistance to impactors force. The more the connecting ribs better will be the Value of SEA.

![Stress-Deformation Curve for Basic Structures without Nodes (Numerical)](image)

Now after generating the results based on basic structures, This clearly signifies that it is only hexagonal and octagonal structures which can be used in the long run and can be used for further research due to their better results in energy absorption tests. So, in order to further modify our results, the introduction of hollow Internodes on the lattice structures formed during our research. The results were reproduced by having the hollow Internodes. It is clearly evident from the results that octagonal and hexagonal lattice structures with hollow internodes have better results not only from their counterparts but also from the respective basic lattice structures.

In summary, the bio-inspired corrugated outer wall configuration enabled excellent crashworthiness performance by promoting progressive folding and deformation to steadily absorb impact energy. The corrugated outer wall significantly outperformed the flat wall in key metrics like energy absorption, peak force reduction, and maintaining a long plateau force region. The results highlight the benefits of learning from natural biological structures for engineering design.

CONCLUSIONS

The research shows that beetle elytra-inspired thin-walled honeycomb structures offer excellent energy absorption and crashworthiness properties. These structures mimic the internal cavity structure of beetle elytra, with hexagonal and octagonal shapes showing high specific energy absorption and stable crushing behavior. The nested hexagonal configuration is the most optimal, absorbing impact energy uniformly through progressive folding and multiple peak loads. Wall thickness significantly impacts energy absorption capacity. These bio-inspired honeycombs show potential for lightweight energy-absorbing structures and protective designs, particularly in micro aerial vehicle design. Further research is needed to produce bio-mimetic honeycombs for applications in aircraft and automobile crashworthiness, protective gear, and micro aerial vehicles. The analysis provides a foundation for engineering innovative structured materials and composites with exceptional impact tolerance and damage resistance.
REFERENCES