DESIGN AND ANALYSIS OF LENGTHWISE GRADIENT HONEYCOMB CORE FOR OBTAINING GRADED BEAM PROPERTIES

A CAPSTONE PROJECT REPORT

Submitted in partial fulfillment of the requirement for the award of the Degree of

BACHELOR OF TECHNOLOGY
IN
MECHANICAL ENGINEERING

by

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DECEMBER 2020

CERTIFICATE

This is to certify that the Capstone Project work titled **DESIGN AND ANALYSIS OF LENGTHWISE GRADIENT HONEYCOMB CORE FOR OBTAINING GRADED BEAM PROPERTIES"** that is being submitted by **PERI SHANMUKHA RAM (17BME7047)** is in partial fulfilment of the requirements for the award of Bachelor of Technology, is a record of bonafide work done under my guidance. The contents of this Project work, in full or in parts, have neither been taken from any other source nor have been submitted to any other Institute or University for award of any degree or diploma and the same is certified.

Dr.P.S.Ramasreekanth
Guide

The thesis is satisfactory / unsatisfactory

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Approved by

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Besides my guide, I would like to thank the rest of my thesis committee: Prof. Manikanta Ravindra Kumar Vakkalagadda, Prof. Pankaj Tambe and, Prof.Amit kumar for their encouragement, insightful comments and hard questions.

ABSTRACT

In this paper different types of honeycomb structures are designed and are different properties are compared like total deformation of structure when fixed at one end and a point load is acted on free end. Also, a gradient Honeycomb structure is designed to check whether the gradient cell honeycomb structure (along length) offers more bending resistance or not. This Gradient honeycomb structure is compared within different cell-oriented structures and also compared with different regular honeycomb structure to prove that gradient honeycomb structure deforms less comparatively to regular honeycomb structure. Modal Analysis is also performed on both vertical and horizontal cell oriented gradient honeycomb structures to study the dynamic characteristics of a structure under vibrational excitation. Natural frequencies, mode shapes and mode vectors of a structure were found out using modal analysis. Gradient honeycomb structures are tested for impact loading on the free end of structure at three different speeds i.e., 40kmph, 20kmph and 10kmph to extract energy absorption graphs.

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CHAPTER 1
INTRODUCTION

Honeycomb Structures are natural or man-made structures that have the geometry of a honeycomb which allows the utilization of material to be minimum. There are different types of geometry for honeycomb structures but the common feature of all such structures is an array of hollow cells formed between thin vertical walls. The most common type is hexagonal cell shape honeycomb. However, to meet different engineering applications triangular cells, square cells, and circular-cored hexagonal cells, and circular-cored square cells are also used.

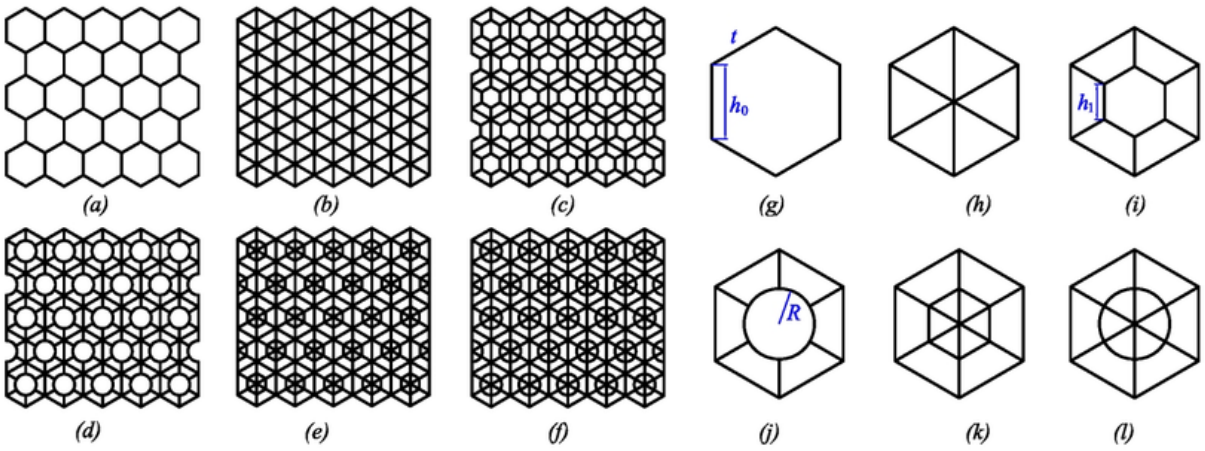

Figure 1 Honeycomb Structures with kinds of inside cells.

a. General Structure
b. Triangular
c. Double hexagonal
d. Inside circular
e. Full double hexagonal
f. Full insider circular

A honeycomb shaped structure provides a material with minimal density and relatively high out-of-plane compression properties and out-of-plane shear properties. Honeycomb structural material between two thin layers that provide strength in tension. This forms a plate-like assembly. Honeycomb materials are widely used where flat or slightly curved surfaces are in need and they have high specific strength. They are widely used in the aerospace industry for this reason,

and honeycomb materials in aluminum, fiberglass and advanced composite materials have been featured in aircraft and rockets since 1950's.

Man-made honeycomb structures include sandwich-structured composites with honeycomb cores. Man-made honeycomb structures are manufactured by using a variety of different materials, depending on the intended application and required characteristics, from paper or thermoplastics, used for low strength and stiffness for low load applications, to high strength and stiffness for high performance applications, from aluminum or fiber reinforced plastics. There are five basic ways of making honeycomb: adhesive bonding, resistance welding, brazing, diffusion bonding and thermal fusion. These methods are based on how the nodes are attached. By far the most common manufacturing method is adhesive bonding; perhaps as much as 95% of the honeycomb cores are made this way. Resistance welding, brazing or diffusion bonding are only used on cores that must see high temperatures or severe environmental conditions as it is much more expensive to manufacture core by these processes.

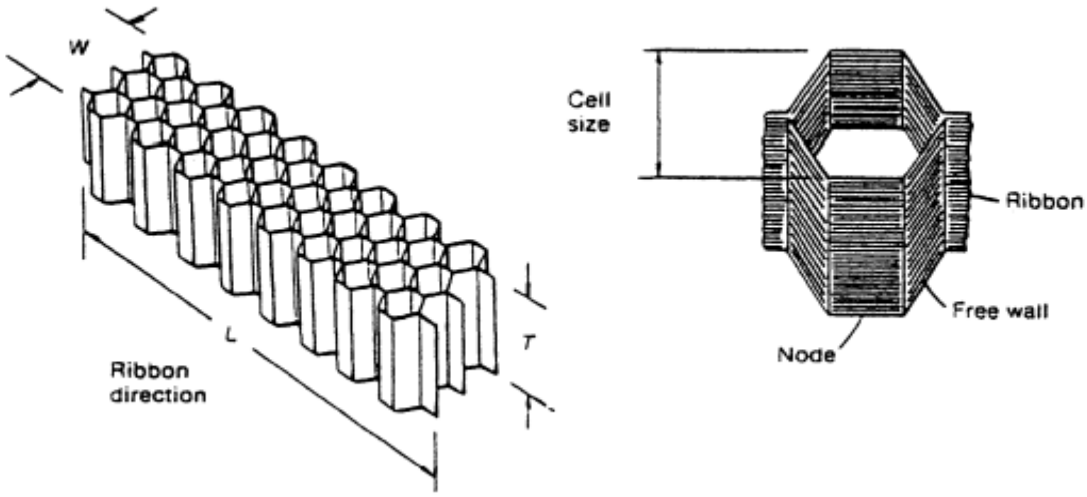

Figure 2 Honeycomb terminology

- Honeycomb density - the weight of one cubic foot of core, expressed in pounds per cubic foot (pcf) or the weight of one cubic meter of core, expressed in kilograms per cubic meter (kg/m3).
- Cell - a single honeycomb unit, usually a hexagon.
- Ribbon - the fiat sheet material constituting the honeycomb, also referred to as web.

- Node - the bonded portion of adjacent ribbon sheets, double sheets.
- Free wall - cell wall sections of single unbonded sheets.
- L direction - the core ribbon direction, the direction of continuous sheets.
- R direction - the core ribbon direction, same as the L direction.
- W direction - the direction in which the core is expanded or perpendicular to the ribbon direction.
- T direction - the core direction parallel with the cell openings.
- HOBE - Honeycomb Before Expansion, the solid block of bonded sheets.
- CUE - Core Unexpanded, the solid block of bonded sheets.

Project Terminology:

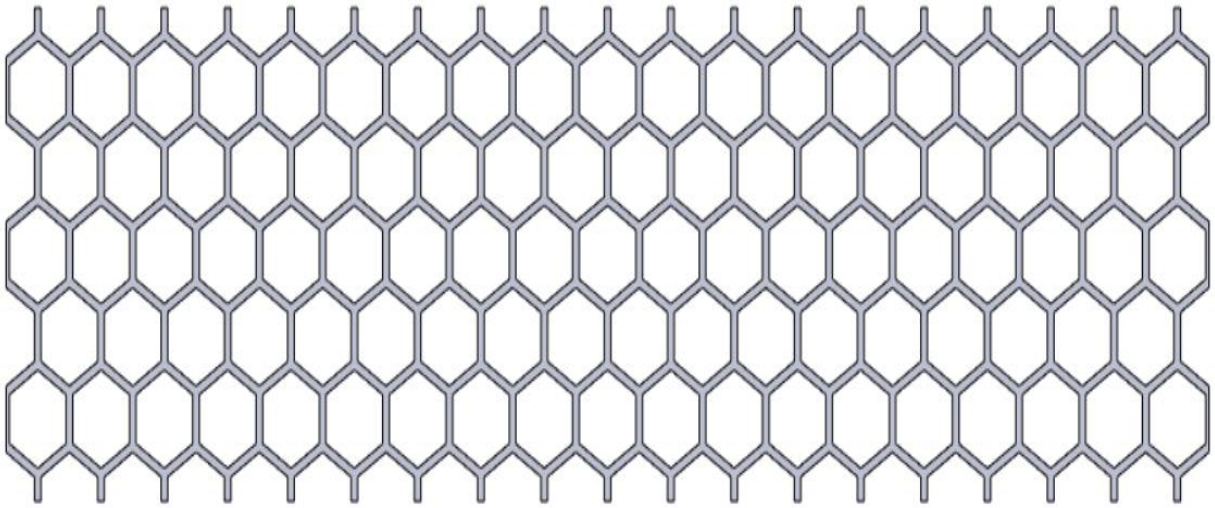

Figure 3 Honeycomb Structure (Vertical cell-orientation)

- Vertical cell-oriented Honeycomb Structure

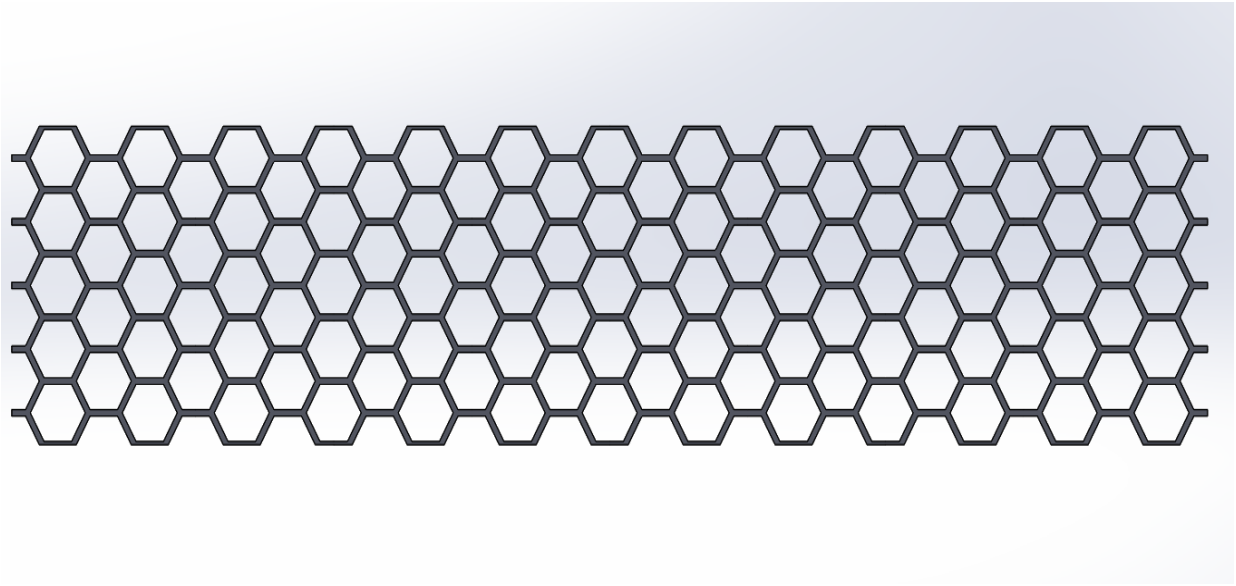

Figure 4 Honeycomb Structure (Horizontal cell-orientation)

- Horizontal cell-oriented Honeycomb Structure
- The basic honeycomb element consists of one ode and two free walls. The various parameters that are derived from geometry of honeycomb given in the following table and are derived as follows:

- Honeycomb density (HD) = $\dfrac{2(q + p)\, t\rho_s}{(q + p\cos\theta)\,(2p\sin\theta)}$

- Cells per honeycomb surface area (C/HSA) = $\dfrac{1}{(q + p\cos\theta)\,(2p\sin\theta)}$

- Exposed foil area per honeycomb volume ($EF\ A/HV$) = $\dfrac{2(q + 2p)}{(q + p\cos\theta)\,(2p\sin\theta)}$

- Foil edge area per honeycomb surface area ($F\ EA/HSA$) = $\dfrac{2(q + p)\, t}{(q + p\cos\theta)\,(2p\sin\theta)}$

- where, p=free wall length, q=node width, θ =expansion angle, t= web thickness, ρs = web density.

- Web density of PCTPE nylon filament is 0.0011gm/mm3 or 1.1kg/m3.

- As cell's longest diagonal length decreases along rows i.e., each column will have same cell size, the properties such as Honeycomb density, Cells per honeycomb surface area, foil edge area per honeycomb surface area, exposed foil area per honeycomb volume decrease.

Cell longest diagonal (mm)	Free wall length (a)mm	Node width (b)mm	Expansion angle (degrees)	Web thickness (t)mm	Web density Gm/mm3	Honeycomb density (HD)kg/m3	C/HAS Cells per honeycomb surface area Cells/mm2	FEA/HSA Foil edge area per honeycomb surface area Mm2/mm2	EFA/HV Exposed foil area per honeycomb volume Mm2/mm3
12	6	6	60	1.2	0.0011	0.3388	0.0106837	0.25667	2.6
15	7.5	7.5	60	1.2	0.0011	0.27104	0.006833376	0.2533	2.08
21	10.5	10.5	60	1.2	0.0011	0.1936	0.00348857	0.146667	1.47571

Table 1 Honeycomb properties

1.3 Organization of the Report

The remaining chapters of the project report are described as follows:

- Chapter 2 contains the background and literature survey and objectives of project
- Chapter 3. proposed system, and hardware and software details, Design of regular Honeycomb structure, boundary conditions, methodology, deformation of regular honeycomb structures, deformation of different cells in regular honeycomb structure.
- Chapter 4 gives designs, boundary conditions, methodology, and design of gradient honeycomb structure, deformation, modal analysis, and impact analysis.
- Chapter 5 discusses the results and inferences obtained after the project was implemented.

- Chapter 6 concludes the project and discusses about future work.
- Chapter 7 gives references.

