DEPARTMENT OF MECHANICAL ENGINEERING

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RUPNAGAR-140001, INDIA

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CP302 ENDSEM PROJECT REPORT

Topic: Design and development of auxetic structures for impact applications

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Second Semester, 2022-2023

Submitted on: 9 May, 2023

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1. Introduction

The issue of road traffic injuries is a pressing concern that requires immediate attention. As motor vehicle usage continues to increase, the need to address this issue becomes even more urgent. Road traffic accidents can have catastrophic impacts on humanity, particularly for individuals between the ages of 5 and 29, who are the most vulnerable. Approximately 1.3 million individuals lose their lives annually due to road accidents, and between 20 and 50 million people sustain non-fatal injuries. These accidents have a significant financial impact on most countries, equivalent to 3% of their gross domestic product. Additionally, it is worth noting that low- and middle-income countries suffer the most, with 93% of fatalities occurring in these regions, despite having only 60% of the world's vehicles.

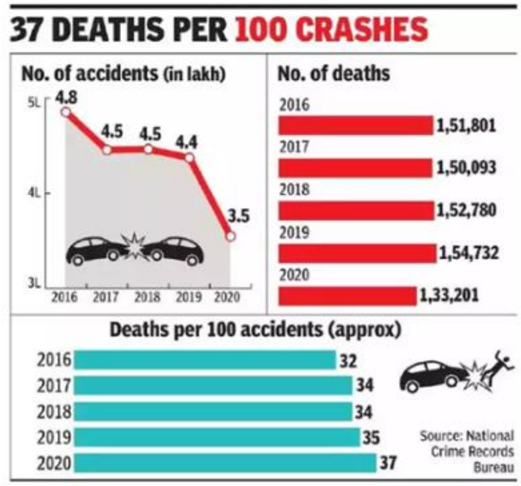

Figure 1.1: NCRB statistics of road accidents

Traumatic brain injuries are a major safety concern in the United States, with an estimated 1.7 to 3.8 million cases each year, of which 10 percent occur due to sports and recreational activities.
Approximately 21% of all traumatic brain injuries suffered by children and adolescents in the United States can be attributed to participation in sports and recreational activities. Every year, an estimated 300,000 sport-related traumatic brain injuries, mostly concussions, occur in the United States. Sports are the second leading cause of traumatic brain injury among people aged 15 to 24, behind only motor vehicle crashes. Contact-sport athletes are particularly vulnerable, with 10% sustaining concussions yearly. In football, brain injuries occur at a rate of one in every 5.5 games, and soccer players have a 5% risk of brain injury. Baseball injuries also frequently involve the head, with almost half of all injuries affecting a child's head, face, mouth, or eyes. Athletes who sustain concussions are 4-6 times more likely to suffer a second concussion, making it crucial to take appropriate precautions when returning to play. Injuries sustained while playing sports can range from mild physical trauma such as a scalp contusion or laceration to severe traumatic brain injury with concurrent bleeding in the brain or coma.

To address the issue of head injuries sustained in road accidents and sports activities, it is essential to invest in safety equipment such as helmets. Helmets can significantly reduce the severity of head injuries and protect the brain from damage. Helmets are highly effective in reducing the risk of head, brain, and severe brain injury for people of all ages who ride bicycles, with studies indicating a reduction in risk ranging from 63% to 88%. This level of protection is consistent across all types of accidents, including those involving motor vehicles (69%) and those resulting from other causes (68%). However, there is a need to improve the effectiveness of helmets further. Efforts should be made to improve the design that provide better protection against various types of impacts. New materials, such as auxetics, should be explored for helmet construction to enhance their safety and durability. Implementing effective solutions to improve the design and effectiveness of helmets will have a significant impact on preventing traumatic brain injuries, saving lives, preventing disabilities, and reducing the financial burden on countries.

The following sections will investigate the possibility of incorporating auxetic materials in the application of helmets for the enhancement of safety of individuals.

2. Existing Studies

2.*1: Structure and functioning of a typical helmet*

A helmet typically consists of 4 layers of materials, namely:

- **Outer shell:** Made of hard, impact-resistant materials such as polycarbonate or fiberglass.
- **Energy-absorbing liner:** Typically made up of expanded polystyrene, provides cushioning and helps absorb energy from impacts.
- **Comfort padding:** Made of soft materials like foam and fabric, provides comfort and cushioning against the head.
- **Face shield:** Typically made up of polycarbonate, protects our eyes against UV rays, insects, dust, etc.
- **Retention system:** Straps and buckle used to secure the helmet on the head. The structure of a motorcycle helmet is designed to provide maximum protection in the event of an impact, while also being comfortable to wear for long periods of time.

Following figure shows all the parts in a typical helmet.

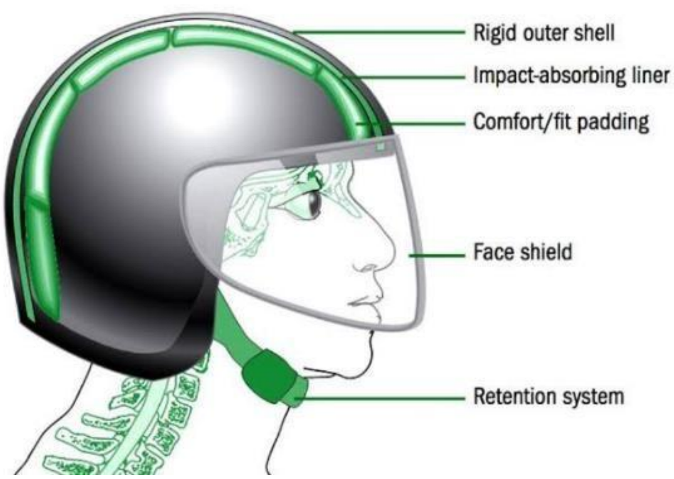

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Figure 2.1: Structure of a typical Helmet

The microstructure of expanded polystyrene foam, commonly used as the energyabsorbing material in motorcycle helmets, is made up of small, interconnected pores. The pores are formed during the manufacturing process, where steam is introduced into a mold containing polystyrene beads, causing them to expand and take on a cellular structure. The resulting foam material is lightweight, strong, and resilient, making it an effective material for absorbing energy in the event of an impact.

