Modelling and Simulation Analysis on Compression Behaviour of PLA 2D Lattices Fabricated by Fused Deposition Modelling

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Abstract:

In this project work, The advent of additive manufacturing processes and lattice structures has been of increasing interest to engineering applications involving light-weighting and energy absorption applications. Mechanical response of three dimensional printed PLA 2D - lattice structures under compression is going to be investigate through experimental and numerical simulation analysis. Six different 2D lattice structures namely, square grid, honeycomb, and Isogrid along with their rotated counterparts were fabricated using (PLA) Poly-lactic acid and experimentally evaluated under uni -axial compression test. Simulations studies on PLA 2D-lattices under large compressive strains are rarely performed. Finite element models are accounting for structure orientation induced an anisotropic mechanical properties and geometrical imperfections are going to be developed to predict the stress–strain characteristics. The stress–strain curves are going to be generated to predict from the numerical simulations. The simulated results are going to be compared with experimental results that have good agreement with the experimental results for various lattice geometries. The outcome of project reveals that, the energy absorption characteristics of designed lattices which exhibit superior energy absorption capability for packing applications.

Keywords: Polylactic acid, Additive manufacturing, Numerical simulation, Compression Test, Energy Absorption.

1.Introduction

Additive manufacturing (AM), also known as 3D printing, is a revolutionary technology that builds objects layer by layer from digital models. Unlike traditional subtractive manufacturing, which removes material to create a part, AM adds material, offers several advantages. Material extrusion AM processes such as fused deposition modelling (FDM), are one of the most widely used AM. FDM typically uses polymer filaments, melted and extruded through a heated nozzle, building the object layer by layer. Its simplicity and relative ease of use make it ideal for prototyping, and small-scale production.

Lattice structures, are highly valued in energy and impact absorption applications due to their numerous advantages. These include their ability to be lightweight, their increased toughness, and their customizable mechanical responses. These structures can be designed by taking inspiration from natural forms or can be engineered to achieve material-independent responses, a concept known as metamaterials.

In this paper, compression characteristics of three different lattices, namely, square gird, honeycomb, and isogrid in two different configurations were investigated. Honeycomb structures excel in energy absorption by efficiently converting mechanical energy into deformation energy through their unique cell geometry. When subjected to compressive forces, the hexagonal or cellular structure of honeycombs allows for controlled buckling and crushing of individual cells, enabling the material to undergo large deformations while maintaining relatively constant stress levels. This mechanism enables honeycomb structures to absorb and dissipate significant amounts of energy without generating excessively high stresses, making them highly effective in cushioning impacts and reducing the risk of structural failure. Isogrid structures are of interest due to their lightweight and superior stiffness responses while square grid is simple, easily manufacturable structure with 90◦ symmetry that is useful in many engineering applications.

2. Literature Review

2.1 MJ Bots

This paper talks about the Cellular solids are characteristically excellent energy absorbers due to their capacity to store large amounts of energy through compression. Quasi-static simple compression results are compared to analytical micro-mechanical models, finite element method simulations and digital image correlation. Dynamic impact data is assessed using high-speed camera images and evaluated with an analytical momentum analysis. Data analysis is discussed and it is concluded that the density grading strategy beneficially influences the energy absorption. This is attributed to a combination of local plasticity manipulation and higher densification strains in static regime. In dynamic tests, the collapse initiation trigger led to controlled, more gradual collapse with lower corresponding loads.

2.2 Vinoj Meshach Aaron Jeyasingh

This paper focuses on Honeycomb materials possess high energy absorption characteristics and are useful for the impact protection of structural members. Various honeycomb configurations are being developed for a variety of applications. Analytical models are now available to determine the energy absorption characteristics of the regular hexagonal type of honeycomb. However, the development a parameterized analytical model that can determine the energy absorption characteristics of various honeycomb shapes is needed. In this research, a parameterized analytical model is developed for the typical honeycomb shape, and is validated using experimental and finite element analysis.

3.Methodology

3.1 CATIA software is used to design the lattice structures . In this study, three different 2D lattice structures extruded in 3D were investigated, namely, square grid, honeycomb grid, and an iso grid; each oriented in two directions as shown in Figure 1

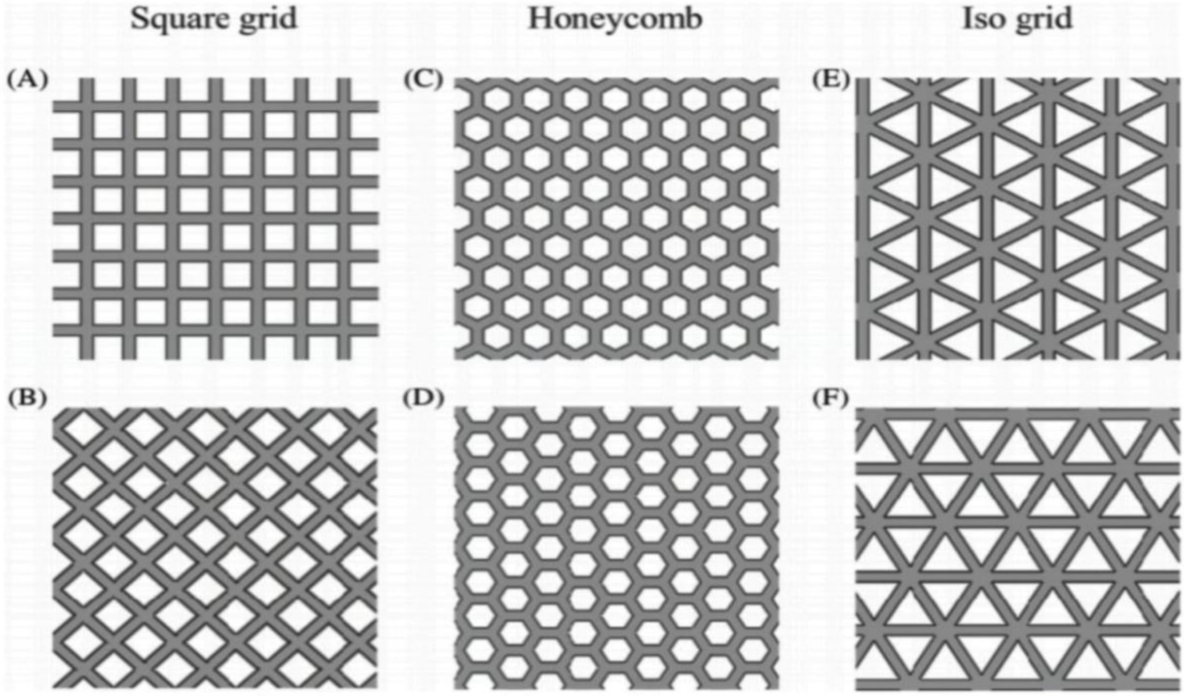


FIGURE -1

A: Grid A has lines running vertically and horizontally, creating a square grid pattern.