Chapter 2
Background and Literature Survey

The book titled "Tom Bitzer auth. Honeycomb Technology Materials, Design, Manufacturing, Applications and Testing." Through this book, we get fundamentals of honeycomb structure, terminology, different web materials, honeycomb types, cell configurations, materials used, manufacturing processes, applications, evolution of applications of honeycomb structures in different fields of study. Particularly I had referred the manufacturing methods of honeycomb structures section. There are five processes, namely, Adhesive bonding, resistance welding, brazing, diffusion bonding and thermal fusion. Depending on web material, manufacturing process is selected. For instance, brazing and resistance welding is only used on cores that see high temperatures or severe environmental conditions. This book also insights about all strength and compares honeycomb structures with different plane panels to prove its maximum strength.

The first paper I referred was "Design and Analysis of Honey Comb Structures with Different Cases." Authored by Shaik.Nazeer and Shaik Allabakshu from department of aerospace engineering, Nirma Institute of Science and Technology. It discussed a case, in which a honeycomb structure was designed of length 0.085m, width of 0.115m and thickness of 0.0007m. One side of Honeycomb structure was fixed and pressure was applied on face panel of structure. Total deformation, stress and strain was found out using Ansys workbench with different material assigned. This paper gave more insights on design methodology, material selection and also explained different phases of design of honeycomb structure.

So, from the above paper and book the understanding is that Honeycomb structures have a wide range of applications. Secondly, the use of honeycomb structures can reduce the weight by certain amount by offering more strength. All the papers, I referred had regular honeycomb structures used for experiments and analyzing results. If we decrease cell size gradually in length direction, the cell wall thickness along length direction also increases resulting in more resistance

than the previous cell as the cell wall thickness of right most cell has more thickness then the left cells to it.

The third paper was authored by Santosh kumar sahu, Nitesh Dhar Badgayan from department of Mechanical Engineering, Amrita School of Engineering and North Eastern Regional Institute of Science and Technology respectively. This paper is titled "Influence of cell size on out of plane stiffness and in-plane compliance character of the sandwich beam made with tunable PCTPE nylon honeycomb core and hybrid polymer nanocomposite skin." This paper talks about fabrication of of hybrid sandwich beams made with PCTPE nylon. Some part of this paper deals with honeycomb core geometry and fabrication section to understand parameters derived from geometry such as Honeycomb density, cells per honeycomb surface area, exposed foil area per honeycomb volume, foil edge area per honeycomb surface area. As I started working on to decrease cell size along length, I had to work on these properties for different dimensions to observe the trend for gradient honeycomb structure.

The fourth paper, "Modal Analysis and Harmonic Response Analysis of a Crankshaft" authored by Dr.C.M Ramesha, Abhijith KG, Department of Mechanical Engineering, M.S.R.I.R Bangalore, India. I used this paper as reference for modal analysis of honeycomb structure. Although this paper was not related to honeycomb structure but, modal analysis part of this paper was used to understand and study the dynamic characteristics of gradient honeycomb structure under vibrational excitation.

1.1 Objectives

The following are the objectives of this project:

- To design Honeycomb Structure of varying diagonal length cell size by keeping cell size constant along length direction.
- To evaluate and compare deformation of regular honeycomb structure and varying cell honeycomb structure.
- To evaluate and compare deformation of different honeycomb structures with different cell orientation (Regular and varying structures).
- To evaluate and compare deformation and energy absorption of varying cell honeycomb structures (Sleeping and standing cell-oriented structures) at different cases.

- To perform modal analysis to determine the vibrational characteristics of honeycomb structure

CHAPTER 3

DESIGN AND ANALYSIS OF LENGTHWISE GRADIENT HONEYCOMB CORE FOR OBTAINING GRADED BEAM PROPERTIES

This Chapter describes the proposed system working methodology, software and hardware details.

2.1 Proposed System

The following block diagram (figure 2) shows the system architecture of this project.

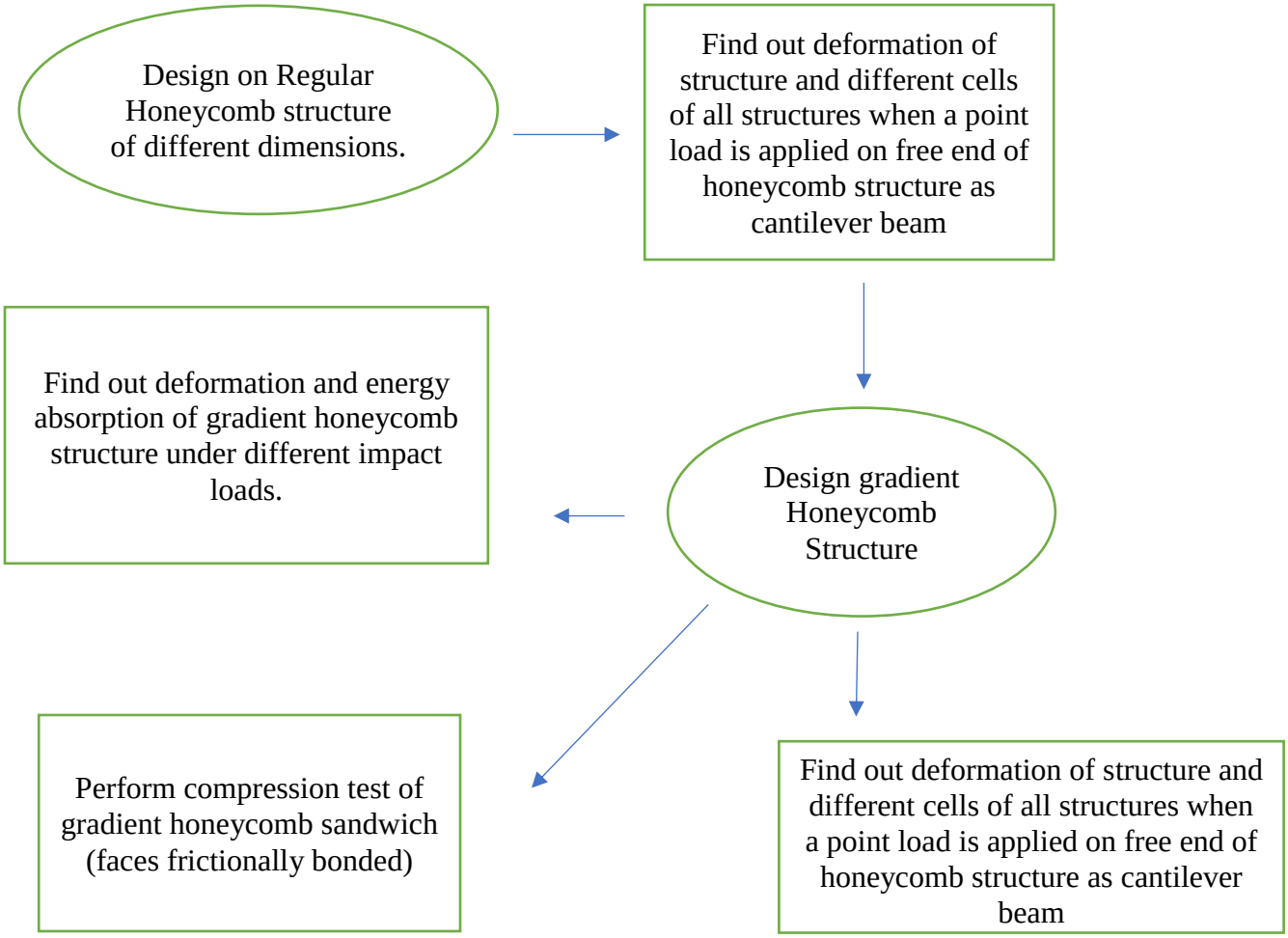

Figure 5 System Block Diagram

2.2 Working Methodology

Whole project was implemented in software by simulations. Firstly, Honeycomb Structures of different cell sizes and cell wall thickness are designed and are simulated to find out deformation of total structure and deformation of different cells in honeycomb when one side of structure is fixed. Secondly, after observing and inferring the relation between dimensions and deformation, gradient honeycomb structure along ribbon direction is designed. Again, the gradient structures are simulated to find out deformation of structure and then compare with regular honeycomb.

To conduct impact loading simulation, a sphere is designed on top plane of honeycomb structure. Before simulating, the sphere is given certain velocity and made it to impact honeycomb structure. This process is repeated for at different velocities and energy graphs are extracted.

Design of Honeycomb Structure (Vertical cell orientation and horizontal cell orientation)

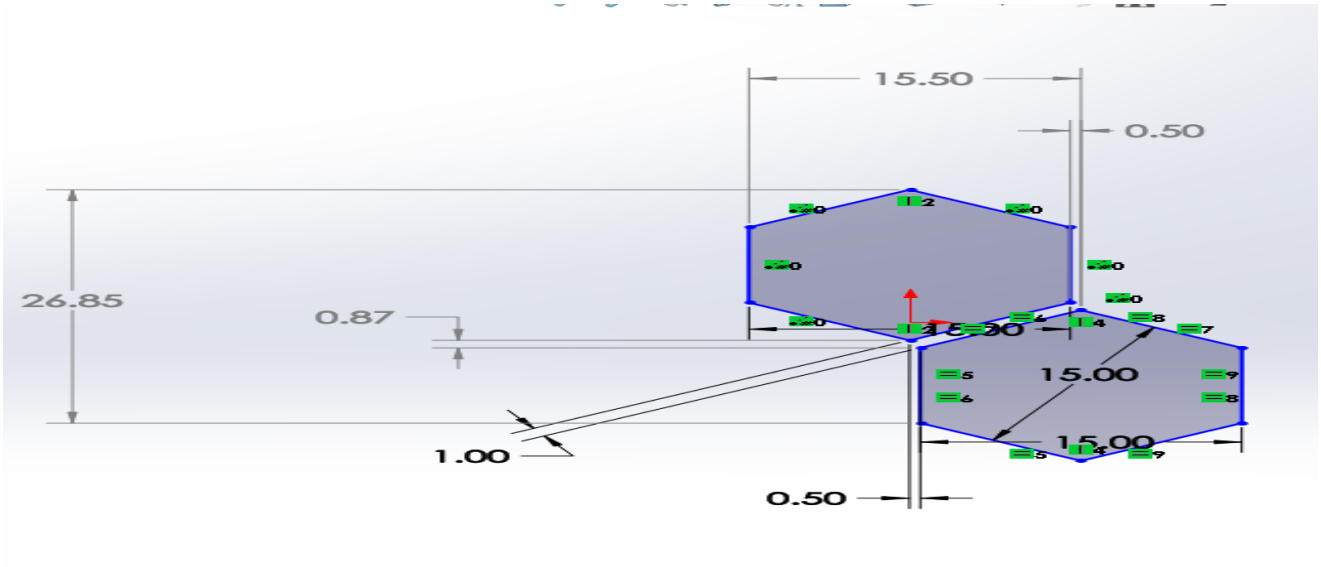

Figure 6 Cell dimensions of Regular Honeycomb Structure

- In total, twelve regular honeycomb structures were designed with different dimensional combinations. All the structure core has approximated length of 220mm, width of 50mm and thickness of 30mm.
- All the twelve different honeycomb structures dimensions are listed in below table.

Cell orientation	Cell diagonal size (mm)	Cell wall thickness (mm)
Vertical	21	1.2
Vertical	15	1.2
Vertical	12	1.2
Vertical	21	1
Vertical	15	1
Vertical	12	1
Horizontal	21	1.2
Horizontal	15	1.2
Horizontal	12	1.2
Horizontal	21	1
Horizontal	15	1
Horizontal	12	1