2.2: *Auxetic materials*

Auxetic materials are an innovative class of materials that exhibit a unique property where they expand in the lateral direction when subjected to tensile stress and vice-versa. This property makes auxetic materials particularly useful in the manufacturing of safety equipment, such as helmets. Auxetic materials are those having a negative Poisson's ratio. Auxetic materials have a unique property where they expand in the lateral direction when subjected to tensile stress and vice-versa. This makes auxetic foam a promising candidate for use in protective gear, including motorcycle helmets. Auxetic materials are now being seen as an alternative in the manufacturing of foam for motorcycle helmets.

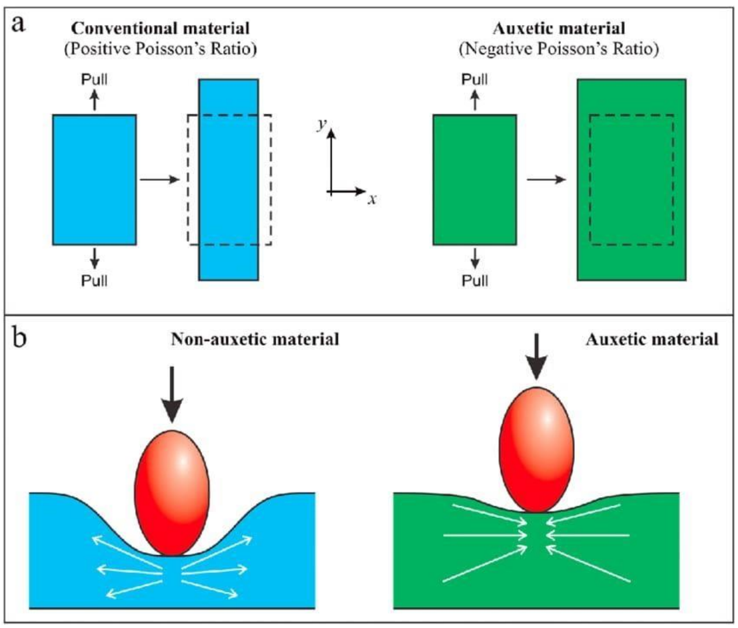

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Figure 2.2: Comparison between conventional and auxetic structures

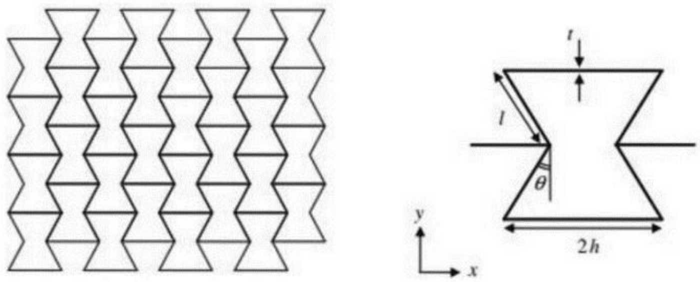
a) Behavior in case of pulling.
b) Behavior in case of an impact.

Auxetic structures can be defined through the unit cells. There are majorly three kind of unit cells namely, Reentrant models, Rotating square and rectangle models, and Chiral models.

2.2.1: Reentrant models

The cells in a reentrant structure resemble a series of interconnected bowties, where each bowtie is composed of four "V" shaped elements. In contrast to most materials, which tend to get thinner in the direction of applied force, when a force is applied to a reentrant structure, the cells deform in a way that causes the material to thicken perpendicularly to that direction. Parameters that define a reentrant model are: a) Width (2h), length (l), and thickness (t) of each element, b) Angle between units (θ), c) Number of repeating units.

Following figure shows the reentrant model with its unit structure.



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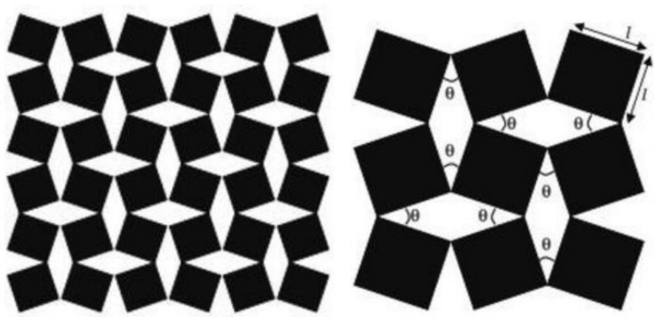
Reentrant structure Unit Cell

Figure 2.3: Reentrant structure along with its unit cell

2.2.2: Rotating square and rectangle models

These kinds of unit cells are based on a series of interconnected squares and rectangles that are rotated at an angle to one another. When we apply a force to the structure, the squares/rectangles slide and rotate against each other, resulting in an expansion in the direction that's perpendicular to the applied force. And this expansion helps to get a negative Poisson ratio. Parameters that define a rotating square and rectangle model are a) Width (l) and length (l) of each element, b) Angle of Rotation between the individual squares/rectangles in this unit cell (θ), c) Number of repeating units.

Following figure shows the rotating square and rectangle model with its unit structure.



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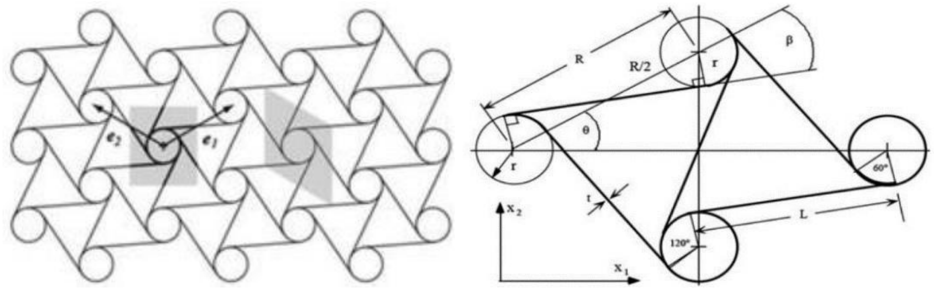
Rotating square model Unit cell

Figure 2.4: Rotating square model along with its unit cell

2.2.3: Chiral models

These unit cells are characterized by their twisted and asymmetrical shape. Applying a force to a chiral structure result in the unit cell rotating around its central axis, causing the structure to expand perpendicularly to the applied force. This unique rotation and expansion lead to negative Poisson's ratio. Parameters that define a chiral model are a) Length (L) and radius (r) of each element, b) Angle of twist (θ), c) distance between elements (R), d) Number of repeating units.