B: Grid B has lines running at 45° and -45° angles, creating a diagonal grid pattern.

C: Grid C has hexagons with two sides oriented vertically, creating a honeycomb grid with a vertical bias.

D: Grid D has hexagons with two sides oriented horizontally, creating a honeycomb grid with a horizontal bias.

E: Grid E has lines with one vertical orientation among the three, creating an iso grid with a vertical bias.

F: Grid F has lines with one horizontal orientation among the three, creating an iso grid with a horizontal bias.

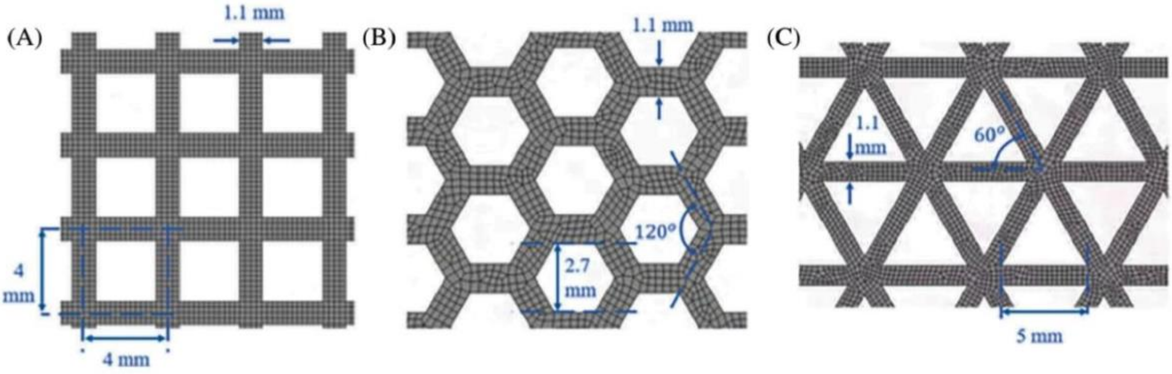


Figure 2 : Geometric features of square grid, honey comb, isogrid

3.2 Finite element analysis

The lattice structures in Figure 1 were analyzed using FE simulations . The simulations considered factors like stress, strain, and failure characteristics using a software called Ansys. The lattice geometries were divided into smaller elements to ensure accurate results. The simulations also accounted for plastic strains and the incompressible nature of the lattice structures. The mesh used in the simulations consisted of around 30,000 to 35,000 elements to capture the behaviour of the lattice structures. The dimensions of the lattices were chosen to maintain a constant relative density of approximately 50%. The material model used in the simulations included properties like linear orthotropic elasticity, Hill plasticity, and fracture to account for different failure mechanisms. The orthotropic elasticity considered the anisotropy in effective properties due to the fiber orientation induced during the additive manufacturing process. The fiber orientation directions were assigned to each element in the simulation based on these paths. The material properties used in the simulation were calibrated using previous experimental results. These properties represent the combined behaviour of the matrix, pores, and voids in the additive manufacturing process. The anisotropic yield ratios were determined using tensile experimental data. The lattice structures in this study experience failure due to bending, buckling, and fracture of the struts, depending on their geometry. Tensile stresses and anisotropic yield ratios are important factors in determining the mechanical response of the lattices and simulation accurately represents the behaviour of the lattice structures. By including these small geometric imperfections in the model, we can better capture the buckling phenomenon that occurs in the struts under compression. This helps us understand how the lattice structures will behave in real-world scenarios and allows us to optimize their design for improved performance and reliability.

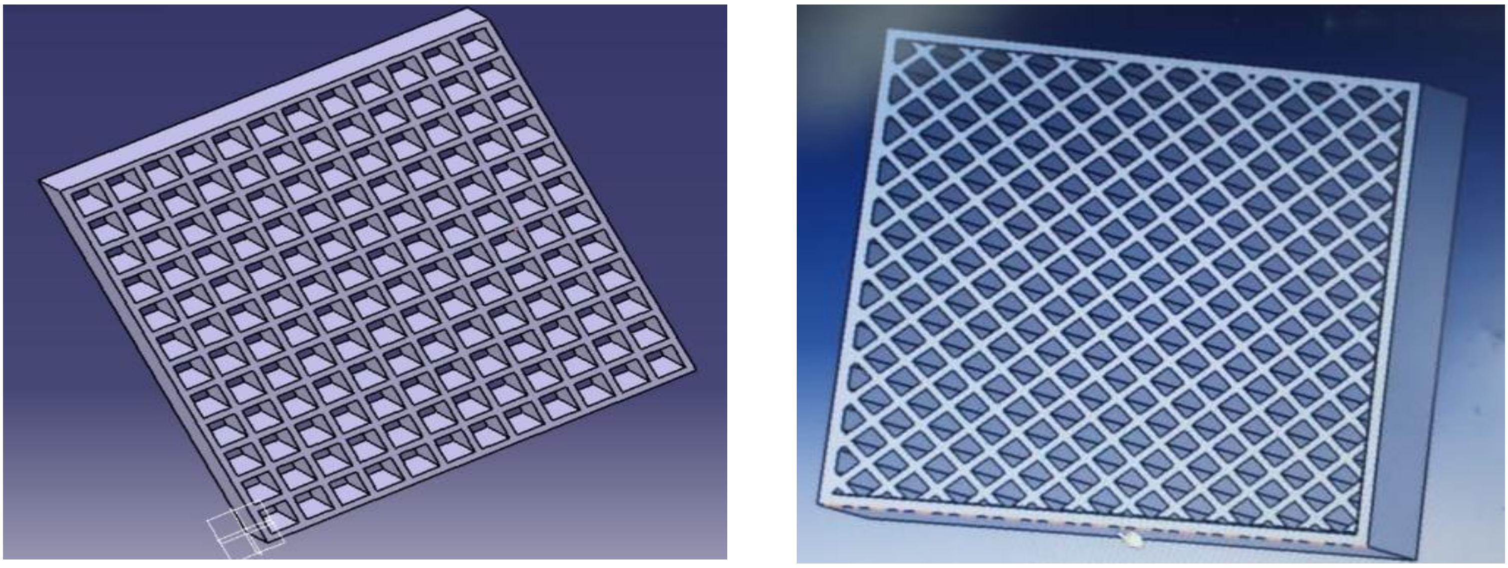


Figure 3: CATIA models of square grids of different angles

3.3 Compression Testing

These components are placed between two plates and compressed vertically at a slow and controlled speed. This helps to test how the material responds to pressure. The tests were done with a strain rate that is commonly used for this type of test. The goal was to push the material to 30% deformation to see how it behaves under stress. Going beyond 30% would require more time and complex calculations due to the material's behaviour at higher deformations.