Table 2 Honeycomb Dimensions

Vertical cell orientation

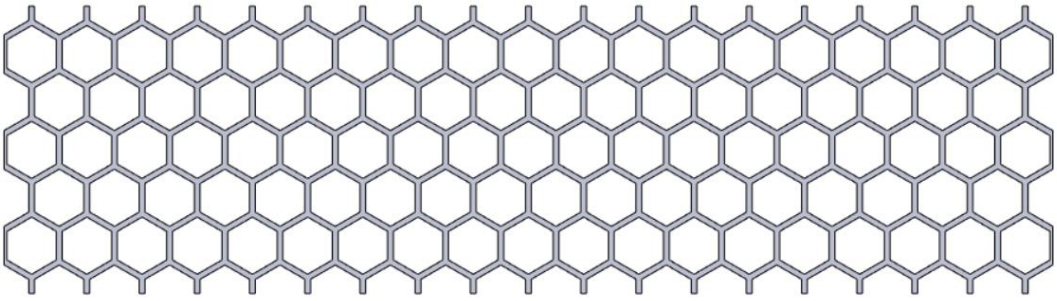

Figure 7 Honeycomb Structure (Vertical cell-orientation). 12,1.2

- Cell diagonal-12mm, Cell wall thickness -1.2mm

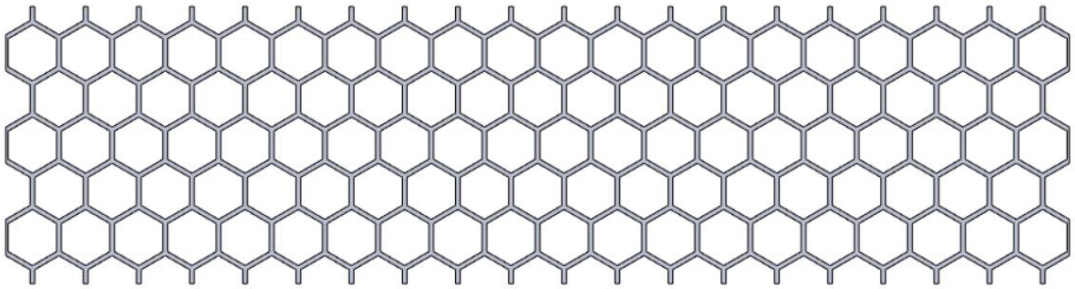

Figure 8 Honeycomb Structure (Vertical cell-orientation). 12,1

- Cell diagonal-12mm, Cell wall thickness -1mm

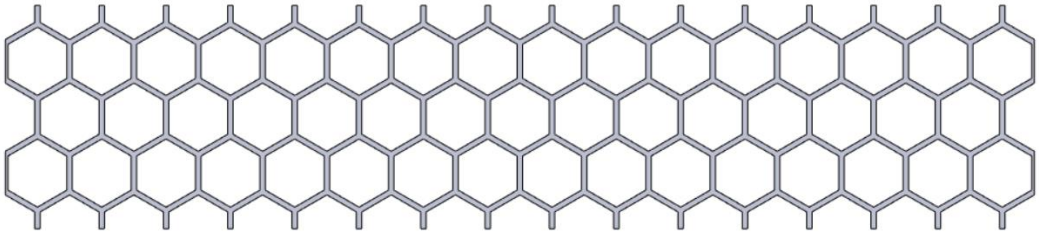

Figure 9 Honeycomb Structure (Vertical cell-orientation). 15,1.2

- Cell diagonal-15mm, Cell wall thickness -1.2mm

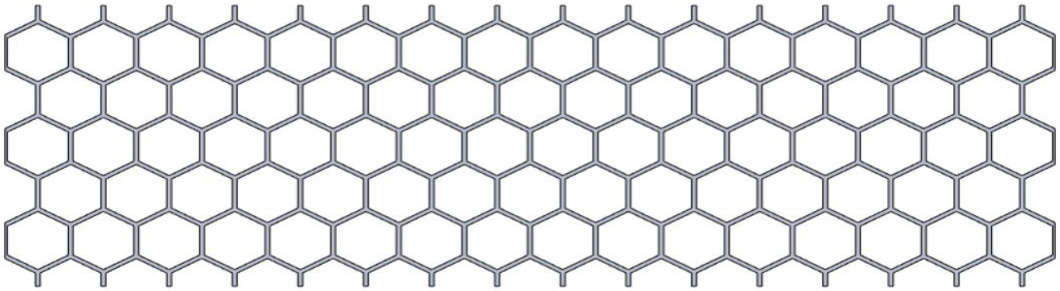

Figure 10 Honeycomb Structure (Vertical cell-orientation). 15,1

- Cell diagonal-15mm, Cell wall thickness -1mm

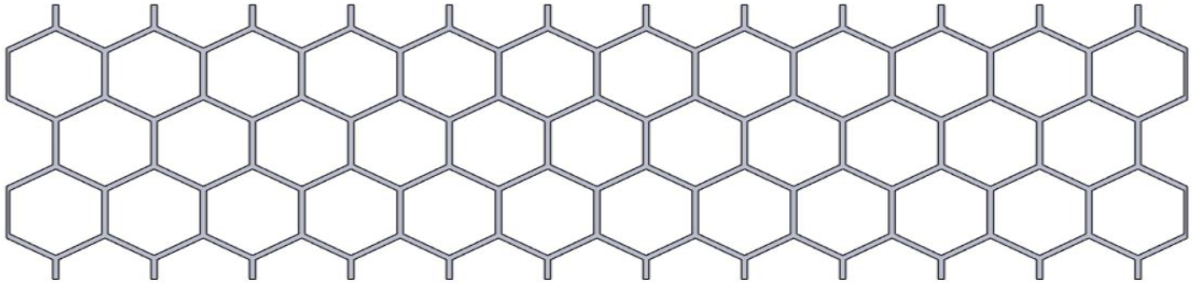

Figure 11 Honeycomb Structure (Vertical cell-orientation). 21,1.2

- Cell diagonal-21mm, Cell wall thickness -1.2mm

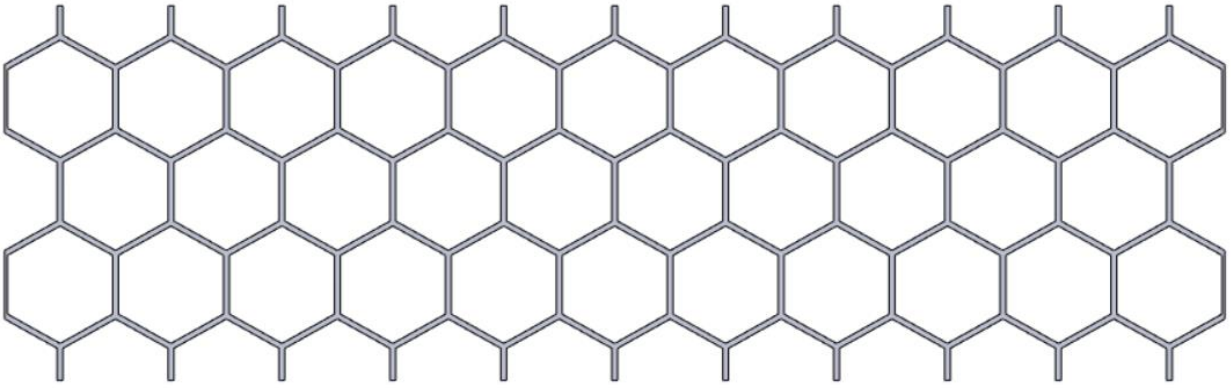

Figure 12 Honeycomb Structure (Vertical cell-orientation). 21,1

- Cell diagonal-21mm, Cell wall thickness -1mm

Horizontal cell orientation

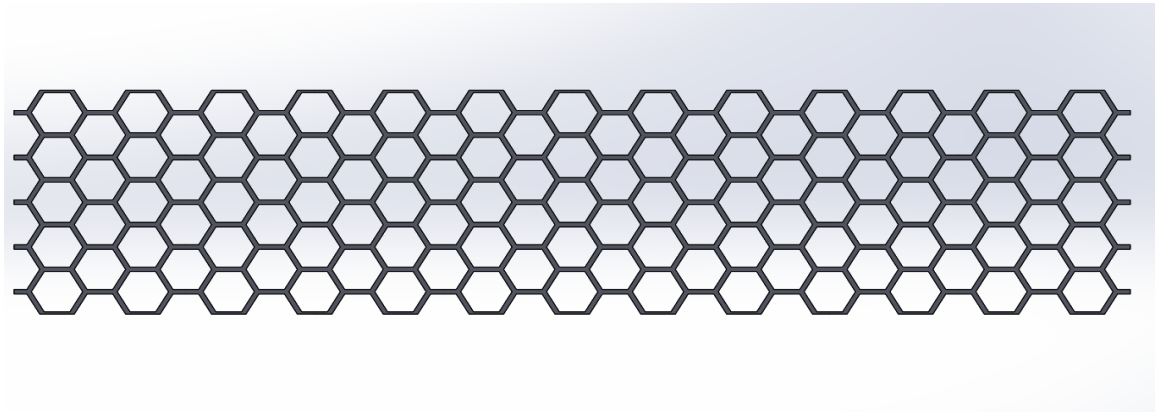

Figure 13 Honeycomb Structure (Horizontal cell-orientation). 12,1.2

- Cell diagonal-12mm, Cell wall thickness -1.2mm

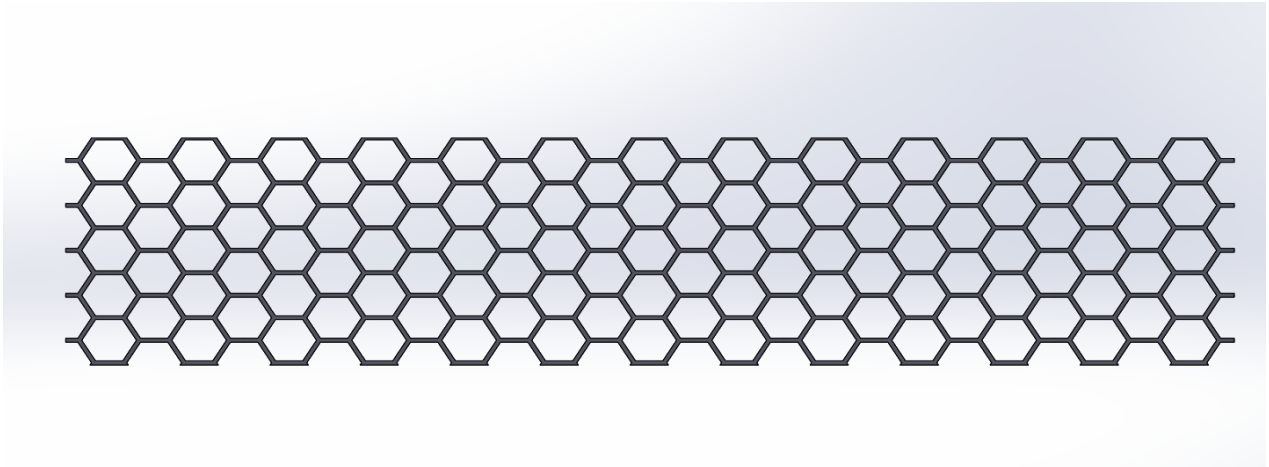

Figure 14 Honeycomb Structure (Horizontal cell-orientation). 12,1

- Cell diagonal-12mm, Cell wall thickness -1mm

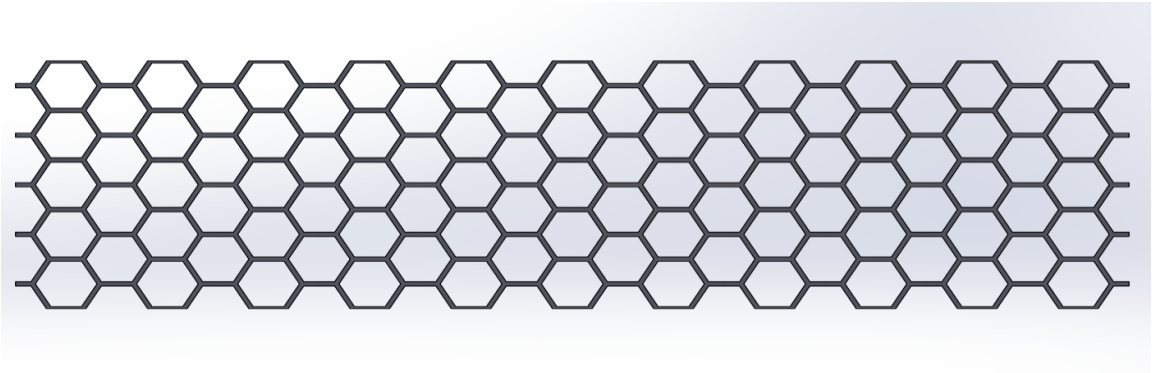

Figure 15 Honeycomb Structure (Horizontal cell-orientation). 15,1.2

- Cell diagonal-15mm, Cell wall thickness -1.2mm

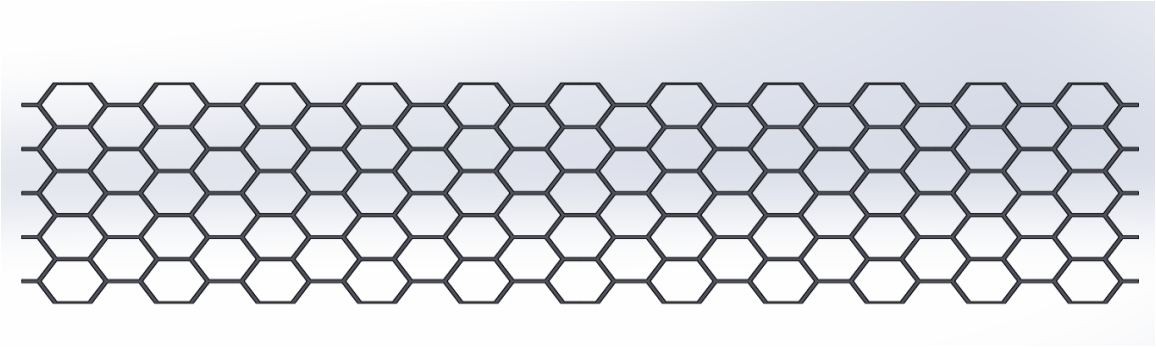

Figure 16 Honeycomb Structure (Horizontal cell-orientation). 15,1

- Cell diagonal-15mm, Cell wall thickness -1mm

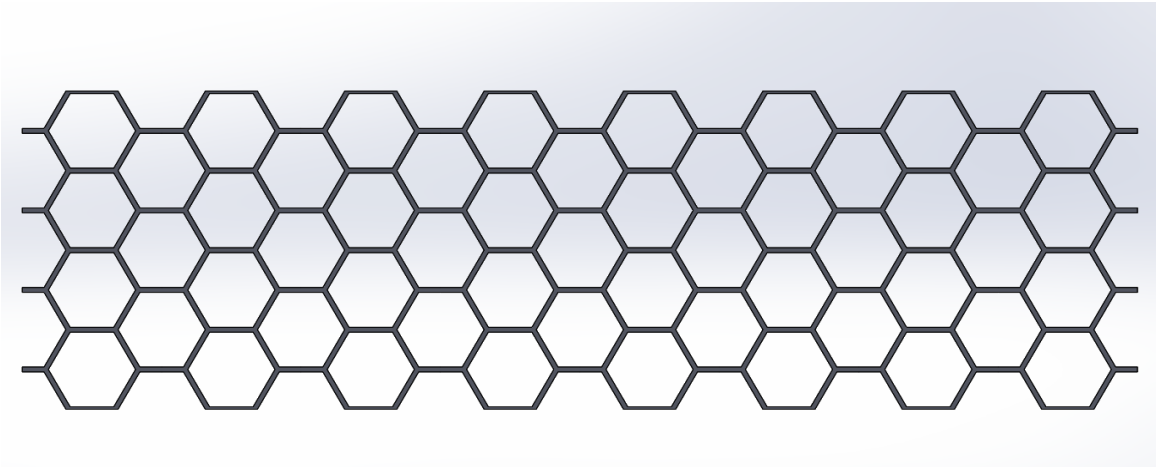

Figure 17 Honeycomb Structure (Horizontal cell-orientation). 21,1.2

- Cell diagonal-21mm, Cell wall thickness -1.2mm

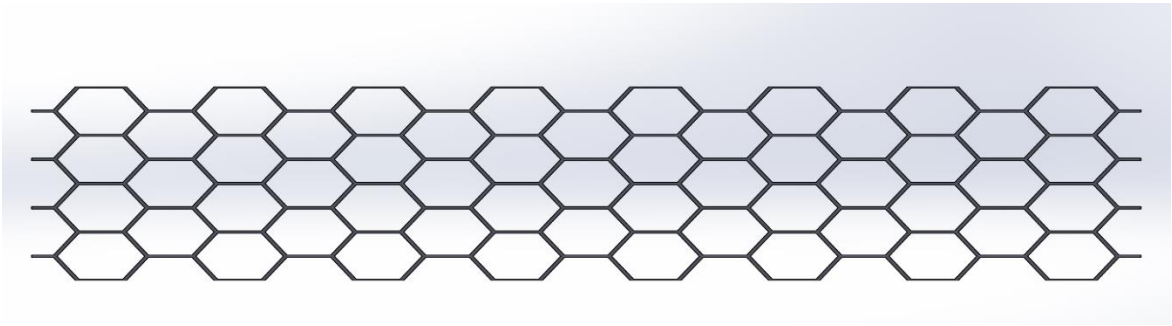

Figure 18 Honeycomb Structure (Horizontal cell-orientation). 21,1

- Cell diagonal-21mm, Cell wall thickness -1mm

Boundary Conditions:

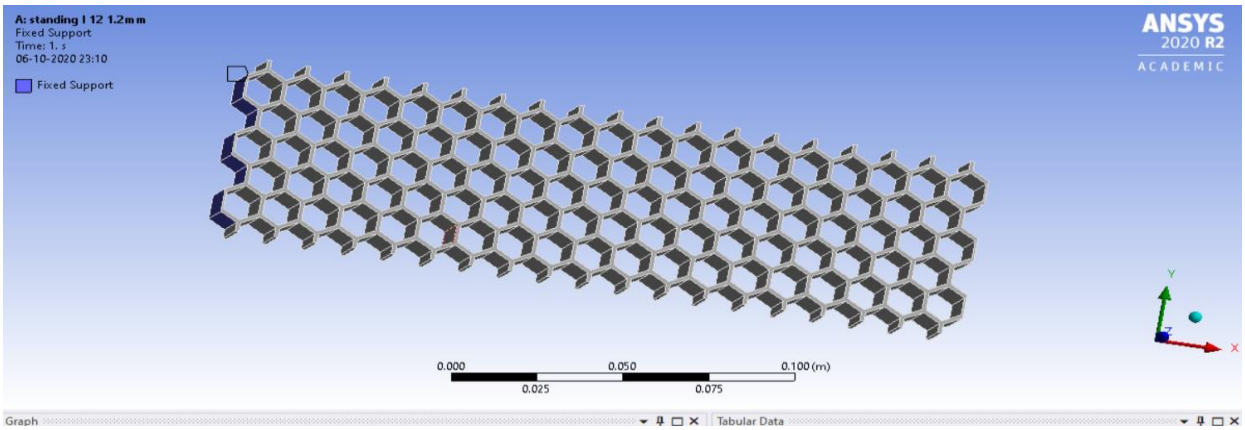

Figure 19 Honeycomb Structure (Vertical cell-orientation), fixed at one end (Cantilever beam).