Following figure shows the chiral model with its unit structure.



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Chiral model Unit cell

Figure 2.5: Chiral model along with its unit cell

2.3: *Improved mechanical properties of Auxetic structures*

Auxetic materials have been shown to offer several advantages over conventional materials. Enhanced impact energy absorption performance allows them to withstand higher levels of stress and strain without failure. They have been shown to exhibit superior bending performance, as they can extend considerably further before undergoing kinking. They exhibit synclastic behavior i.e., curved towards same side in all the directions. Furthermore, as the value of Poisson's ratio (v) tends towards -1, the indentation resistance (H) of auxetic materials tends towards infinity, which means that they have exceptional resistance to indentation. This property is especially valuable in applications where materials are subjected to repeated or high levels of indentation, such as in protective equipment or machinery components.

2.3.1: Crushing behavior

Auxetic structures have been found to outperform honeycomb and traditional structures under low stress conditions. Specifically, they exhibit higher specific energy absorption and improved damping abilities. In a crash, the honeycomb tube shows fluctuating deceleration, while the auxetic tube maintains consistent deceleration after the initial peak, indicating superior damping capabilities under low impact conditions.

In a drop test, a helmet with auxetic foam combined with a head form was used to reduce linear acceleration. The results showed that the peak linear accelerations were lower than those of a conventional helmet, both in frontal and side orientations, at the highest impact energy. The Gadd Severity Index, which measures the likelihood of head injury, also showed a decrease of 11% for frontal impacts and 44% for side impacts when using the helmet with auxetic foam. These findings suggest that helmets with auxetic foam are more effective in reducing impact severity compared to conventional helmets.

2.4: *Limitations of auxetic structures*

Auxetic materials are typically characterized by porous, foamy structure, where the individual pores usually being bigger than a micron in size. An auxetic material can therefore expand only by a certain amount. Anymore before it weakens and possibly collapses. Additionally, the manufacturing process for creating auxetic structures is highly precise and requires careful attention to detail. Even small errors in the fabrication process can lead to unusable structures.

Despite these challenges, the potential benefits of auxetic materials make them an attractive option for safety equipment particularly helmets.

3. Problem description

Though auxetic structures show a great potential in safety equipment, they are still not commercially adopted. The obvious reasons being lack of research. Even though the interest of researchers in auxetic structures is gradually increasing, still there is a research gap that is needed to be fulfilled. There are very limited studies present that compare different kind of auxetic structures based on mechanical properties. Again, a very limited literature is present regarding analyzing the helmets as the application of auxetic structures. The study wishes to fulfill these research gaps through comparing different kinds of auxetic materials will be compared based on various mechanical properties namely Poisson ratio, Material Density, Material Stiffness, Deformation and stress distribution and Energy absorption. After this analysis, the best choice for unit structures can be made. Then, a suitable 3D printing approach for the manufacturing of plates must be found and an extra care would be needed to choose the suitable value of parameters while 3D printing. Finally, the mechanical testing of manufactured helmet will be carried out to verify the results got in computer simulations.

4. Objectives

The following objectives are needed to be fulfilled.

- Study of different kinds of auxetic materials based on unit cells and understanding how auxetic materials can be incorporated in the impact applications, particularly helmets.
- Comparing different kinds of auxetic materials to find the best auxetic unit cell structure along with optimal parameters.
- Manufacturing plates comprising of auxetic unit cell structure through additive manufacturing approach and perform its mechanical testing. Checking how the manufacturing plates will be incorporated with helmets to improve their efficacy.

5. Methodology

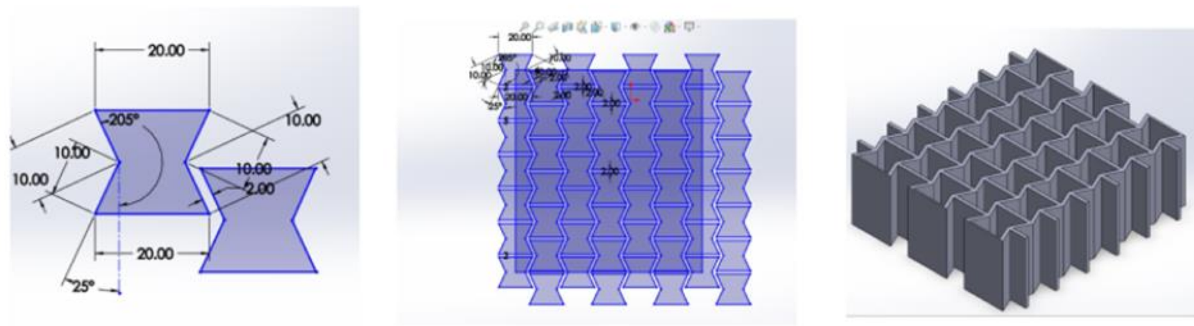
This section will mainly focus on the methods employed to fulfill the research objectives.

5.1: Computer simulations of auxetic structures

The idea of using the Pyauxetic is dropped since its new version has downgraded various options to chose the various parameters for reentrant unit cell. The analysis part is divided into two parts – 1) Fabrication and 2) Simulation

1. *Fabrication:* This is done using SOLIDWORKS. Three plates consisting of honeycomb, reentrant, and rotating square unit cell are designed in SOLIDWORKS. The main functionality used are Linear pattern, and Solid extrusion. Major steps followed were: a) sketching unit cell, b) generating linear pattern, c) extruding the

sketch to form a solid structure, and d) exporting the file as Parasolid. These steps were followed for all three types of unit cells.