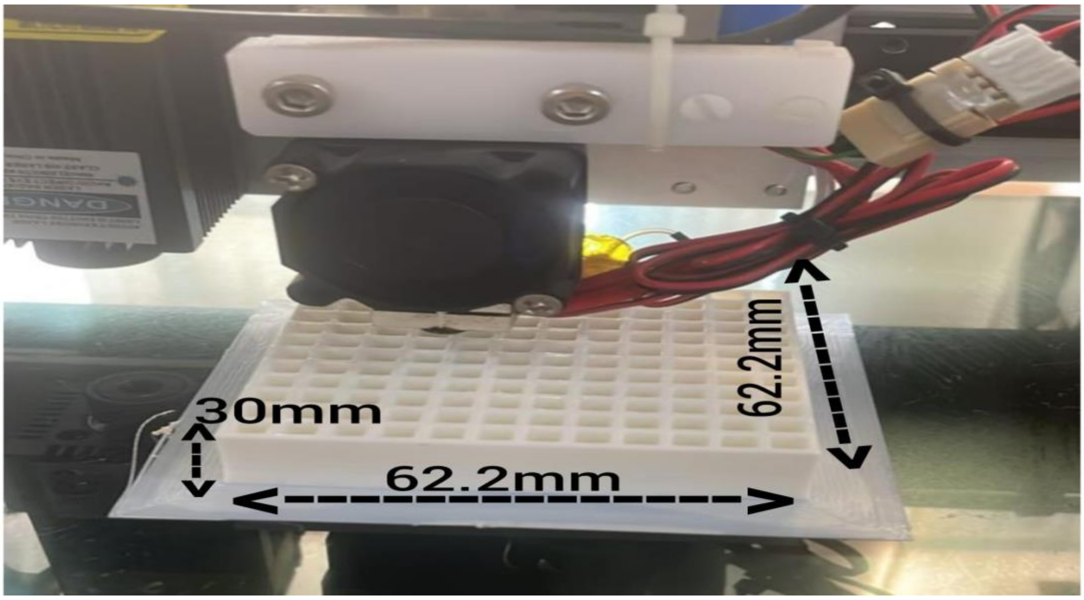


Figure 4 : 3D printed lattice sample structure and its dimensions

4. Results and discussions

Polylactic acid filament was used to make the lattice structures .provisions of the used filament material were shown in Table 1

Table 1

Filament Diameter	1.75mm
Print Temperature	170°C
Bed Temperature	50°C
Print Speed	50-100mm/s
Nozzle Temperature	200°C
Nozzle size	0.4mm

Figure 5: Grey PLA filament

With the help of the PLA filament square grid, honey comb, Iso grid components are fabricated by fused deposition modelling

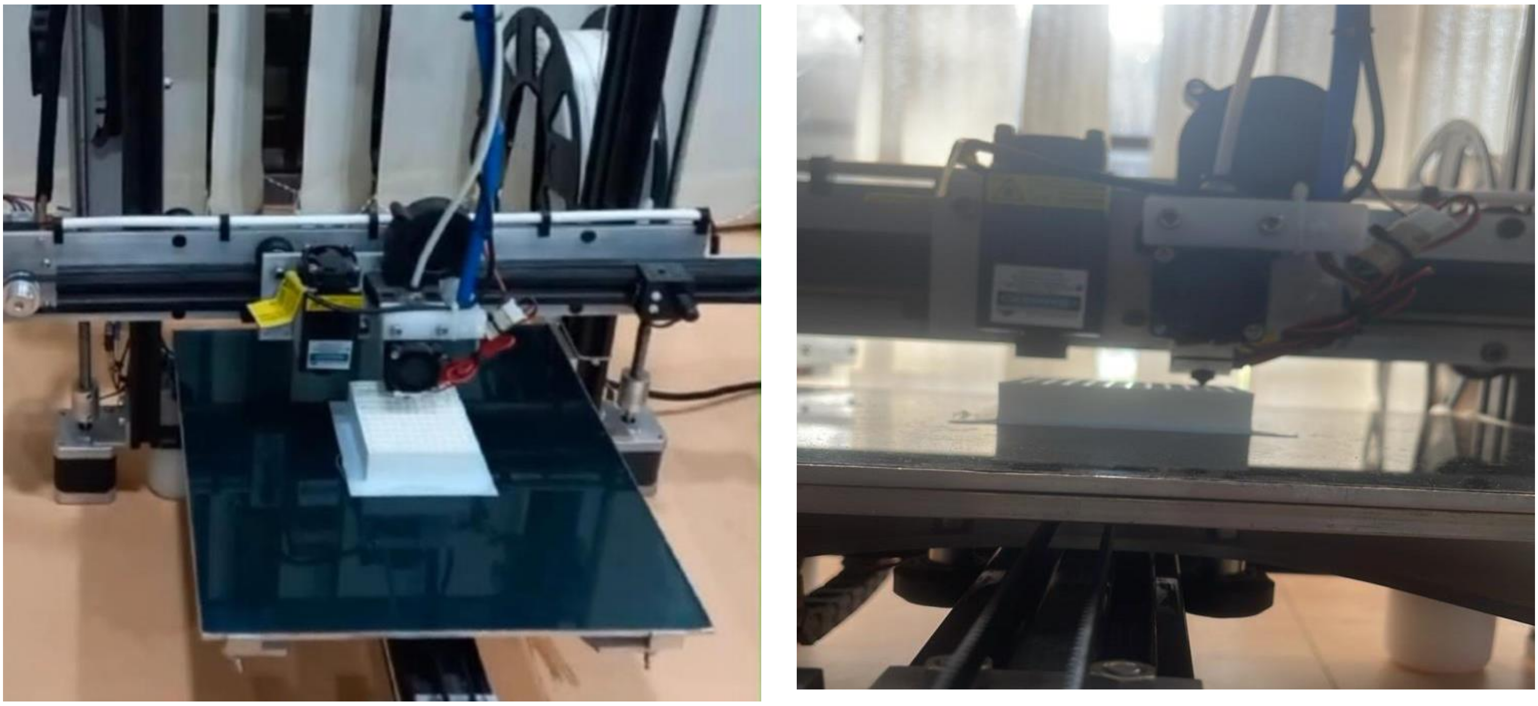


Figure 6: working of 3D Printer

To predict the buckling behaviour of lattice structures under compression, it is essential to consider the impact of geometric imperfections introduced during manufacturing. These imperfections can lead to strut buckling, significantly affecting the structural integrity. To address this, a frequency or modal analysis was conducted on various lattice structures to identify the critical structural modes that could trigger buckling. The stress-strain profile of the 45°/−45° square grid exhibited an oscillating pattern, the overall stress level was lower than that of the 0/90 square grid. During the compression test, after the first collapse of a diagonal row, subsequent collapses of adjacent diagonal rows occurred in the same direction. This row-by-row collapse resulted in the oscillatory stress strain behaviour .