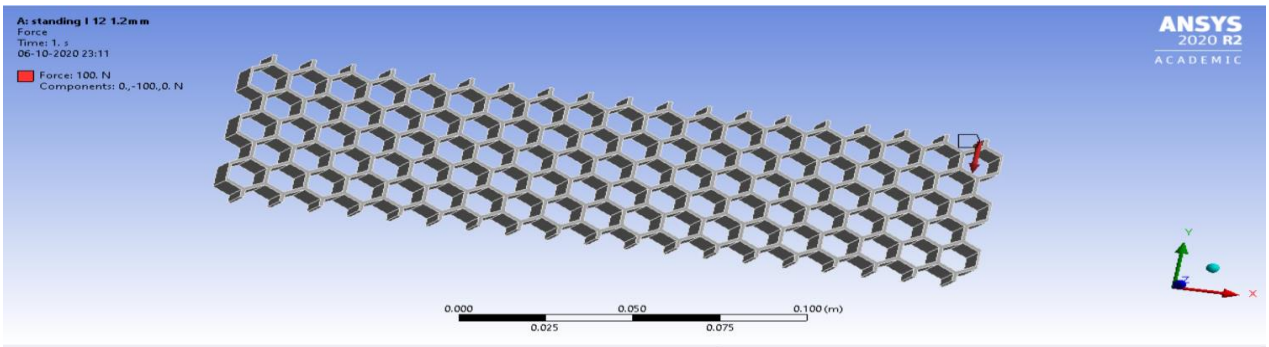

Figure 20 Honeycomb Structure (Vertical cell-orientation), Applying point load (100N) at free end.

- Honeycomb Structure is fixed at one end and 100N force is applied on the other end of structure.
- Total deformation of structure and cell deformation of different cells in different columns were found out in ANSYS.
- Element type- Linear tetrahedral
- All the simulations are performed at ambient temperature (22 °C)

Deformation of regular Honeycomb Structures

- **Vertical Cell Orientation.**

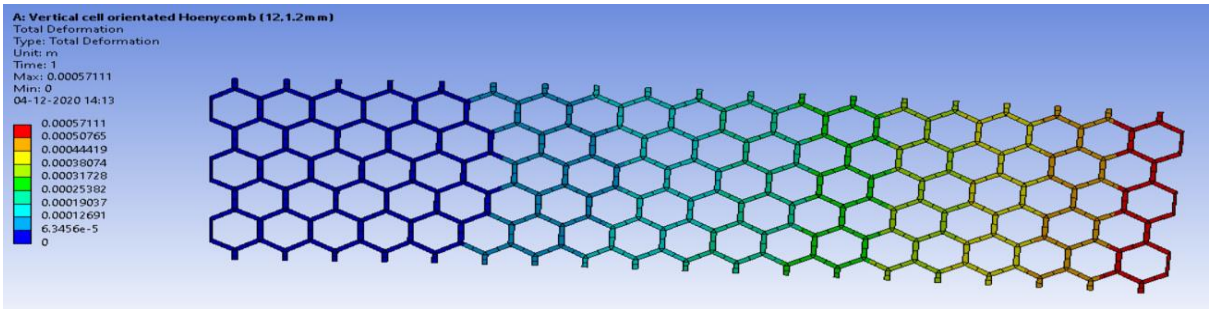

Figure 21 Deformation of regular Vertical cell-orientation Honeycomb Structure (12,1.2)

- Minimum Deformation-0m
- Maximum Deformation-5.7111e-004 m
- Average Deformation-2.1381e-004 m

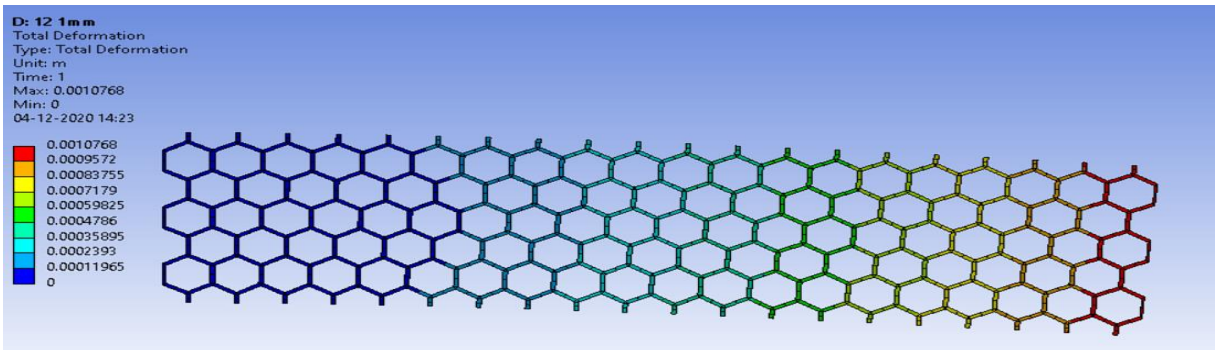

Figure 22 Deformation of regular Vertical cell-orientation Honeycomb Structure (12,1)

- Minimum Deformation-0m
- Maximum Deformation-1.0768e-003 m
- Average Deformation-4.0268e-004 m

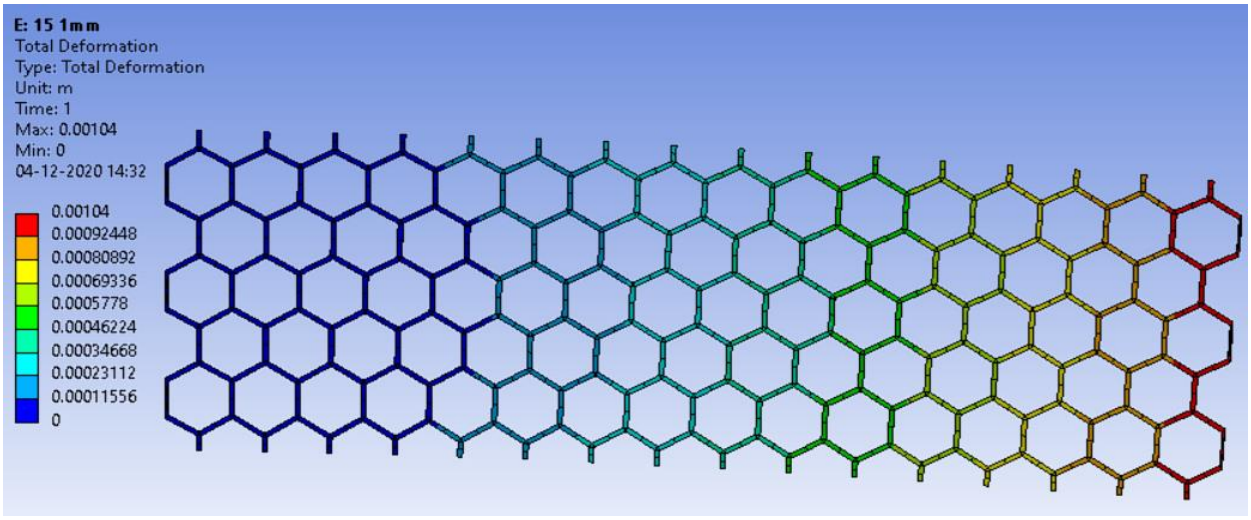

Figure 23 Deformation of regular Vertical cell-orientation Honeycomb Structure (15,1)

- Minimum Deformation-0m
- Maximum Deformation-1.04e-003 m
- Average Deformation-3.8921e-004 m

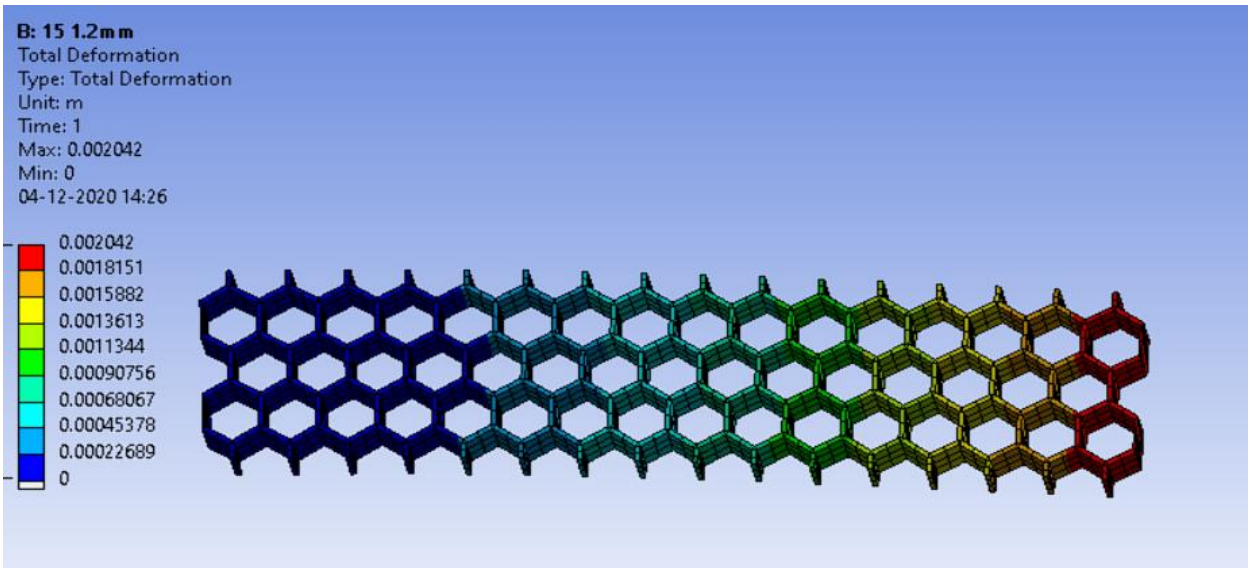

Figure 24 Deformation of regular Vertical cell-orientation Honeycomb Structure (15,1.2)

- Minimum Deformation-0m
- Maximum Deformation-2.042e-003 m
- Average Deformation-7.6092e-004 m

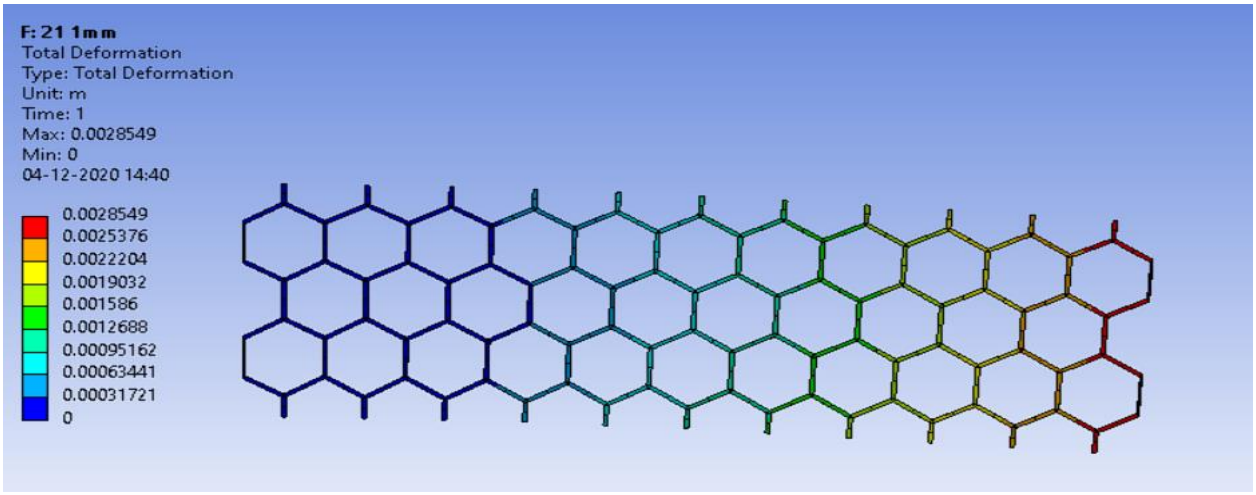

Figure 25 Deformation of regular Vertical cell-orientation Honeycomb Structure (21,1)

- Minimum Deformation-0m
- Maximum Deformation-2.8549e-003 m
- Average Deformation-1.0764e-003 m

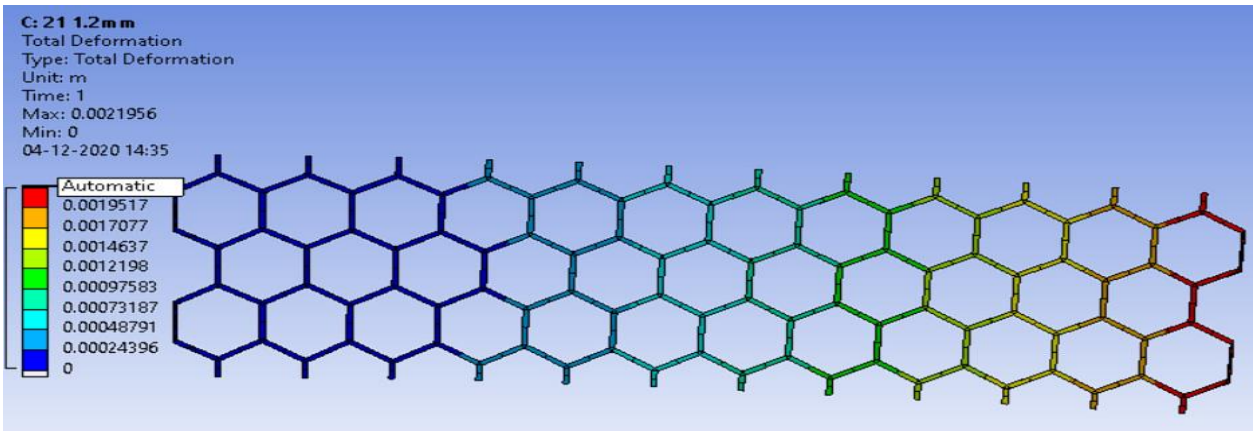

Figure 26 Deformation of regular Vertical cell-orientation Honeycomb Structure (21,1.2)

- Minimum Deformation-0m
- Maximum Deformation-2.1956e-003 m
- Average Deformation-8.1628e-004 m

- **Horizontal Cell Orientation**

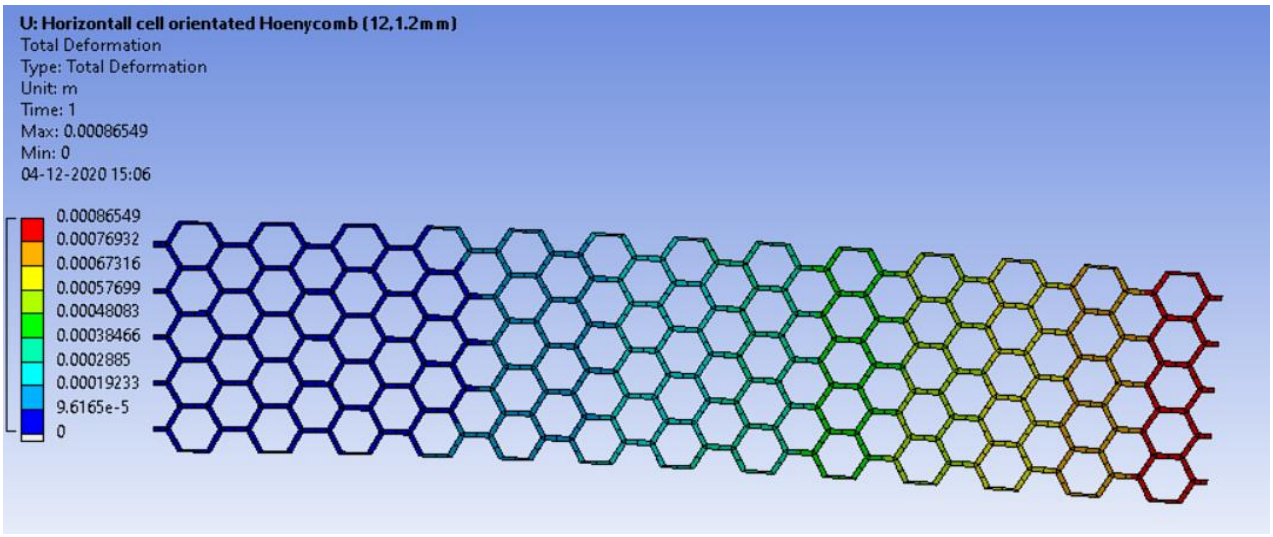

Figure 27 Deformation of regular Horizontal cell-orientation Honeycomb Structure (12,1.2)