Step-1 Step-2 Step-3

Figure 5.1: Showing steps for designing the plates

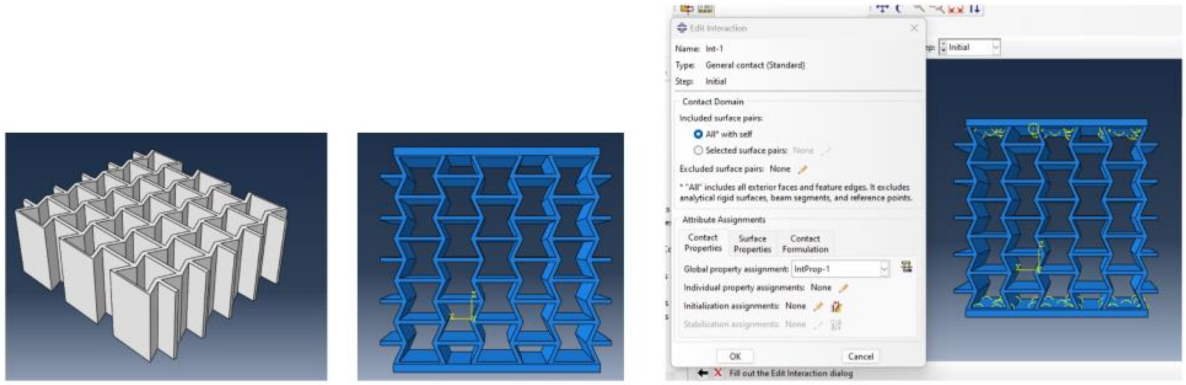
2. *ABAQUS Simulation:* To perform the FEA analysis of both the structures, ABAQUS 2017 is used.

   Following steps are performed in ABAQUS:

   a) Importing Parasolid file on Abaqus
   b) Generating two solid plates
   c) Assembling solid plates and imported part to make a single entity
   d) Defining material property
   e) Assigning sections to each part
   f) Defining step
   g) Defining interactions between parts
   h) Defining boundary conditions and load
   i) Generating mesh
   j) Creating the job and final visualization.

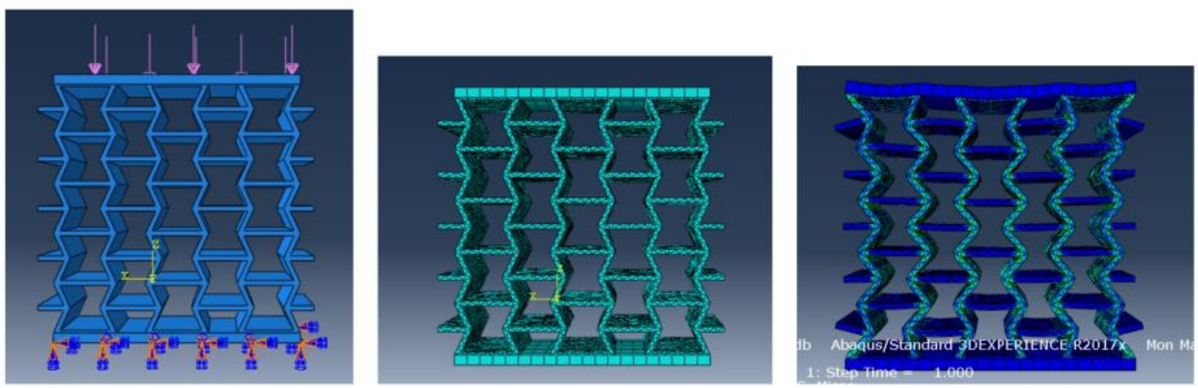
   After these steps, the certain results will be obtained and mesh should be further refined and the analysis should be repeated with refined mesh. This should be done till the mesh is converged and the analysis is yielding near similar results.

   The following figures will show the steps in the interface of ABAQUS 2017.



Importing Parasolid file | Creating assembly | Defining interaction

Figure 5.2: Showing first three steps



Defining load and BCs | Generating Mesh | Final visualization

Figure5.3: Showing next steps

3. *Visualization and data analysis:* ABAQUS final visualization are analyzed for various parameters and table summarizing results were created in MS Excel. For the calculation of Poisson's ratio, lateral and axial deformation is found using query feature of ABAQUS and then calculations were performed in MS Excel.

5.2: Manufacturing the optimal design of the plates.

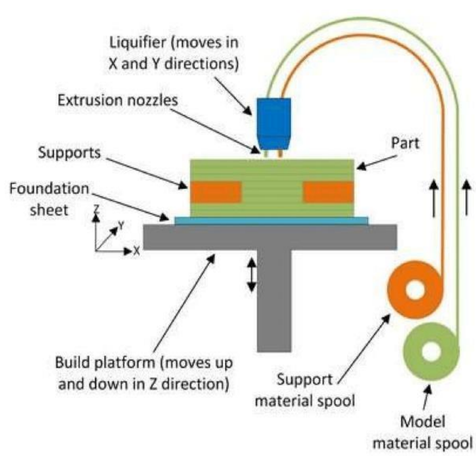
Though there are various approaches to manufacture the auxetic plates like 3D printing, laminating, injection molding and cutting and folding, the 3D printing approach was chosen due its following advantages over traditional methods.

- *Complex geometries:* The process of additive manufacturing involves the layer-by-layer construction of the helmet using computer-aided design (CAD) software and a 3D printer. This allows for greater design freedom, enabling the creation of more intricate and efficient geometries that would be difficult or impossible to achieve with traditional manufacturing methods.

- *Design flexibility:* With 3D printing, designers have more flexibility to experiment with different materials and structures to create helmets with specific properties, such as increased impact resistance or improved ventilation. This allows for more customized helmets that can be tailored to individual needs.
- *Customization:* 3D printing allows for mass customization, meaning that each helmet can be customized to fit an individual's head size and shape. This is important because poorly fitting helmets can reduce the effectiveness of the helmet in protecting against impacts.
- *Reduced waste:* 3D printing can be more efficient than traditional manufacturing methods because it can produce parts with little or no waste material. This is important because traditional manufacturing methods can produce a lot of waste material, which can be environmentally harmful and costly.

The choice of the type of 3D printing approach is extremely important while dealing with the manufacturing of intricate structures. Following are the potential 3D printing methods that can be employed for the manufacturing.