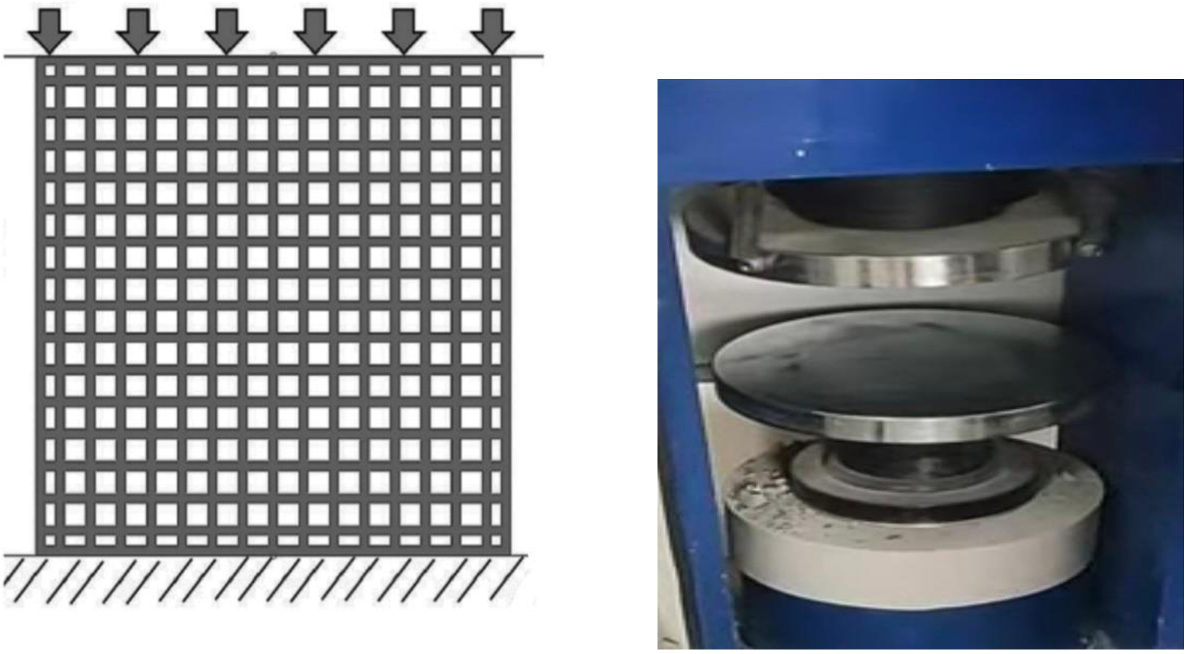


Fig : unidirectional compression on lattice structure

In the case of the honeycomb grid configurations studied, the presence of geometric imperfections played a significant role in determining the initiation of collapse and the subsequent failure patterns. The vertical honeycomb grid exhibited a high initial peak in the stress-strain curve, followed by cascading failures along the 45° direction. This pattern of collapse along the diagonal was similar to the failure observed in the 45/−45 square grid samples, indicating a certain level of consistency in the failure modes across different configurations. The horizontal honeycomb grid showed a different failure pattern, with the first collapse occurring in the −30° direction. Subsequent failures occurred along different directions, leading to a more stable stress-strain response compared to the vertical honeycomb grid. This variation in failure patterns between the two loading directions highlights how geometric imperfections can influence the behavior of honeycomb structures under compression.

The vertical isogrid lattice, it showed a similar profile to the vertical honeycomb grid. For the horizontal isogrid lattice, the initial failure occurred along a -60° direction, which is different from compressive loading or buckling. Instead, the initial fracture happened due to tensile loading along the horizontal struts, resulting in a very high initial stress peak. Both the vertical and horizontal isogrid lattices exhibited localized buckling sites as well as row-by-row buckling.

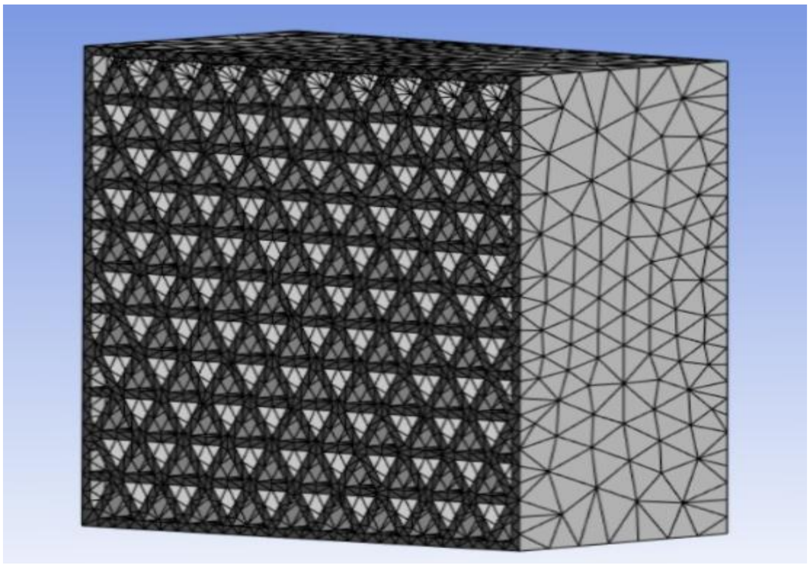
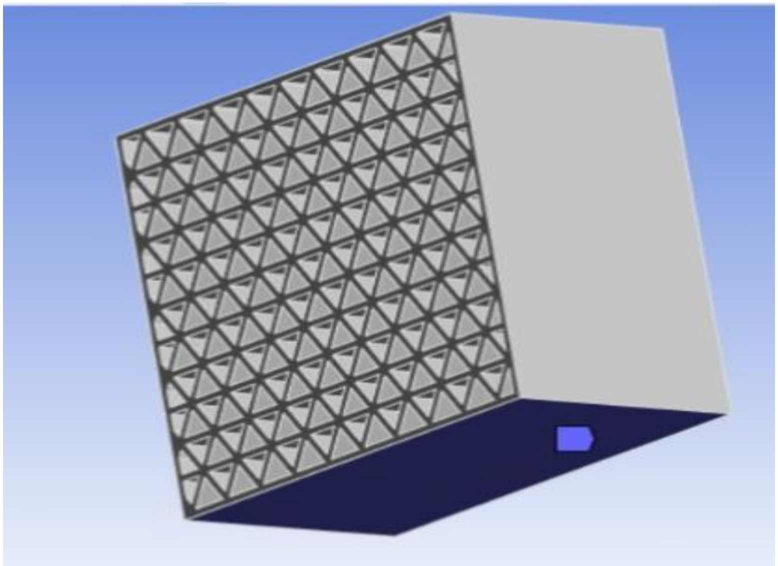