- Minimum Deformation-0m
- Maximum Deformation-8.6549e-004 m
- Average Deformation-3.1971e-004 m

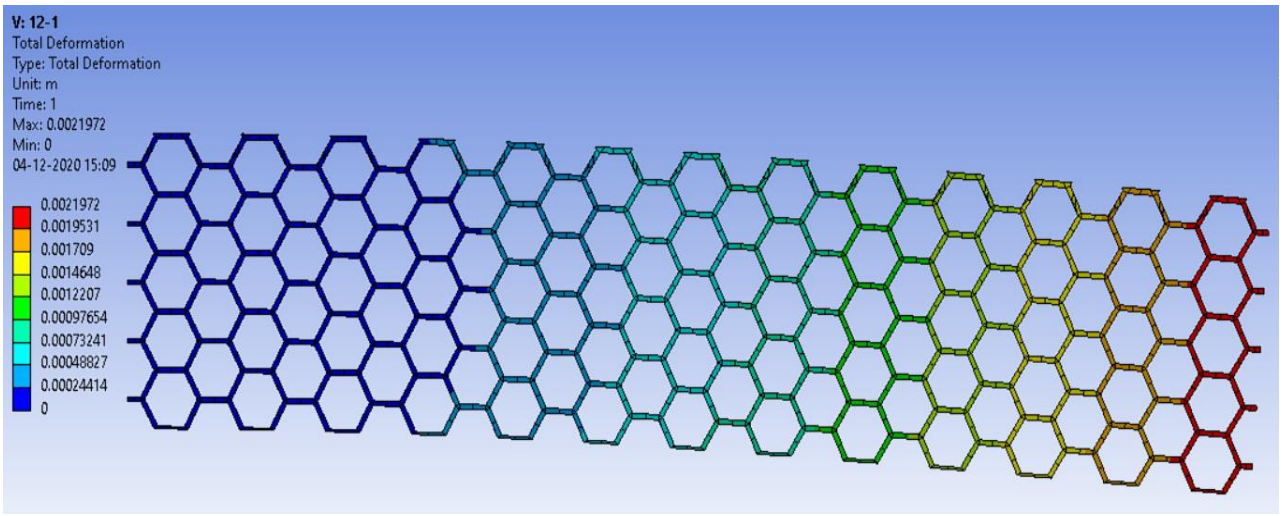

Figure 28 Deformation of regular Horizontal cell-orientation Honeycomb Structure (12,1)

- Minimum Deformation-0m
- Maximum 2.1972e-003 m
- Average Deformation-8.1239e-004 m

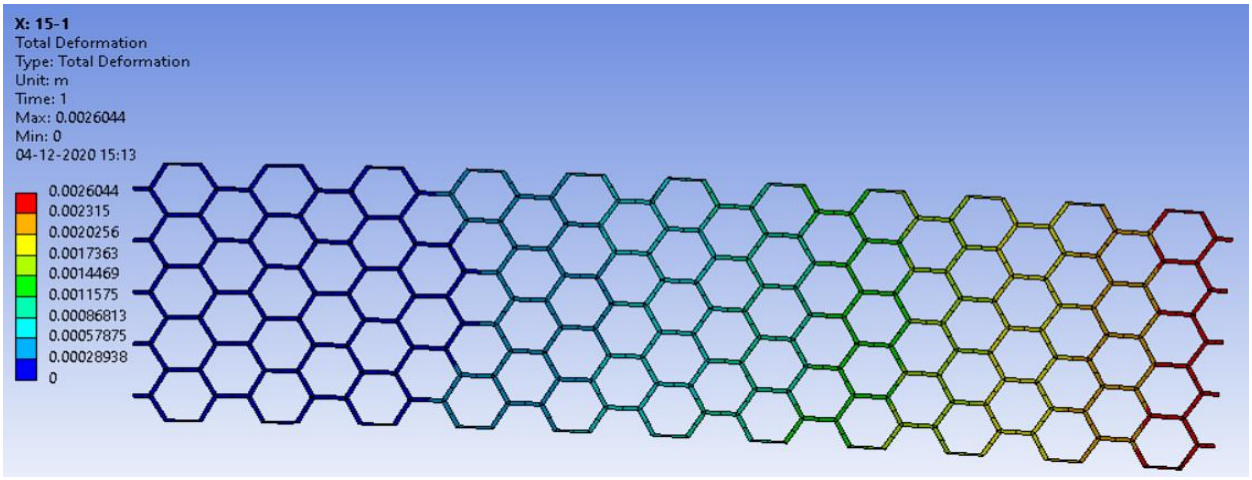

Figure 29 Deformation of regular Horizontal cell-orientation Honeycomb Structure (15,1)

- Minimum Deformation-0m
- Maximum Deformation-2.6044e-003 m
- Average Deformation-9.6152e-004 m

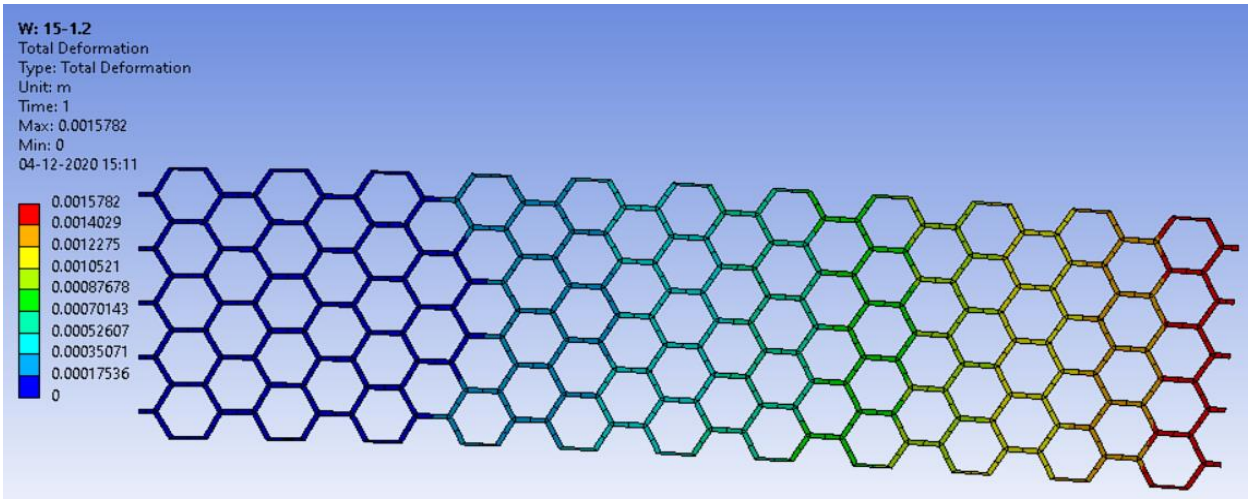

Figure 30 Deformation of regular Horizontal cell-orientation Honeycomb Structure (15,1.2)

- Minimum Deformation-0m
- Maximum Deformation-1.5782e-003 m
- Average Deformation-5.8187e-004 m

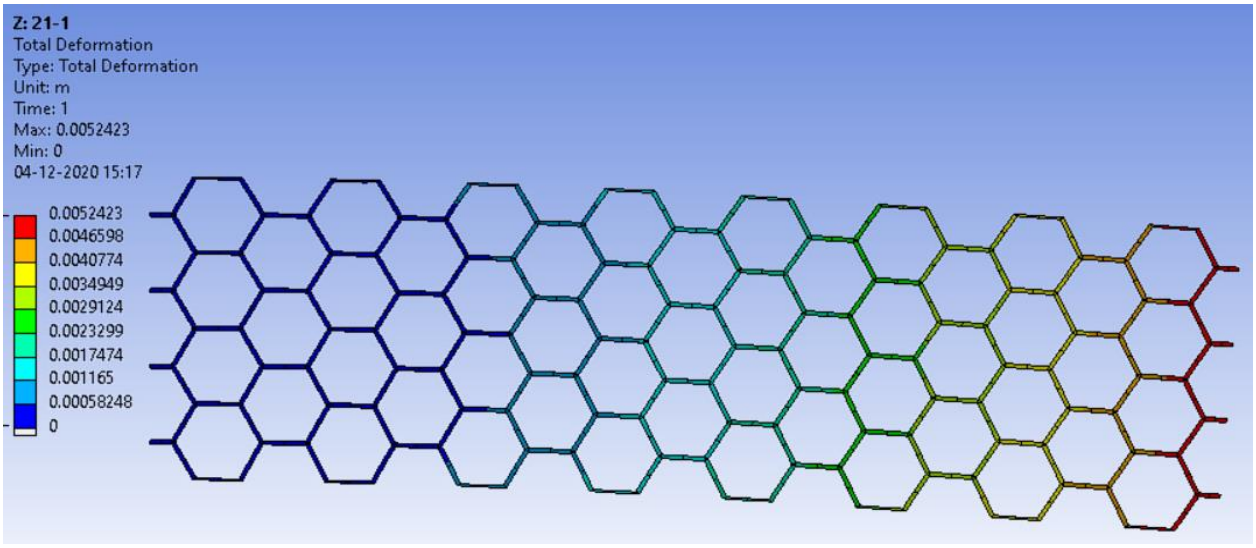

Figure 31 Deformation of regular Horizontal cell-orientation Honeycomb Structure (21,1)

- Minimum Deformation-0m
- Maximum Deformation-5.2423e-003 m
- Average Deformation-1.9082e-003 m

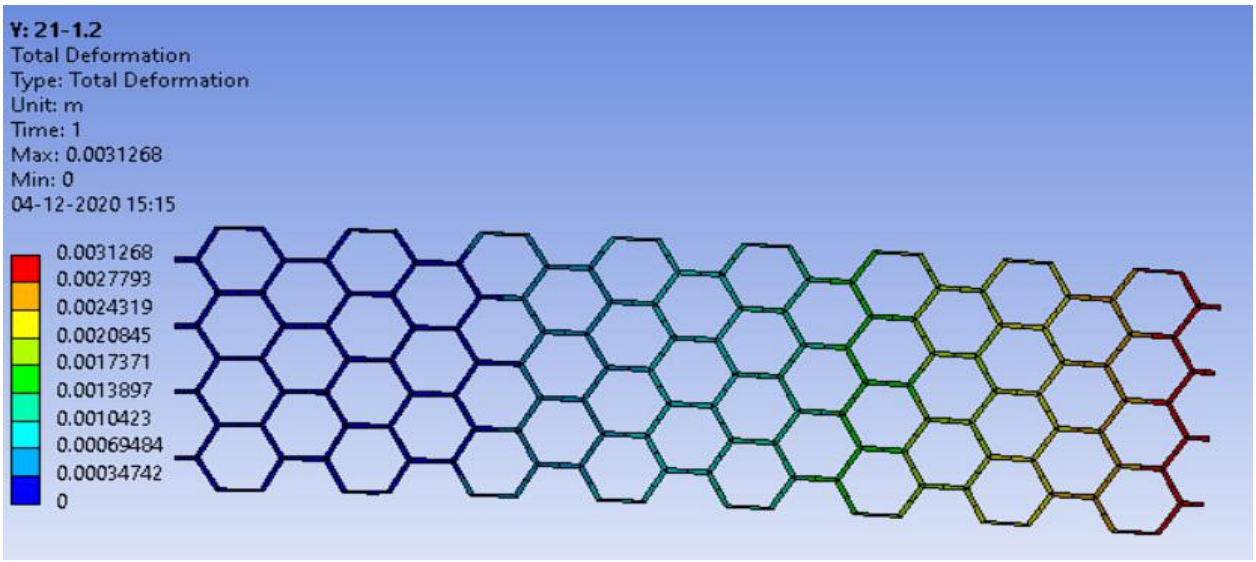

Figure 32 Deformation of regular Horizontal cell-orientation Honeycomb Structure (21,1.2)

- Minimum Deformation-0m
- Maximum Deformation-3.1268e-003 m
- Average Deformation-1.1405e-003 m

End cell deformation (Vertical cell orientation)

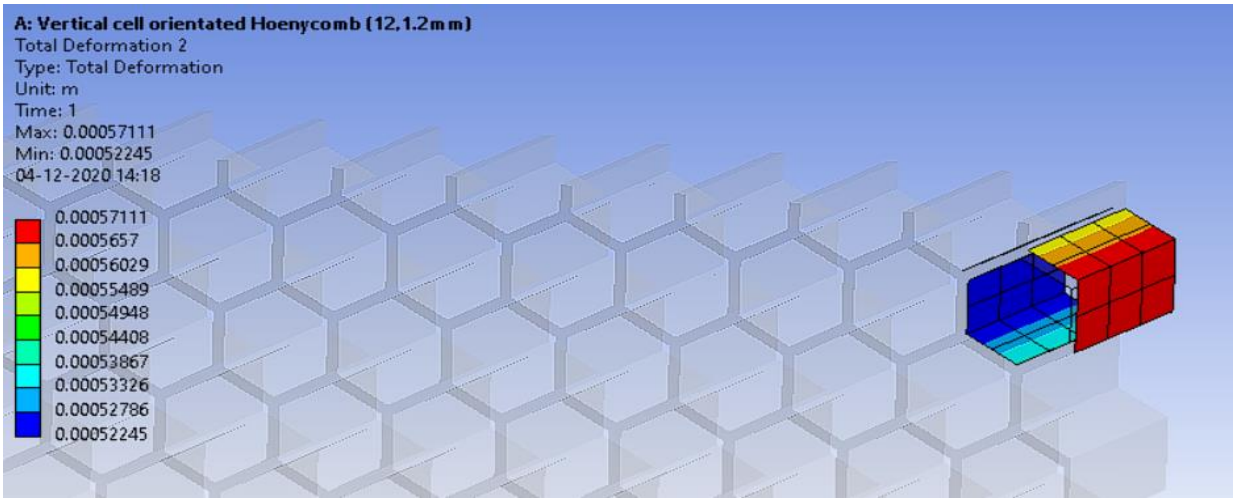

Figure 33 End cell deformation of regular Vertical cell-orientation Honeycomb Structure (12,1.2)

- Minimum Deformation- 5.2245e-004 m
- Maximum Deformation-5.7111e-004 m
- Average Deformation- 5.4967e-004 m