- *Fused Deposition Modeling (FDM):* Fused Deposition Modeling (FDM) is a popular 3D printing technology used to create three-dimensional objects by depositing layers of molten material on top of each other. A spool of thermoplastic material, like ABS or PLA, is heated and extruded via a nozzle in this sort of additive manufacturing technique. The first step in the process is to slice a digital 3D model of the item to be printed into numerous layers. After reading the sliced file, the printer begins printing the item layer by layer, working its way up. The build plate moves down along the Z-axis to make space for the next layer as the nozzle moves back and forth along the X and Y axes as each layer is printed. To create an auxetic helmet using FDM, a special infill pattern can be used, such as a Voronoi or gyroid structure, which creates the negative Poisson's ratio effect. Following diagram shows a typical FDM based 3D printing.

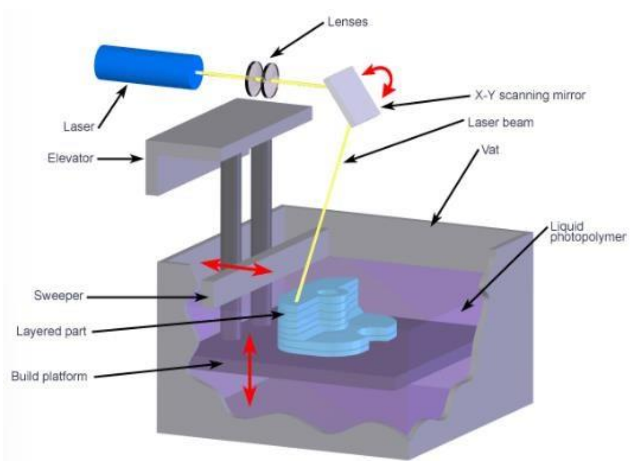


(Source)

Figure 5.4: FDM

- *Stereolithography:* Stereolithography (SLA) is a 3D printing technology that uses a process called photopolymerization to create three-dimensional objects. A photosensitive resin that solidifies when exposed to light is the foundation of this technique. A digital 3D model of the thing to be printed serves as the basis for the SLA process. The printer uses this information to build a physical object layer by layer once the model has been divided into several levels by the slicing software. The print medium is a vat of liquid resin, and each layer is created by selectively curing the resin with a UV laser beam at the required position and shape. The liquid resin solidifies and adheres to the layer below it as the UV laser beam follows the outline of each layer on its surface. The build platform is then lowered, and the procedure is repeated until the object is finished for each subsequent layer. A distinct lattice structure, such as a chiral or re-entrant structure, which can produce the negative Poisson's ratio effect, can be used to construct an auxetic helmet using SLA.

  Following diagram shows a typical SLA based 3D printing.



(Source)

Figure 5.5: SLA

- *Selective Laser Sintering:* SLS is another popular 3D printing technique that uses a laser to sinter (or melt) powdered material layer-by-layer to create the final object. The process involves spreading a thin layer of powder material over a build platform and then scanning a high-powered laser beam over the powder bed, selectively melting, and fusing together the particles in a specific pattern to create a solid layer. After each layer is completed, the build platform lowers, and a new layer of powder is spread over the previous layer. This process is repeated layer by layer until the final 3D object is complete. Once the printing is finished, the excess powder is removed, and the printed object is cleaned and post-processed as needed. To create an auxetic helmet using SLS, a similar infill pattern (like FDM) can be used to create the negative Poisson's ratio effect. Following diagram shows a typical SLS based 3D printing.

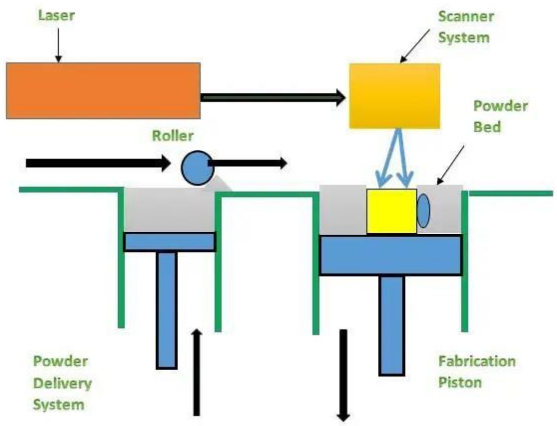


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Figure 5.6: SLS

After the correct 3D printing approach is finalized, the next step is to create a CAD model of the plates and exporting it to a .stl file to the 3D printer. The parameters like bed temperature, layer thickness, inclination of support system, and infill ratio will be chosen as the final step. After that, a command will be given to initiate the printing process. The plates manufactured will be incorporated with helmets.

5.3: Mechanical testing of the plates manufactured.

After manufacturing the helmet, it is necessary to perform its mechanical testing to verify the findings in the simulation results.

- *Selection of relevant tests:* Identifying the tests that are most relevant to the specific properties and parameters of the auxetic material being tested. For example, the compression test, tensile test, or drop test may be used to measure different mechanical properties of the material. These tests will include:

    - *Tensile testing:* In this method, the helmet is pulled apart in opposite directions until it starts getting deformed or breaks. Amount of force required is measured and will be used in calculating elasticity and tensile strength.
    - *Compressive testing:* Like tensile testing, here the helmet is compressed between two opposite directions until it deforms or breaks. Amount of force required is measured and will be used in calculating elasticity and compressive strength. o *Microhardness testing*: A small diamond or tungsten carbide tip is used to indent the surface of the helmet and to measure the size of indentation. This test evaluates the helmet's resistance to deformation and measures the hardness of the material at the surface.
    - *Drop testing*: Here we will drop the helmet from a specific height and measure the amount of force absorbed by the helmet during impact. It will help us to analyze the helmet ability to absorb or dissipate energy during an impact.

- *Shear Strength Testing:* In this test we apply a force parallel to the surface of the helmet until it deforms or breaks. The amount of force required to cause the deformation or breakage is measured and used to calculate the shear strength of the material.

- *Test sample preparation:* Prepare the test samples in a way that accurately represents the material used in the simulation. This includes ensuring the geometry and size of the test sample are the same as the simulated model.
- *Execution of the tests:* Perform the selected tests in accordance with established industry standards or protocols. This may involve applying a specific load or impact force to the test sample and measuring the resulting deformation or stress.
- *Data analysis:* Analyze the data collected during the tests to determine if the findings are consistent with the simulation results. Compare the values of relevant parameters, such as Young's modulus and Poisson's ratio, to verify the consistency between the simulation and experimental data.
- *Interpretation of results:* Interpret the results of the mechanical tests to understand the material's mechanical properties and how they compare to the simulation findings. Consider any discrepancies between the simulation and experimental data and determine the reasons for any differences.