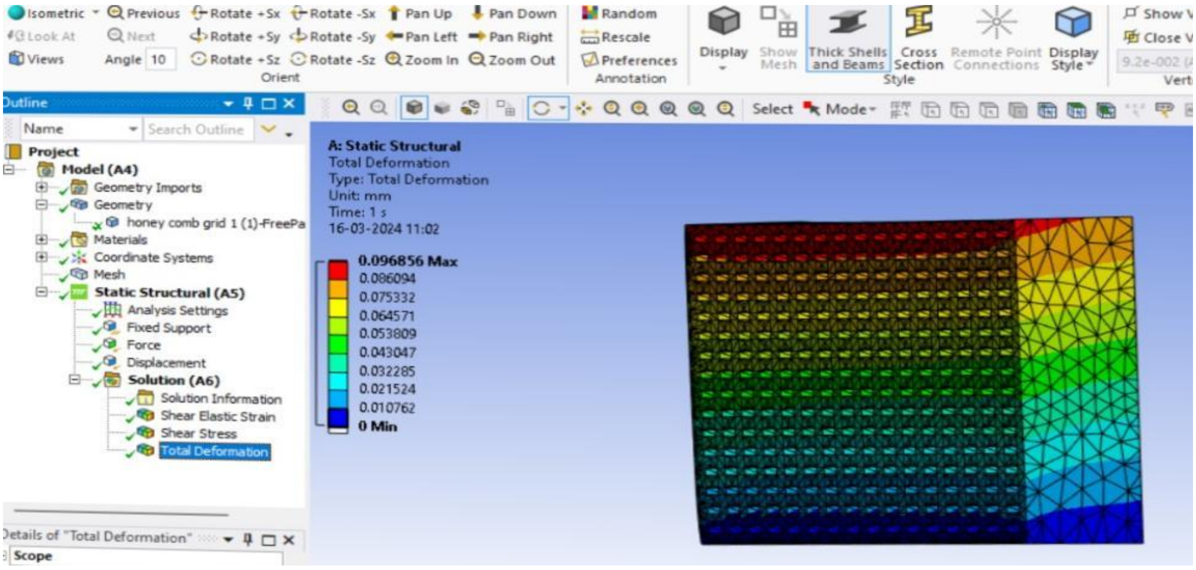
Fig : meshing

Fixed Support

Force (N)



The simulated failure initiation locations in each of the tested configurations for the square grid, honeycomb, and isogrid patterns, respectively. Failure in lattice structures can also be attributed to the development of localized stress concentrations at points where the thin walls intersect, leading to the initiation and propagation of cracks. As the structure is subjected to mechanical loads, these stress concentrations can cause the thin walls to undergo bending and deformation, creating conditions that are conducive to crack formation. Over time, these cracks can propagate across the structure, weakening and ultimately breaking individual thin walls. This process of crack initiation and propagation can ultimately lead to the failure of the lattice structure due to the loss of structural integrity and load-bearing capacity.



A: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1 s
16-03-2024 11:02

0.096856 Max
0.086094
0.075332
0.064571
0.053809
0.043047
0.032285
0.021524
0.010762
0 Min

Fig : Total deformation of square grid

i. $$\text{Ultimate Compressive Stress} = \frac{\text{Ultimate Compressive load (N)}}{\text{Cross sectional Area (mm}^2\text{)}}$$

ii. $$\text{Working Stress} = \frac{\text{Ultimate Compressive Stress}}{\text{Factor of safety}}$$

Where,

Fos -factor of safety for PLA is 3

By calculating the ultimate Compressive Stress for square grid ,rotated square grid, horizontal honeycomb, vertical honeycomb, horizontal isogrid and vertical isogrid we observed that vertical honeycomb have the highest value when compared to other lattice structures.

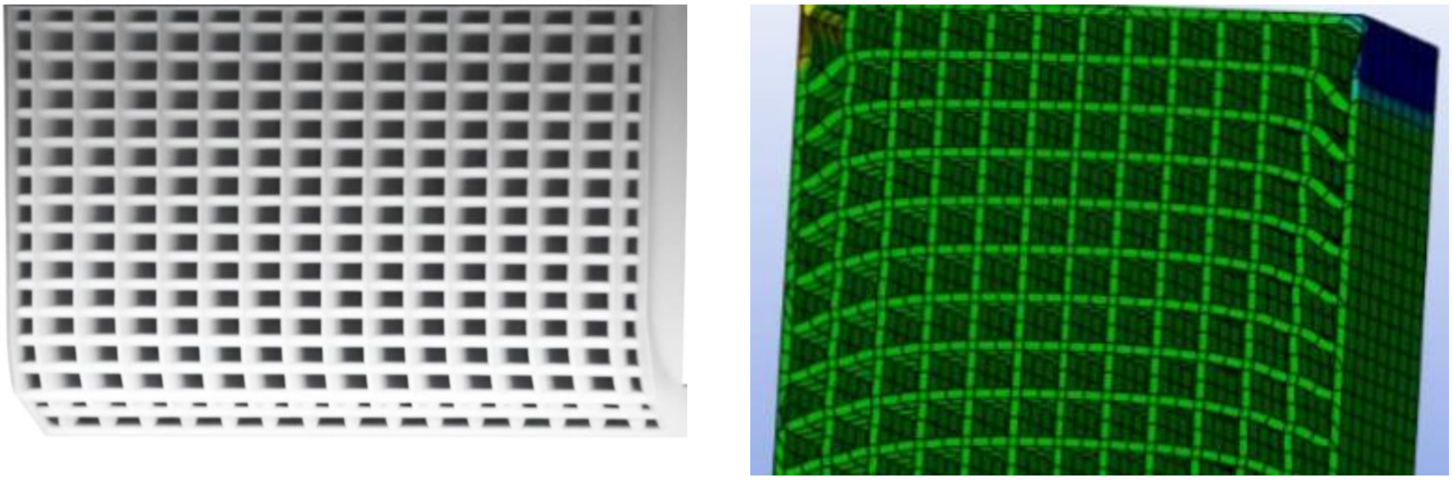
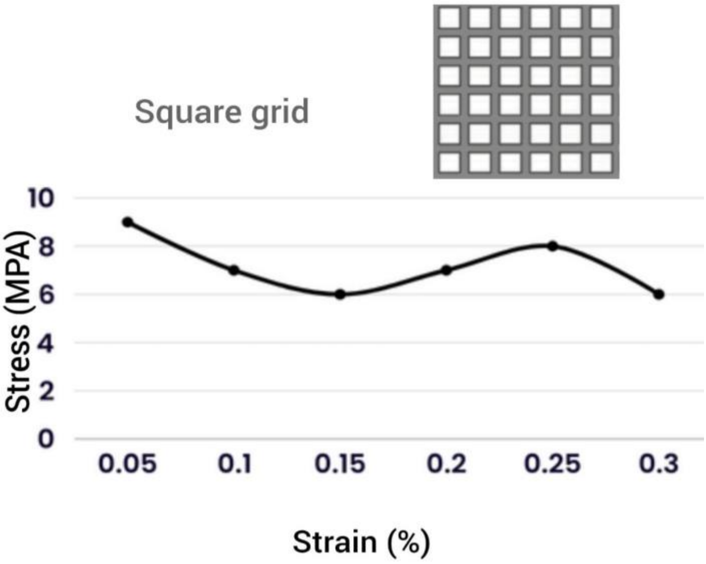
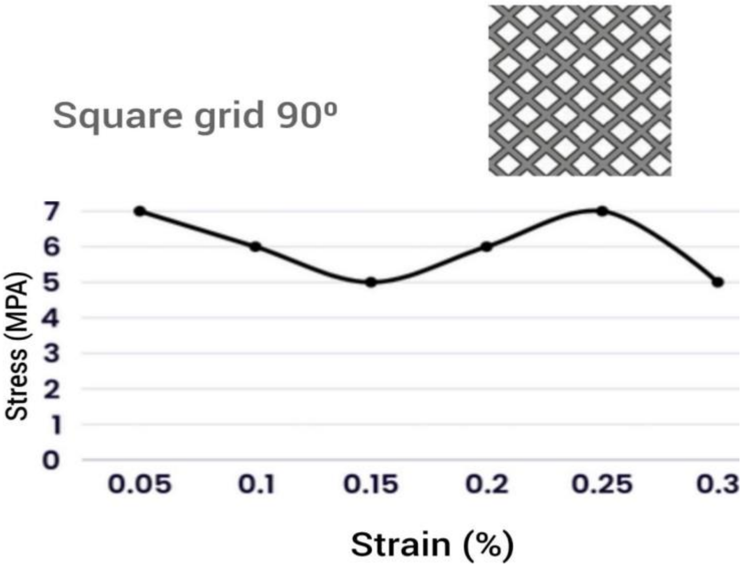