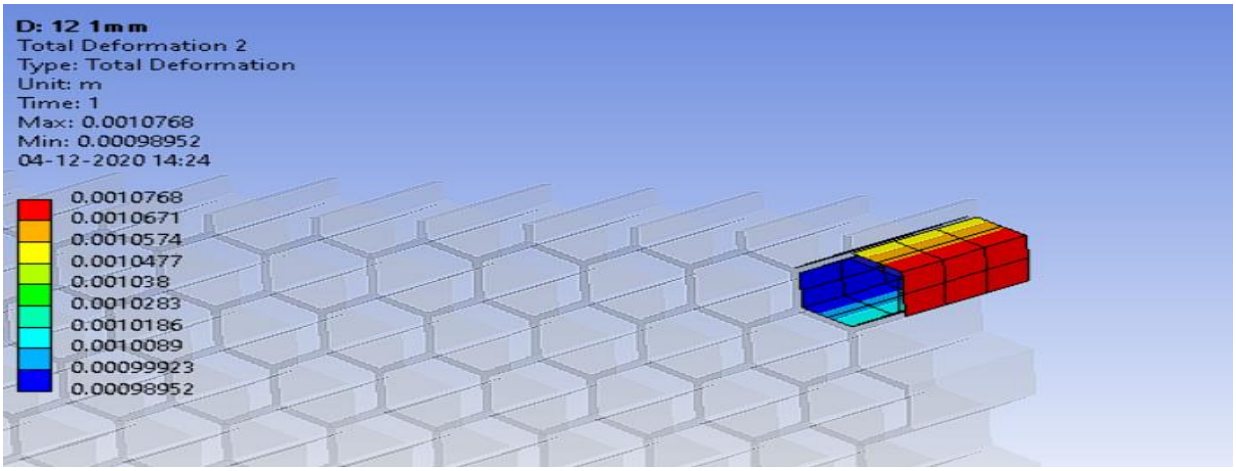

Figure 34 End cell deformation of regular Vertical cell-orientation Honeycomb Structure (12,1)

- Minimum Deformation- 9.8952e-004 m
- Maximum Deformation-1.0768e-003 m
- Average Deformation- 1.0385e-003 m

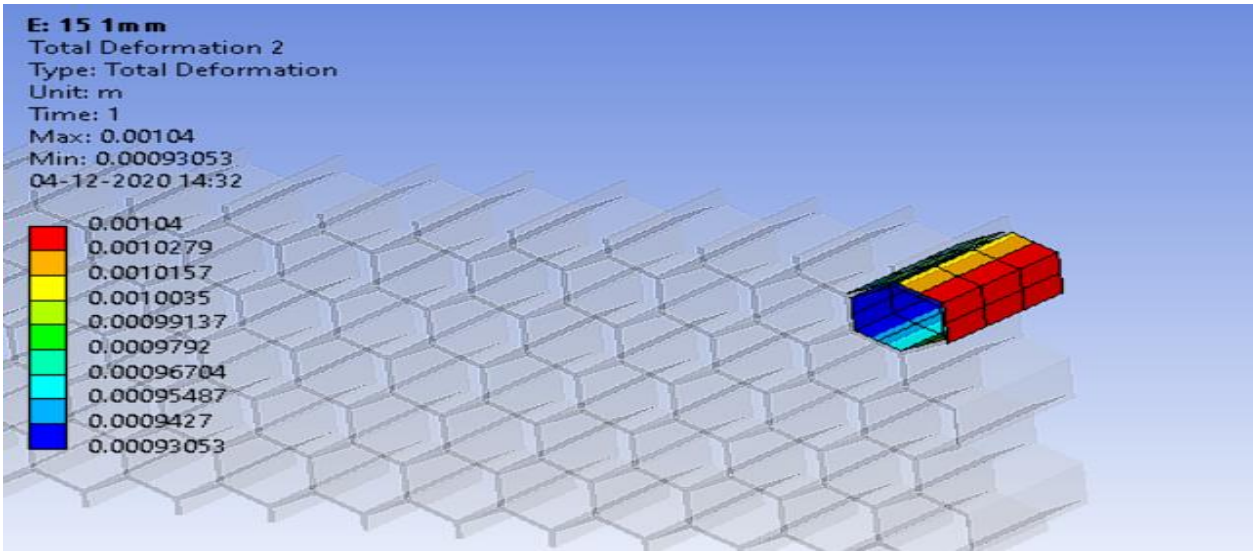

Figure 35 End cell deformation of regular Vertical cell-orientation Honeycomb Structure (15,1)

- Minimum Deformation- 9.3053e-004m
- Maximum Deformation-1.04e-003 m
- Average Deformation- 9.9345e-004 m

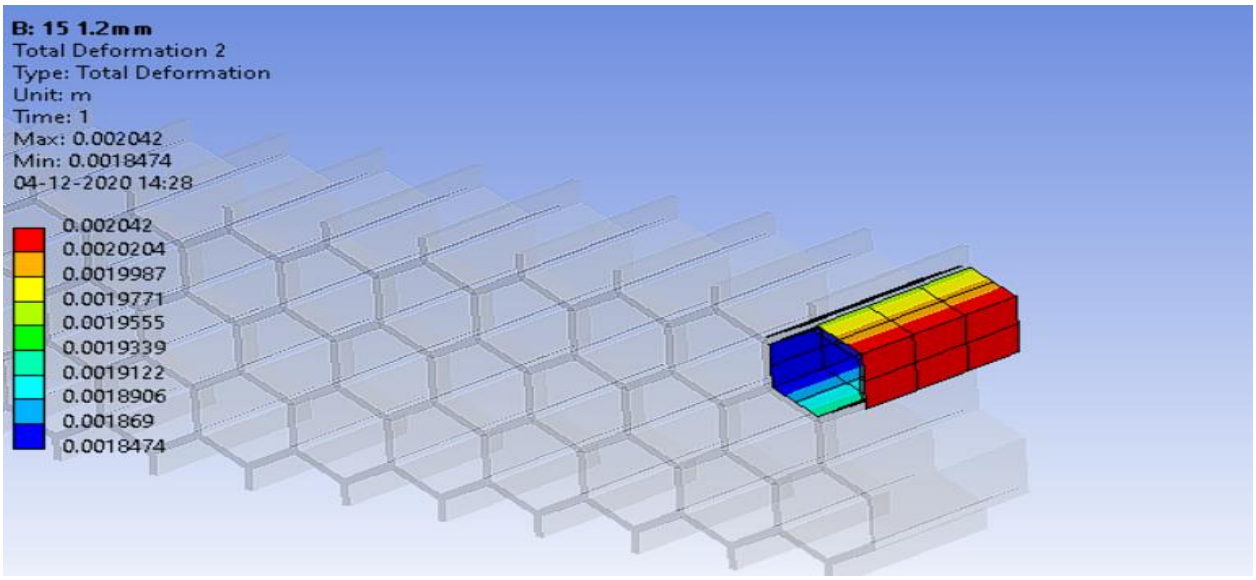

Figure 36 End cell deformation of regular Vertical cell-orientation Honeycomb Structure (15,1.2)

- Minimum Deformation- 1.8474e-003 m
- Maximum Deformation-2.042e-003 m
- Average Deformation- 1.9544e-003 m

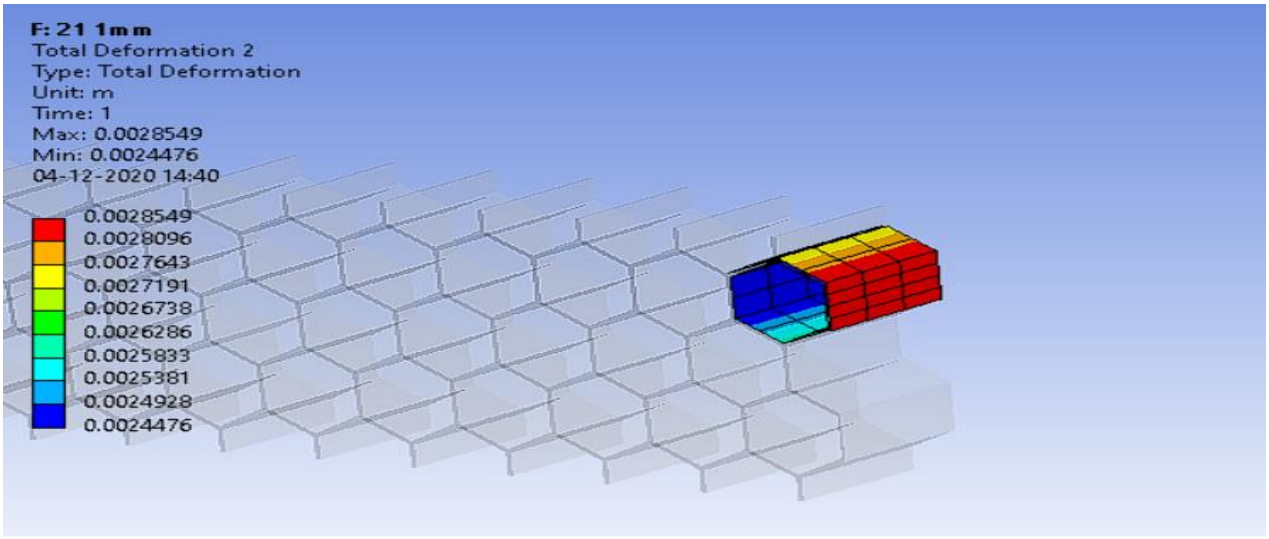

Figure 37 End cell deformation of regular Vertical cell-orientation Honeycomb Structure (21,1)

- Minimum Deformation- 2.4476e-003 m
- Maximum Deformation-2.8549e-003 m
- Average Deformation- 2.6949e-003 m

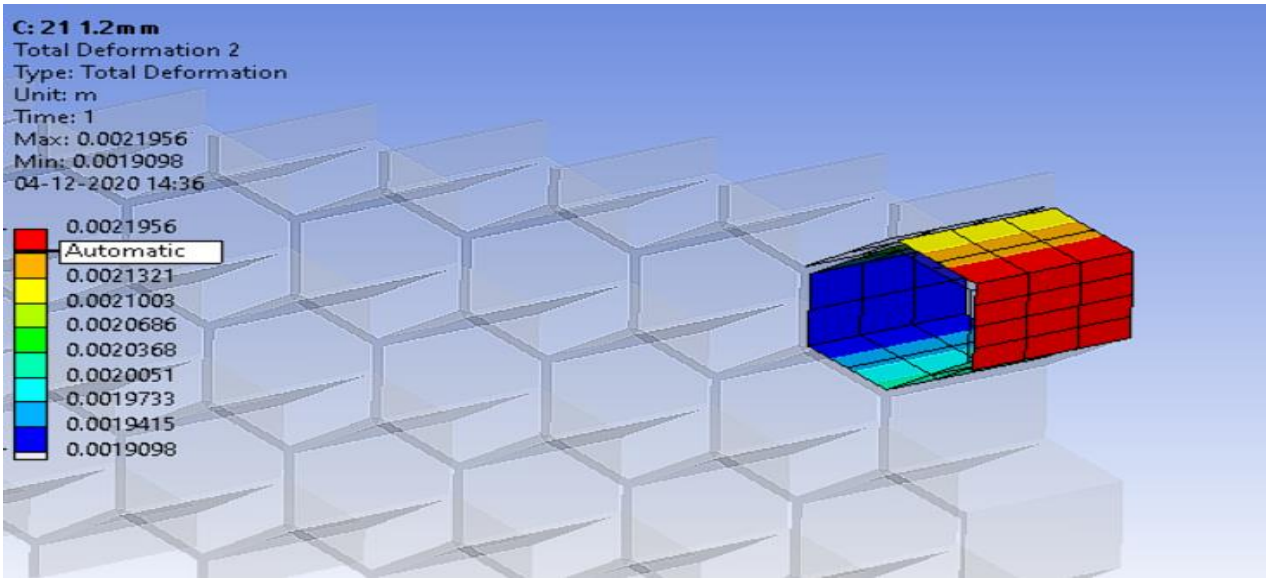

Figure 38 End cell deformation of regular Vertical cell-orientation Honeycomb Structure (21,1.2)

- Minimum Deformation- 1.9098e-003 m
- Maximum Deformation-2.1956e-003 m
- Average Deformation- 2.0818e-003 m

- **End cell deformation (Horizontal cell orientation)**

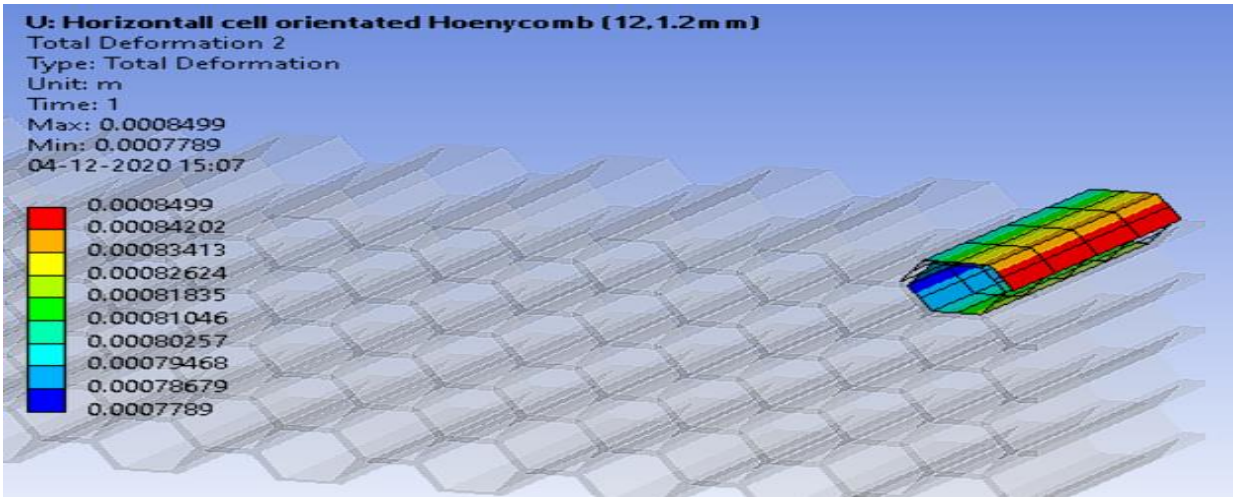

Figure 39 End cell deformation of regular Horizontal cell-orientation Honeycomb Structure (12,1.2)

- Minimum Deformation- 7.789e-004 m
- Maximum Deformation-8.499e-004 m
- Average Deformation- 8.155e-004 m

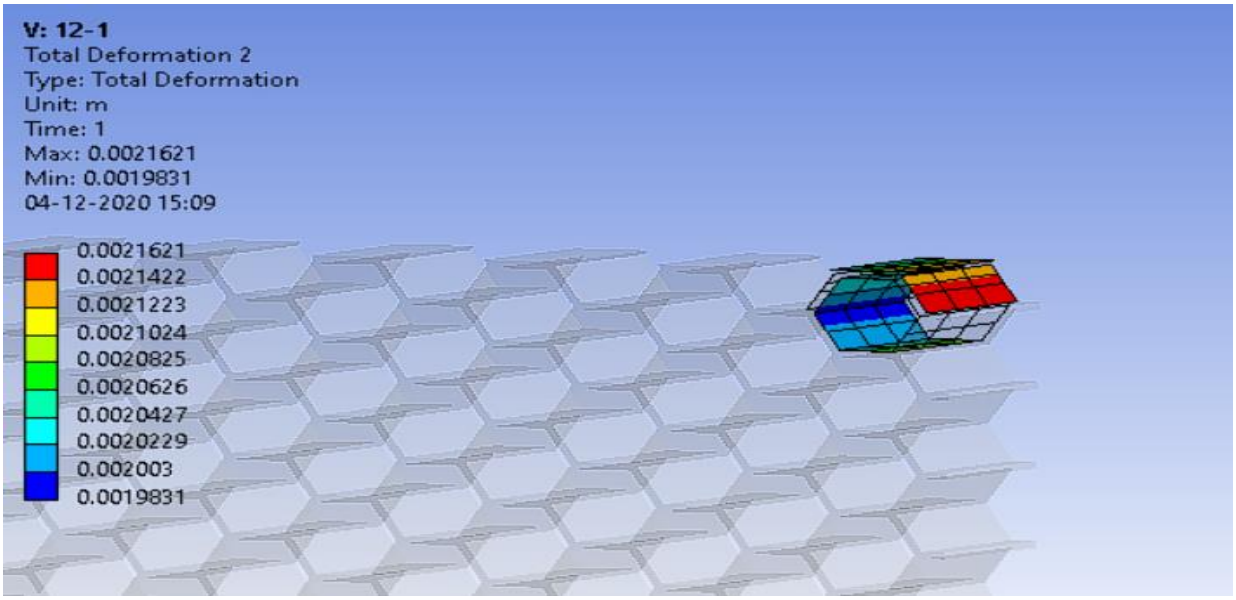

Figure 40 End cell deformation of regular Horizontal cell-orientation Honeycomb Structure (12,1)