6. Results

This section aims to present the findings of computer simulations.

6.1: Designing plates in SOLIDWORKS

For designing the plates, SOLIDWORKS 2019 is used. Honeycomb unit cell structure and Reentrant unit cell structure is designed. For honeycomb unit cell structure, the following parameters were taken.

Length of unit cell	Distance between unit cell
10 mm	2 mm

Here is the final designed honeycomb plate.

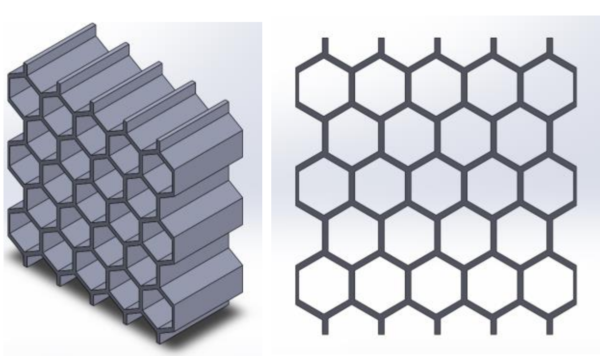
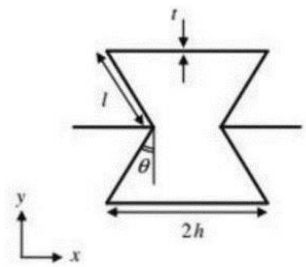


Figure 6.1: Designed honeycomb plate

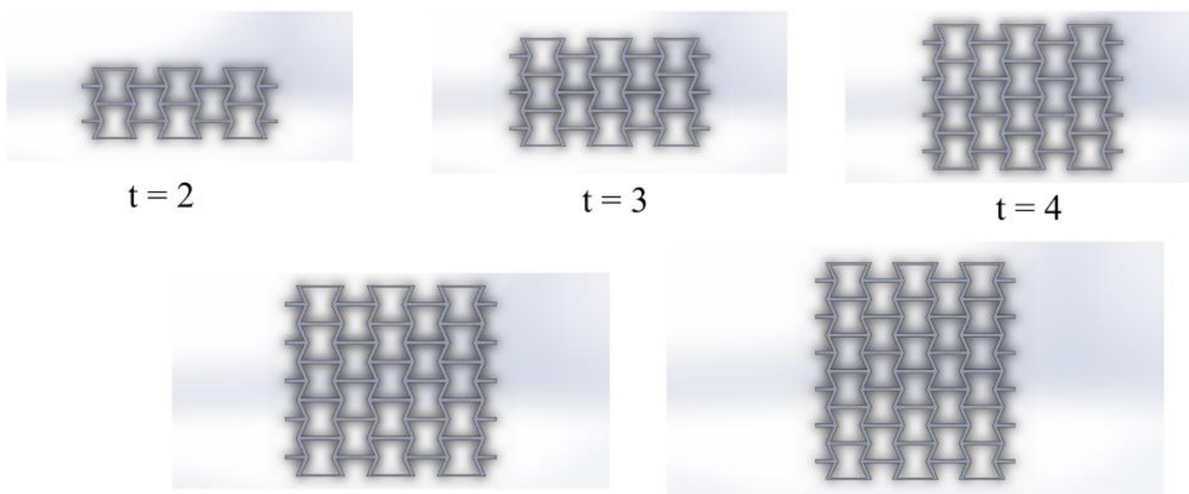
For reentrant unit cell structure, the following parameters were taken.



Length (l)	Distance (t)	Width (2h)	Angle (θ)
10 mm	2 mm	20 mm	25°

In this case, the thickness of plate is also varied from 2 layers to 6 layers.

Here are the final designed reentrant plate structures. (Front view is shown)



t = 2 t = 3 t = 4

t = 5 t = 6

Figure 6.2: Designed reentrant plate

6.2: Simulation in ABAQUS

For stress and deformation analysis, ABAQUS 2017 is used. Initially, honeycomb structure and reentrant structure with same thickness (5 layers) and same material is taken and the von mises stress and deformation is compared for both the unit cells.

The complete structure comprises of the pattern of unit cells in both the directions along with the identical plates on upper and lower portion. The compressive force will be applied on one of the plates while the other kept fixed.

The following image shows the final assembly in both the cases.

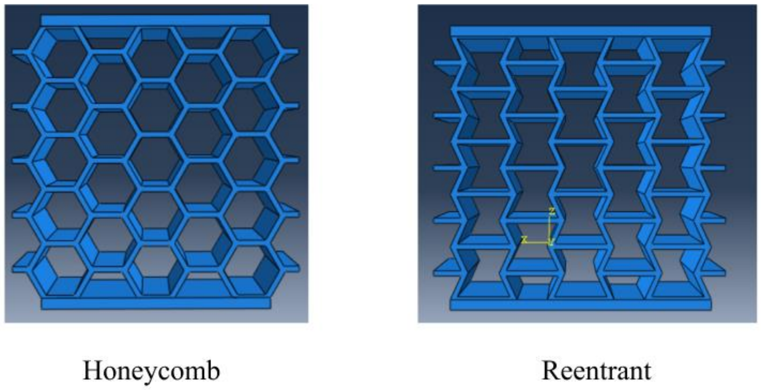


Figure 6.3: Developed assembly

6.2.1: Poisson's ratio calculation

Both the structures are sandwiched between two plates. One of the plates is fixed and the same force is applied to the other plate for both the cases. The response of both the structures is shown in the image below.