Fig: Both Experimental and Simulation analysis on Square grid Structure

Square grid :

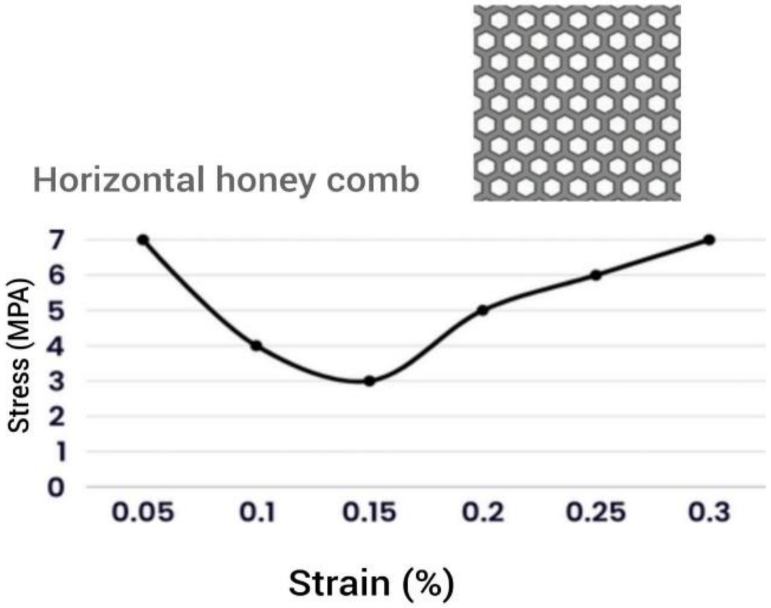
In the case of the square grid, failure occurs when a horizontal row collapses and the buckled struts detach from adjacent cells, although it happens at a slightly different height compared to the experiments. On the other hand, the rotated square grid configuration exhibits buckling along the diagonal, which aligns with the behaviour observed in experiments.

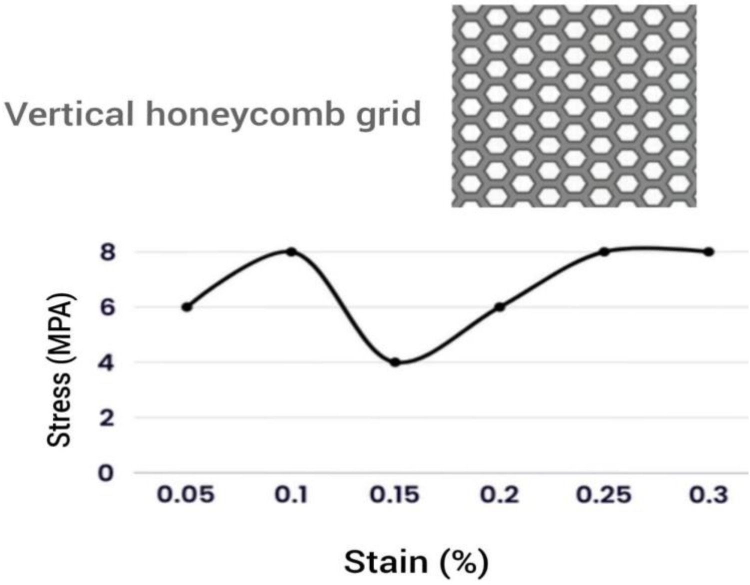




Honeycomb:

Moving on to the honeycomb configurations , the vertical honeycomb display a failure path along a line of approximately -45°. This is followed by the breakage of buckled struts due to high tensile stresses at the junction of adjacent honeycomb cells. Similarly, the horizontal honeycomb configuration shows a failure path under the same angle as observed in the experimental sample. Some are predicted from the simulation analysis.