- Minimum Deformation- 1.9831e-003 m
- Maximum Deformation- 2.1621e-003 m
- Average Deformation- 2.0774e-003 m

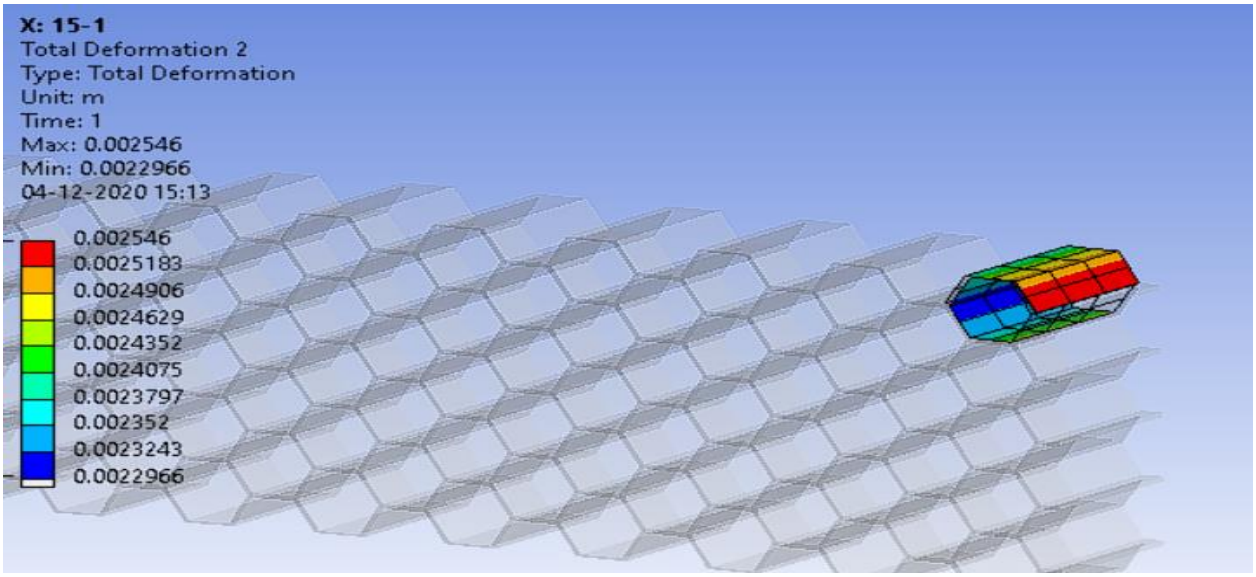

Figure 41 End cell deformation of regular Horizontal cell-orientation Honeycomb Structure (15,1)

- Minimum Deformation- 2.2966e-003 m
- Maximum Deformation-2.546e-003 m
- Average Deformation- 2.4248e-003 m

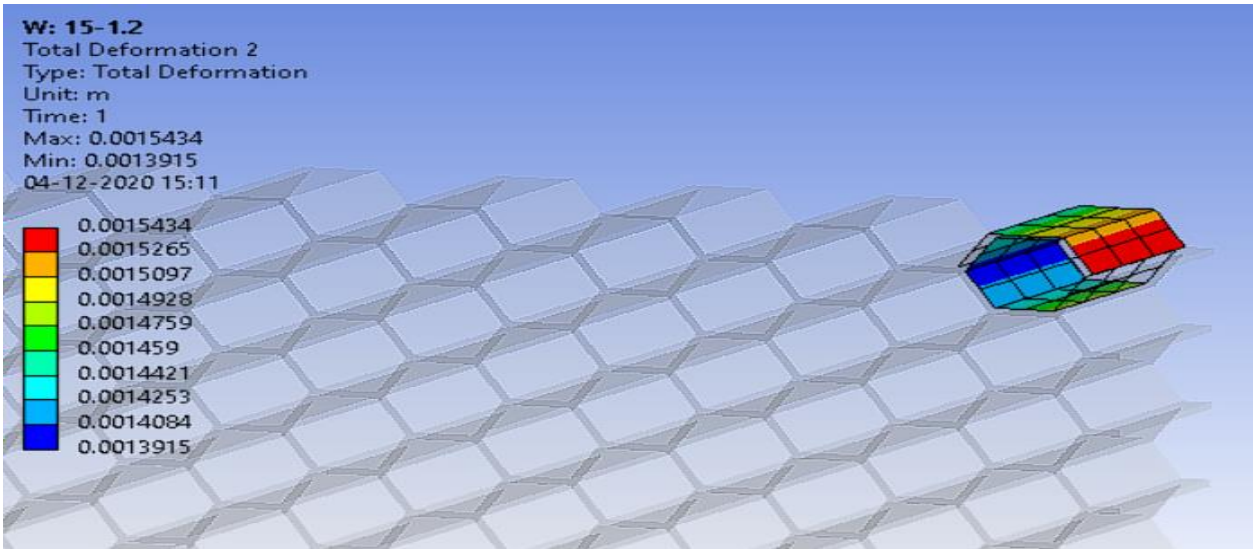

Figure 42 End cell deformation of regular Horizontal cell-orientation Honeycomb Structure (15,1.2)

- Minimum Deformation- 1.3915e-003 m
- Maximum Deformation-1.5434e-003 m
- Average Deformation- 1.4707e-003 m

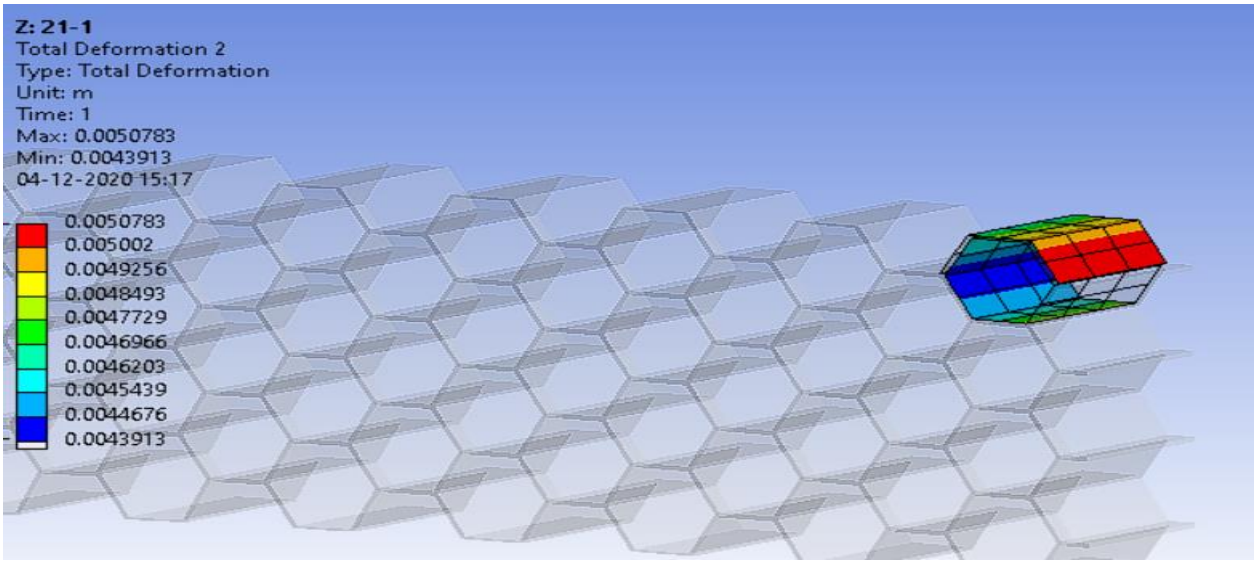

Figure 43 End cell deformation of regular Horizontal cell-orientation Honeycomb Structure (21,1)

- Minimum Deformation- 4.3913e-003 m
- Maximum Deformation-5.0783e-003 m
- Average Deformation- 4.7529e-003 m

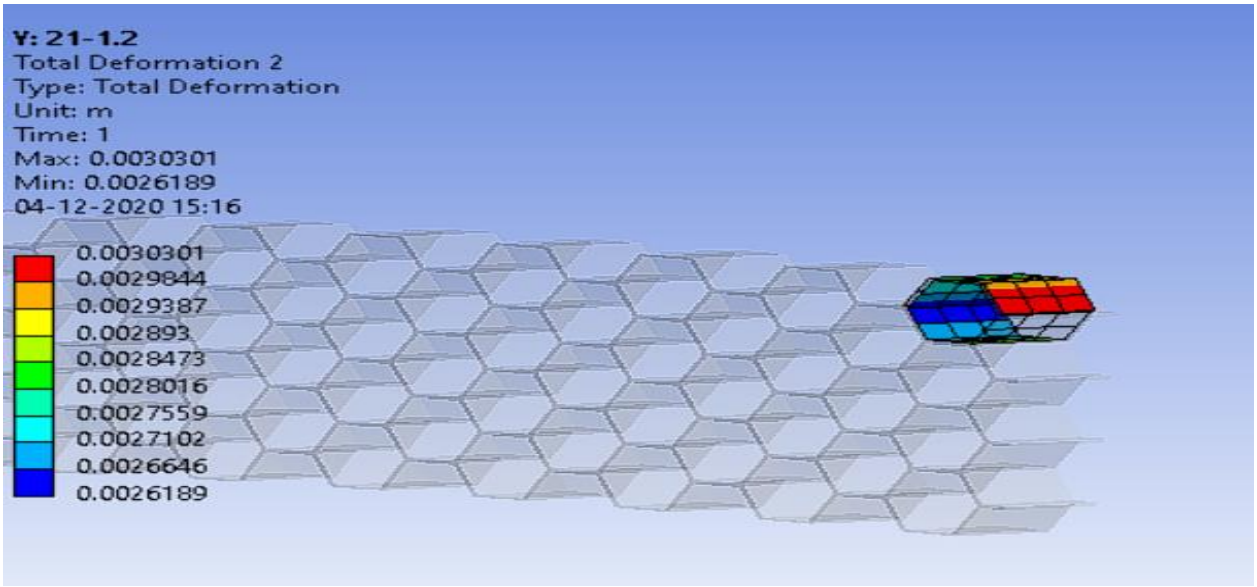

Figure 44 End cell deformation of regular Horizontal cell-orientation Honeycomb Structure (21,1.2)

- Minimum Deformation- 2.6189e-003 m
- Maximum Deformation-3.0301e-003 m
- Average Deformation- 2.8349e-003 m

Mid-Cell deformation

- **Vertical Cell Orientation**

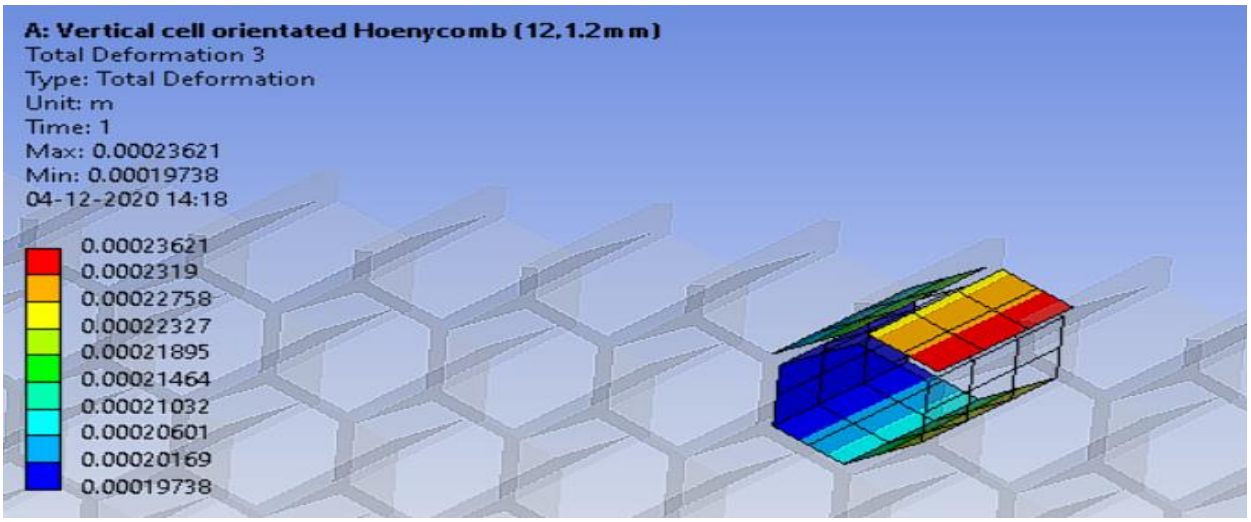

Figure 45 Mid-Cell deformation of regular Vertical cell-orientation Honeycomb Structure (12,1.2)

- Minimum Deformation-1.9738e-004 m
- Maximum Deformation - 2.3621e-004 m
- Average Deformation- 2.175e-004 m

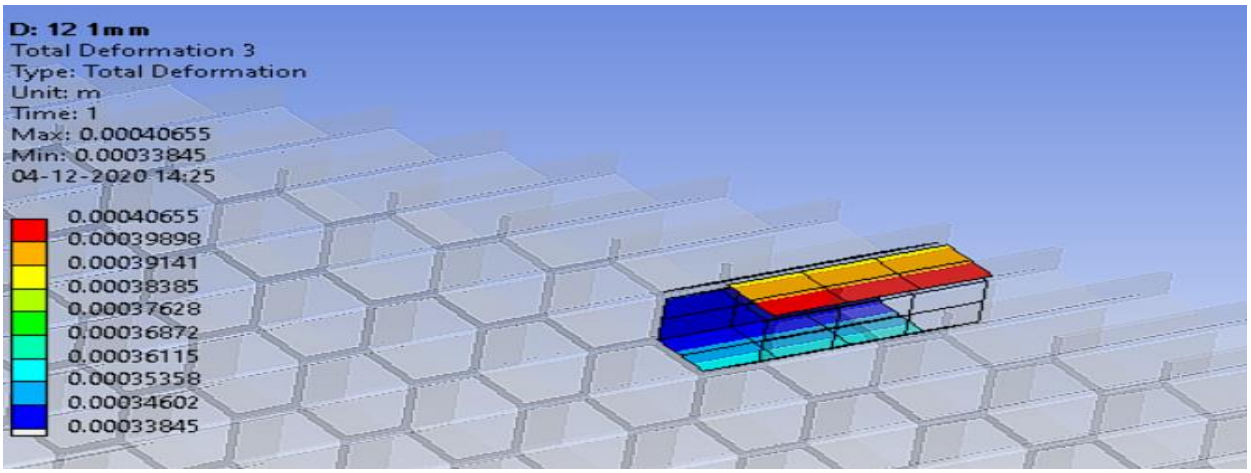

Figure 46 Mid-Cell deformation of regular Vertical cell-orientation Honeycomb Structure (12,1)