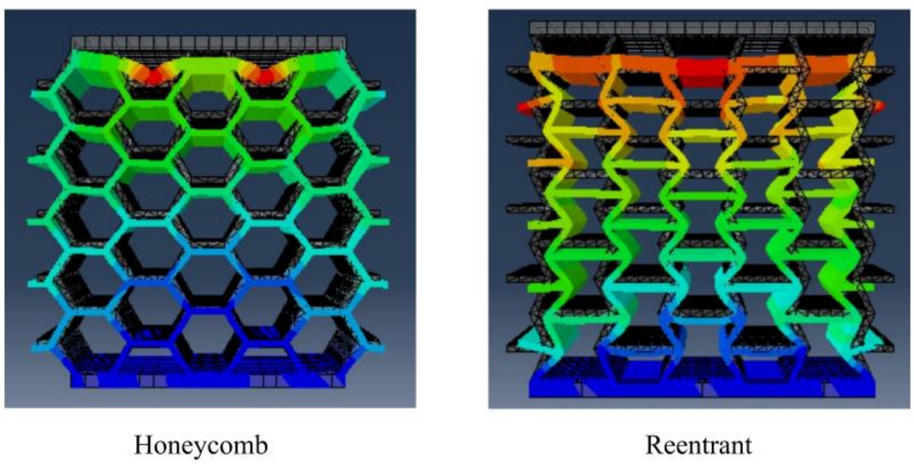


Figure 6.4: Behavior of both the structures

It is observed that honeycomb unit cell expands in lateral direction when a compressive force is applied and reentrant unit cell compresses in lateral direction upon the application of same compressive force indicating that it would be having negative Poisson's ratio.

Following table shows the calculated Poisson's ratio.

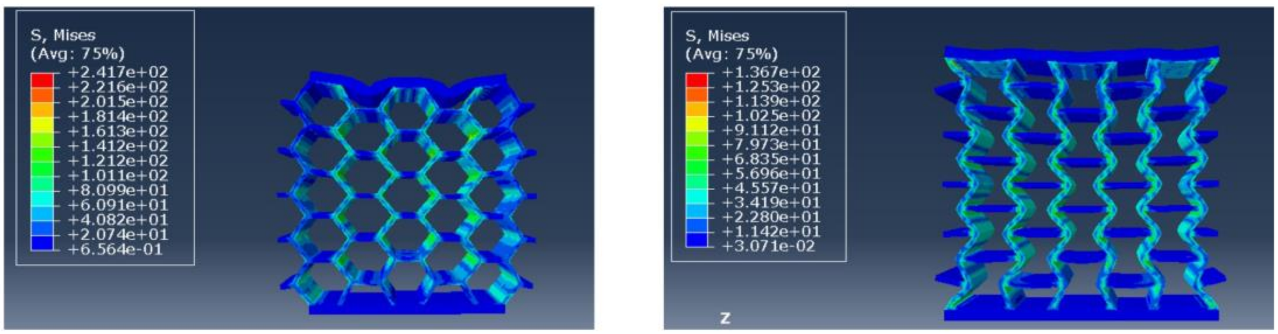
Unit cell	Axial deformation (mm)	Lateral deformation (mm)	Poisson's Ratio
Honeycomb	-0.205	0.192	0.868
Reentrant	-0.20	-0.13	-0.585

Negative Poisson's ratio for reentrant unit cell indicates that it should have less stress and deformation when subjected to compressive loading indicating a better indentation strength, better strength in joints. In the next section, the stress distribution and deformation will be seen in both the structures.

6.2.1: Stress and deformation comparison

Initially, both the structures are sandwiched between two plates. One of the plates is fixed and the same force is applied to the other plate. Stress distribution and deformation for both the structures is compared.

<u>Comparison of stress distribution</u>

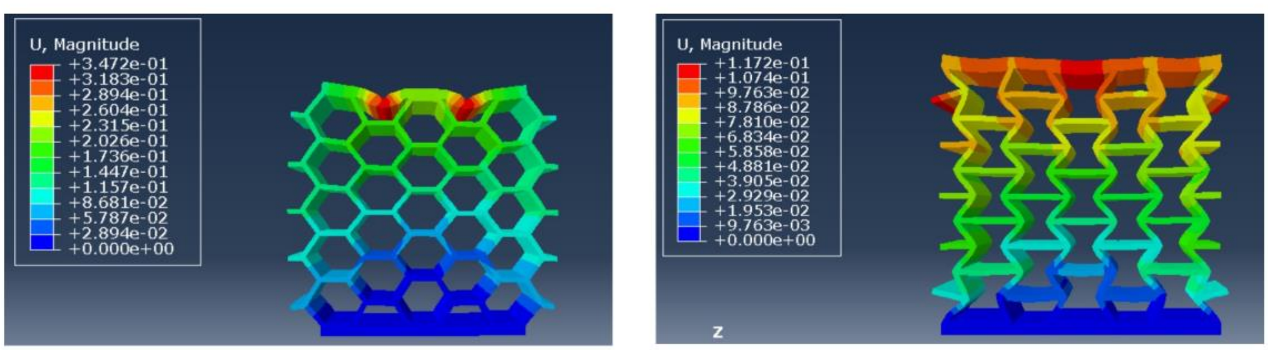


Honeycomb Reentrant

Figure 6.5: Stress distribution

Unit cell	Maximum Stress (MPa)	Stress in links (MPa)
Honeycomb	241.7	121.2
Reentrant	136.7	68.4

<u>Comparison of deformation</u>



Honeycomb Reentrant

Figure 6.6: Deformation comparison

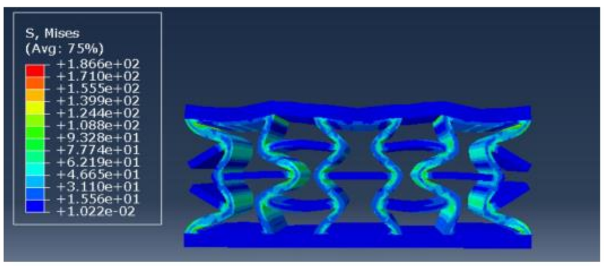
Following table summarizes the results.

Unit cell	Deformation (mm)
Honeycomb	0.3472
Reentrant	0.1172

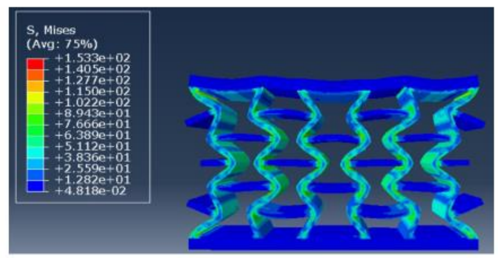
6.2.3: Optimal thickness of reentrant cell

As the reentrant unit cell shows better performance in stress distribution and deformation upon application of compressive load, the optimal thickness (in terms of number of layers) of reentrant cell will be analyzed.