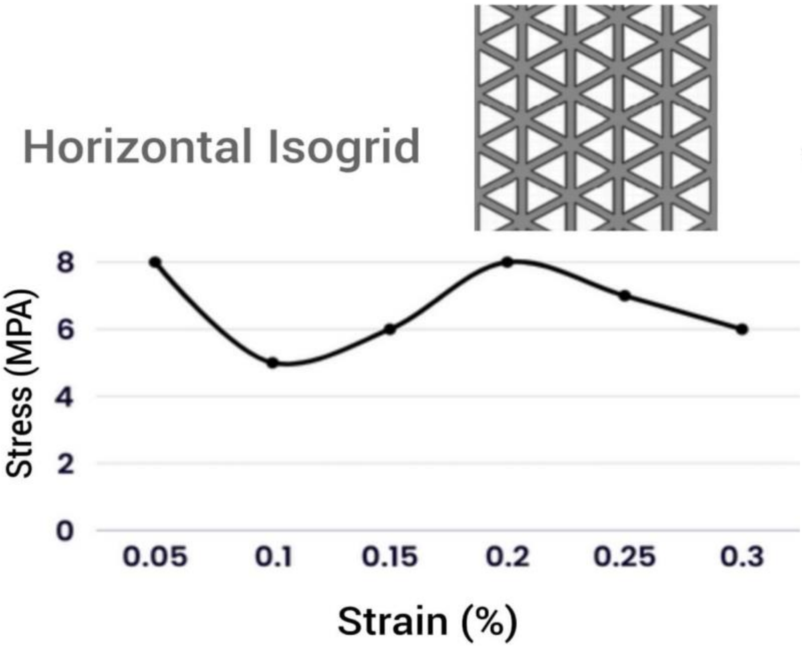


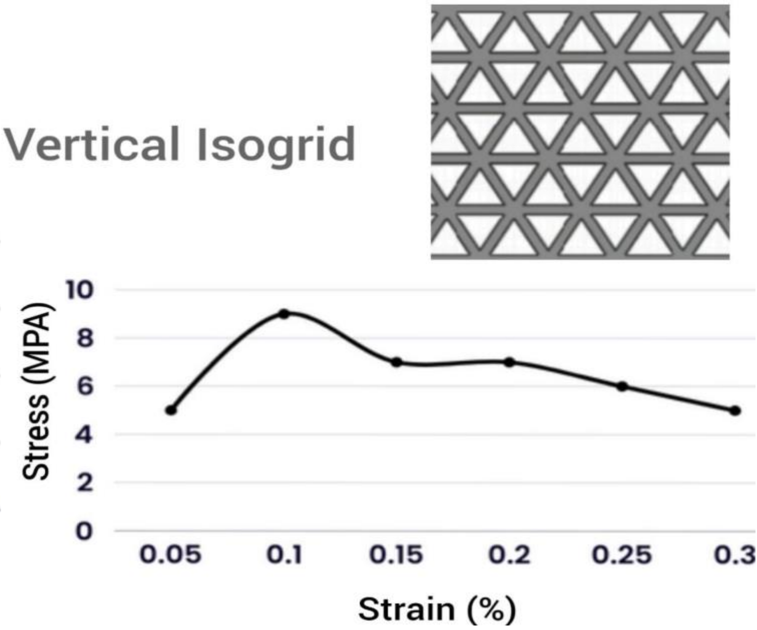


Honeycomb structures, in particular, are known for their superior energy absorption capabilities, largely due to the nature of their "plateau stress" . This means that even as the material undergoes large strains, the stresses within the structure remain constant. While regular honeycomb structures have been extensively studied using numerical and analytical approaches, they do have limitations in terms of customizability, design flexibility, cell size, and resolution.

Isogrid :

The vertical isogrid component follows the same fracture pattern as the experimental counterpart of isogrid component. However, in the case of the horizontal isogrid, the collapse occurs at a different angle, and the failure mechanism exhibits more excessive bending in the simulation compared to the experiments. Specifically, for the horizontal isogrid, simulation results showed the horizontal struts breaking (detaching) due to tension.





Strain energy for six different lattice structures were obtained from the simulation analysis, where we can easily found that horizontal honey comb and vertical isogrid structures has the highest strain energy.

Lattice Configuration	**strain energy density (MJ/m³)**	**Energy Absorption efficiency for 30%strain**
Square grid	1.98	20%
Square grid rotated	1.06	21%
Vertical honeycomb	1.680	26%
Horizontal honey comb	2.32	27%
Vertical isogrid	2.201	20%
Horizontal isogrid	1.476	18%

To express the energy absorption efficiency of lattice structures is, by defining it as the ratio of the total absorbed strain energy to the maximum stress at a given strain level. This can be represented as the absorbed strain energy divided by the product of stress and strain, which provides a measure of how effectively the structure absorbs and dissipates energy under loading conditions. Mathematically, the energy absorption efficiency can be formulated as the absorbed strain energy divided by the product of stress and strain at a specific strain value.

$$E = \frac{\int \sigma(\epsilon) d\epsilon}{\sigma_{\max}(\epsilon)}$$

where E is efficiency, σ is stress, ϵ is strain, and $\sigma_{\max}$ is maximum stress until the strain reaches maximum value. As for physical intuition of the efficiency measure, one could consider the case when efficiency is equal to 100%, the material then behaves like rigid-perfectly plastic up to the point of 100% compressive strain where sudden densification happens.

Energy Absorption is calculated for all six lattice structures under 30% strain and then compared to each lattice structure. This comparison helps in understanding which lattice structure is more effective in energy absorbing.