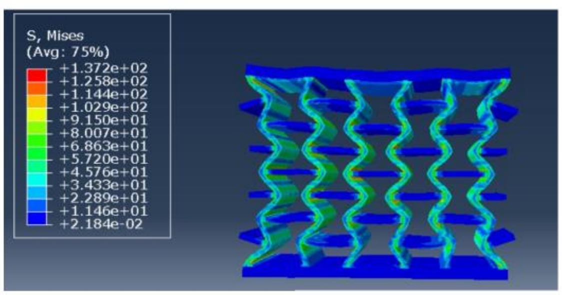
The following images shows the stress distribution as the number of layers is increased.



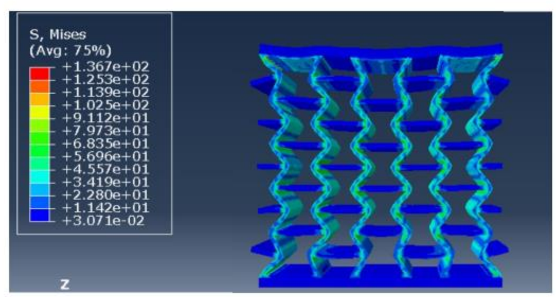
2 layers



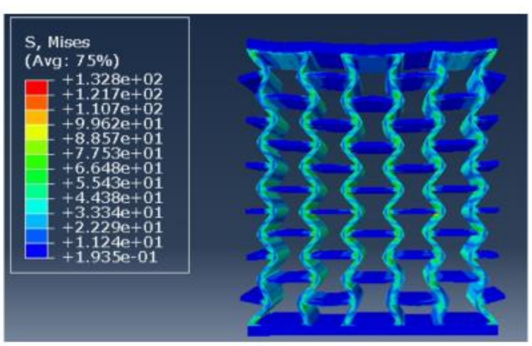
3 layers



4 layers



5 layers



6 layers

Figure 6.7: Stress distribution compared for number of layers

Following table summarizes the results of stress distribution.

Number of layers	Maximum Stress (MPa)	Stress in links (MPa)
2	186.6	93.2
3	153.3	76.6
4	137.2	68.6
5	136.7	68.3
6	132.8	66.4

Maximum stress decreases as the number of layers are increased. However, the difference gets smaller with each progressing layer. Around the thickness of 5 layers, the optimality is achieved.

The following plot shows the variation with number of layers.

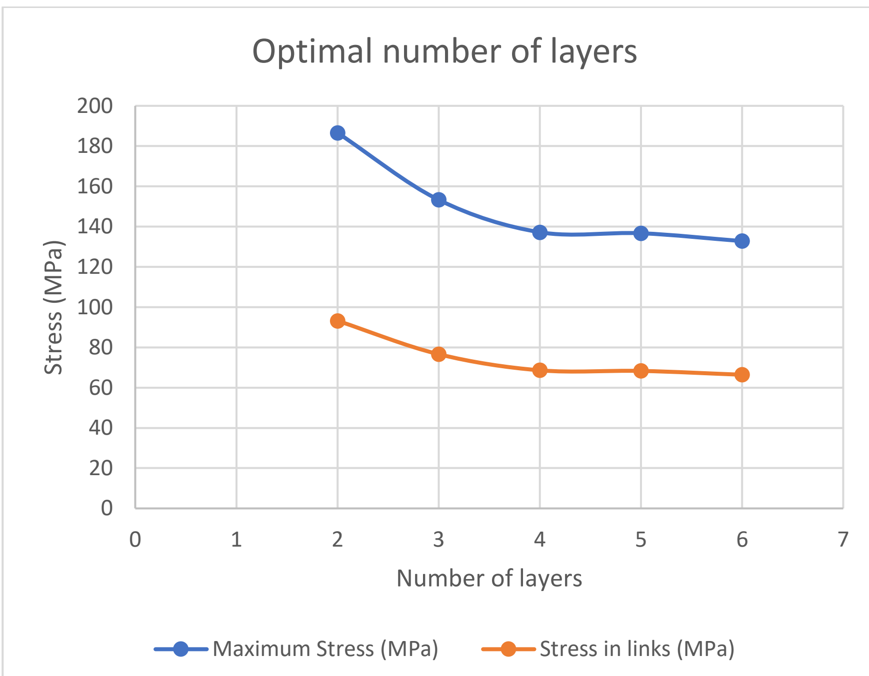


Figure 6.8: Plot showing the convergence of in stress generated

7. Conclusion

In this work, the honeycomb and reentrant unit cells are compared. For both the unit cell, Poisson's ratio is calculated and it was found that reentrant unit cells have a negative Poisson's ratio while honeycomb unit cells have a positive Poisson's ratio. This is validated by existing literature. Following this, stress distribution and deformation is also compared for both the unit cells. It is found that reentrant unit cell has approximately **40% lesser** maximum stress as compared to honeycomb structure while approximately **44% lesser** stress in links. Reentrant unit cell has shown approximately **66% lesser** deformation when subjected to same compressive stress. These results make reentrant structure a better candidate for applications requiring better indentation strength. As the reentrant unit cell showed better performance, it is tested for optimal thickness in terms of number of layers. As the number of layers increases in reentrant unit cell, the stresses generated starts to decrease. However, the amount of decrease gets smaller with each addition of layer and the optimality is achieved at around **5 layers**. Overall, it is concluded that reentrant unit cell is a better candidate when compared to honeycomb unit cell.

8. Future Scope

This section aims to mention the future roadmap of the project. Till now, a thorough study of literature on auxetic structures is done and an idea about the potential of auxetic structures is gotten. As of now, the reentrant unit cell is compared to honeycomb unit cell. The upcoming task would be to optimize other parameters like angle, length, and width of unit cell in case of reentrant unit cell. Other unit cells will also be compared and a best choice with optimal parameters will be chosen. After that, the plates will be manufactured by 3D printed techniques and it will require a study of parameters affecting the manufacturing approach. The task will be to minimize the defects in 3D printing of plates. Finally, several mechanical tests would be conducted on plates and the plates will be incorporated in helmets.

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