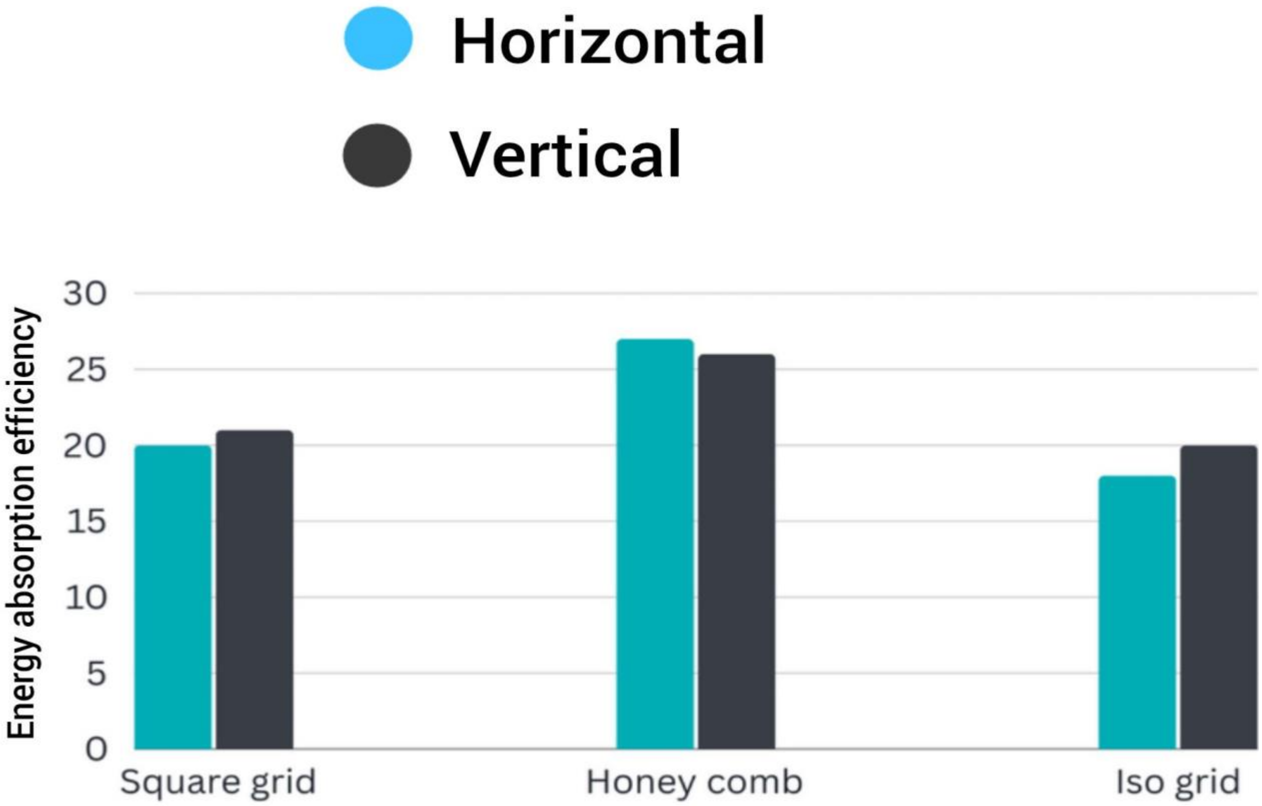


Fig : Energy Absorption efficiency of different lattice structures

We compare the energy absorption of different lattice structures and we observed that both the horizontal and vertical honey comb grid have superior energy absorption when compared to the square grid and Iso grid. Square grid showed a stable compressive behaviour, and Isogrid showed a peak stress at initial stage.

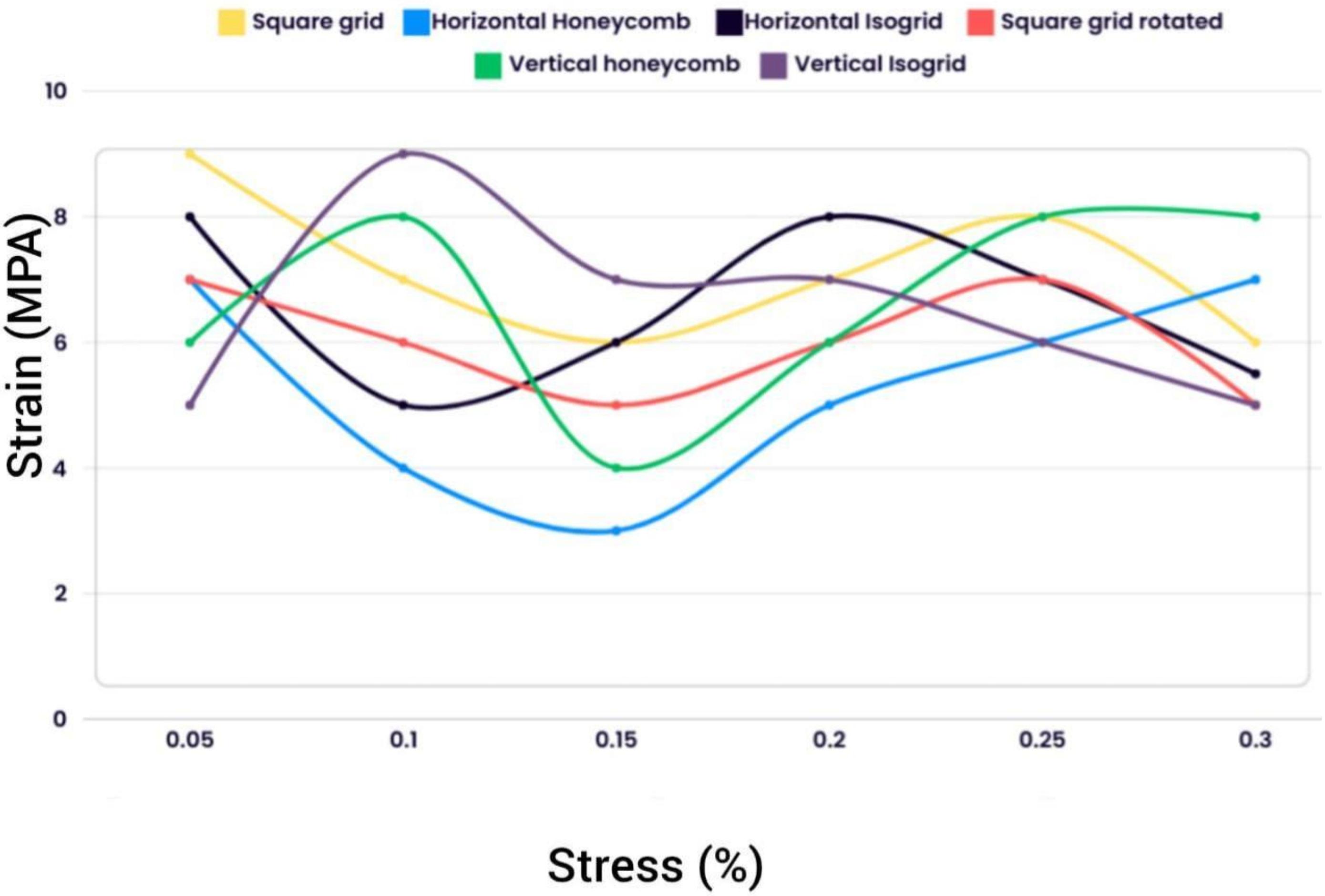


Fig : stress -strain profile for each lattice structures

Conclusion :

Square Grid: This pattern, resembling a stack of dominoes, exhibited a unique behaviour when subjected to pressure. As the rows buckled one after another, a wavy stress pattern emerged with a peak stress of 11 MPa. Despite its lightweight nature, it demonstrated remarkable strength, making it suitable for lightweight structures.

Isogrid: The Isogrid pattern, characterized by its angled design, initially displayed a peak stress of 10.5 MPa. However, its stress distribution became uneven upon failure, possibly due to its complex shape. Nevertheless, it retained significant strength even after reaching its limit.

Honeycomb: Researchers were pleasantly surprised by the performance of the Honeycomb pattern. Although it started off relatively weak, it maintained a steady plateau stress of 6.5 MPa for an extended period. Additionally, it exhibited the ability to absorb the most energy (2.3 MJ/m3) by deforming significantly without fracturing. This quality makes it an excellent choice for applications requiring impact absorption, such as padding**.**

Among the six lattice structures ,both vertical and horizontal honeycomb structure is consider as an excellent energy absorbing material because it can undergo a large compressive strain at nearly constant stress level and absorb a large amount of energy without creating high stresses.

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