- Minimum Deformation-3.3845e-004 m
- Maximum Deformation - 4.0655e-004 m
- Average Deformation- 3.7415e-004 m

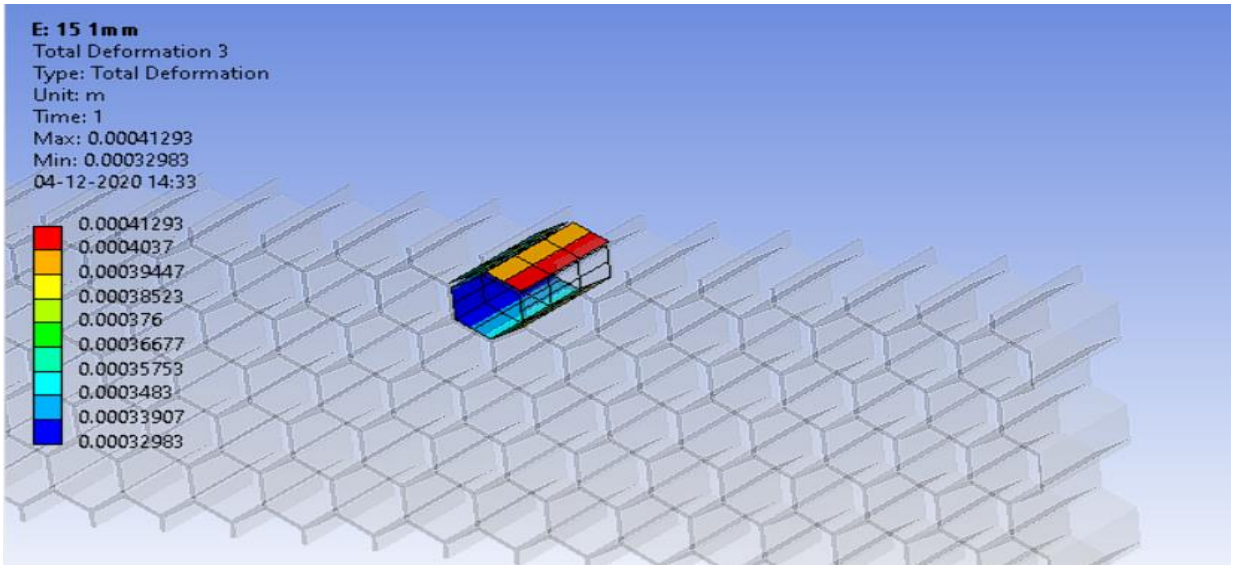

Figure 47 Mid-Cell deformation of regular Vertical cell-orientation Honeycomb Structure (15,1)

- Minimum Deformation-3.2983e-004 m
- Maximum Deformation - 4.1293e-004 m
- Average Deformation- 3.7429e-004 m

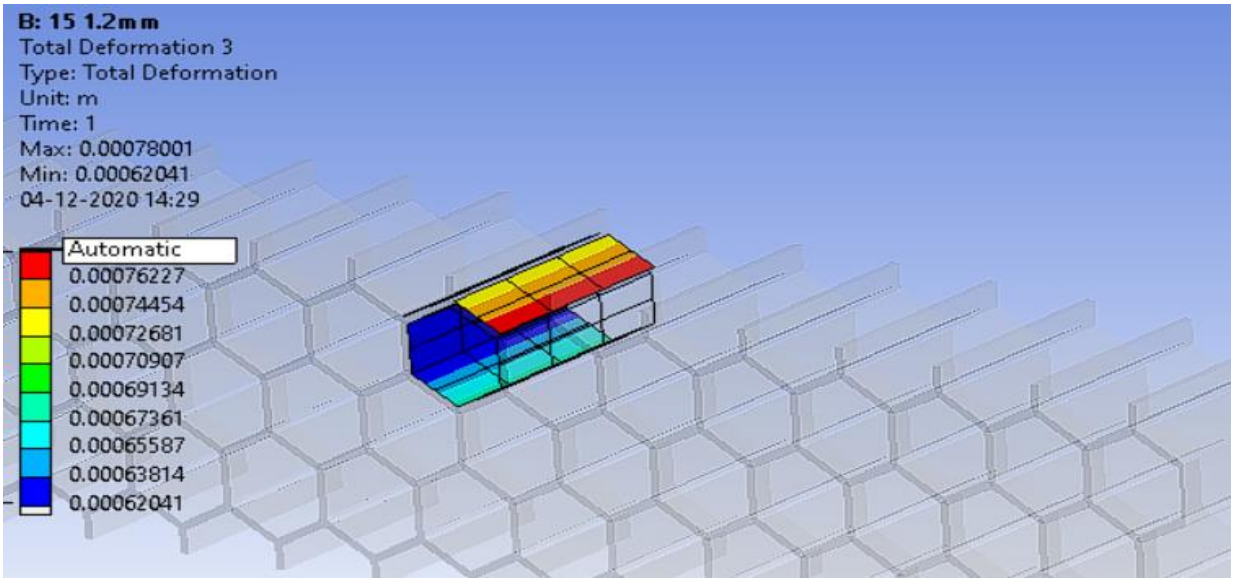

Figure 48 Mid-Cell deformation of regular Vertical cell-orientation Honeycomb Structure (15,1.2)

- Minimum Deformation-6.2041e-004 m
- Maximum Deformation - 7.8001e-004 m
- Average Deformation- 7.0279e-004 m

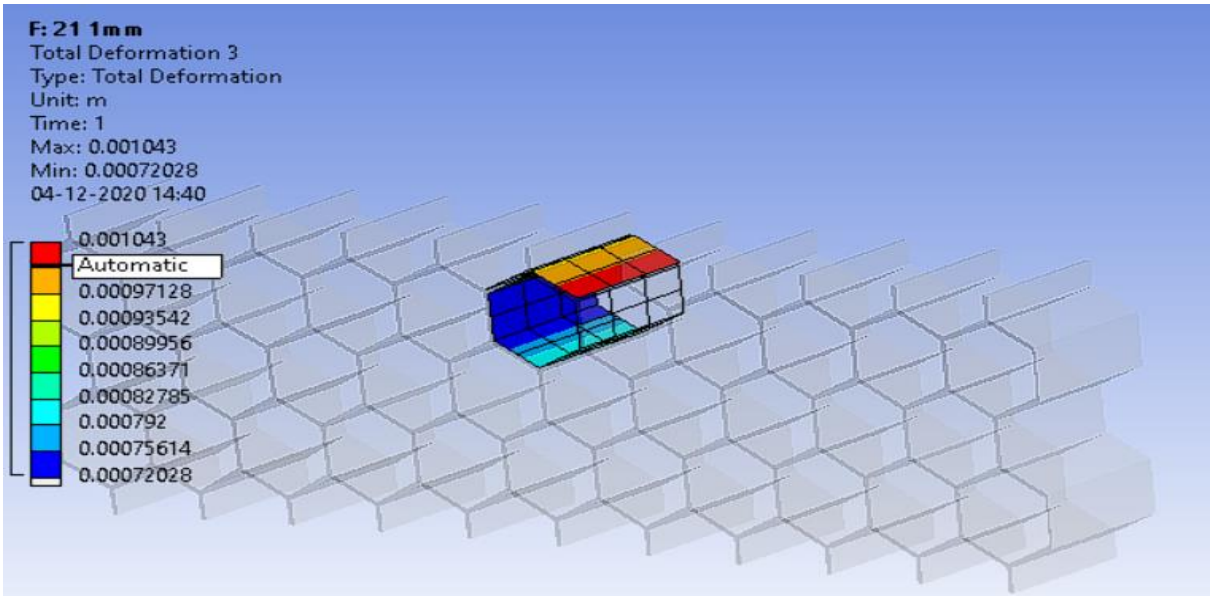

Figure 49 Mid-Cell deformation of regular Vertical cell-orientation Honeycomb Structure (21,1)

- Minimum Deformation- 7.2028e-004 m
- Maximum Deformation-1.043e-003 m
- Average Deformation- 8.9446e-004 m

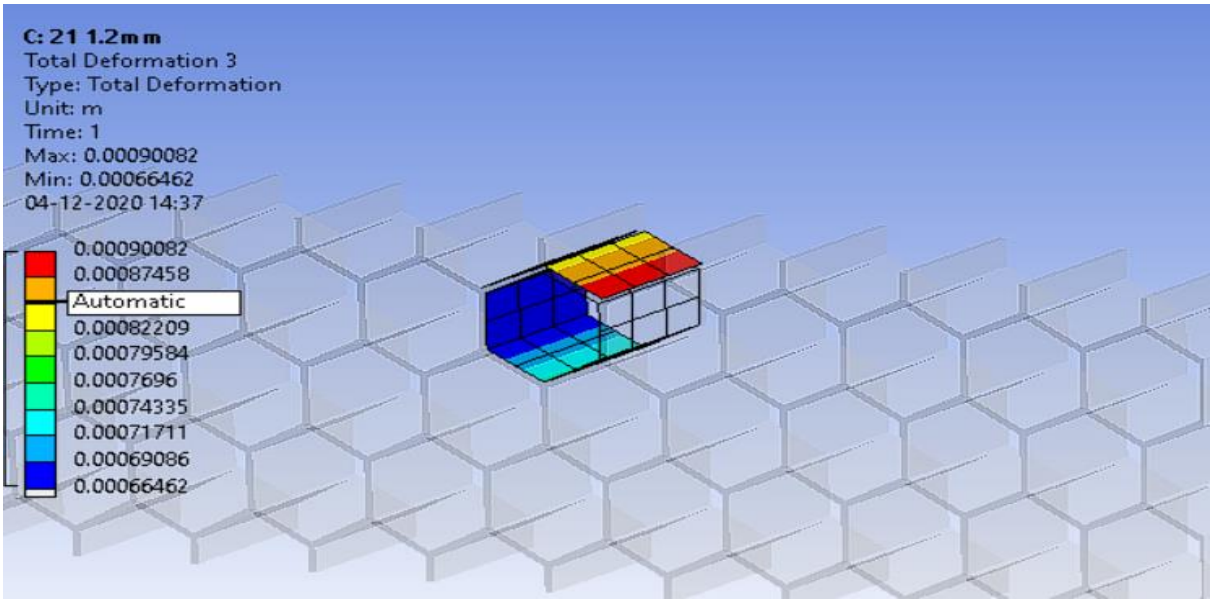

Figure 50 Mid-Cell deformation of regular Vertical cell-orientation Honeycomb Structure (21,1.2)

- Minimum Deformation- 6.6462e-004 m
- Maximum Deformation-9.0082e-004 m
- Average Deformation- 7.8991e-004 m

- **Horizontal cell orientation**

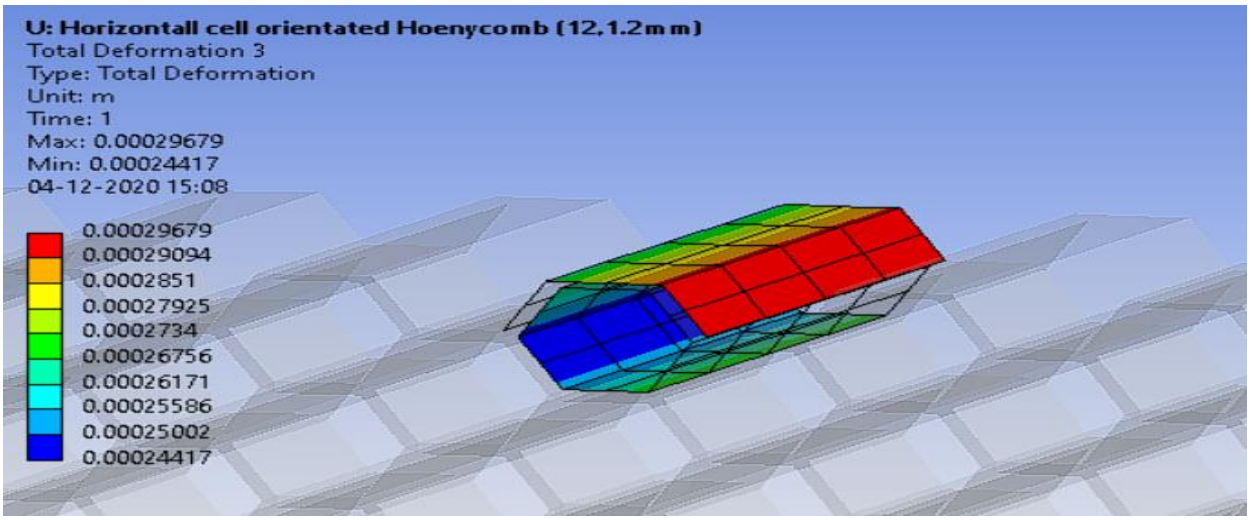

Figure 51 Mid-Cell deformation of regular Horizontal cell-orientation Honeycomb Structure (12,1.2)

- Minimum Deformation-2.4417e-004 m
- Maximum Deformation - 2.9679e-004 m
- Average Deformation- 2.7226e-004 m

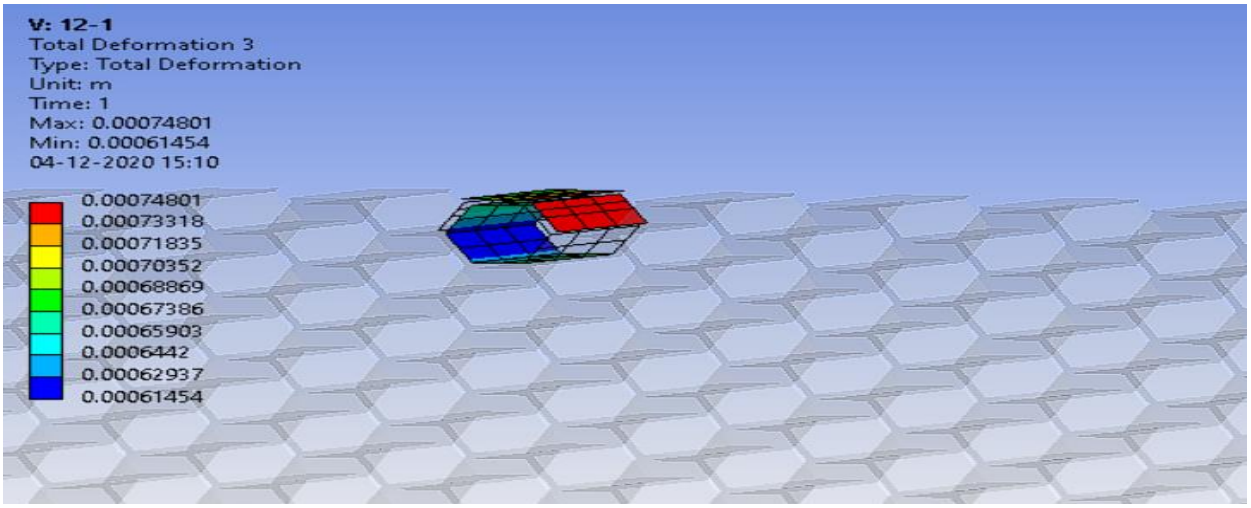

Figure 52 Mid-Cell deformation of regular Horizontal cell-orientation Honeycomb Structure (12,1)

- Minimum Deformation-6.1454e-004 m
- Maximum Deformation - 7.4801e-004 m
- Average Deformation- 6.897e-004 m

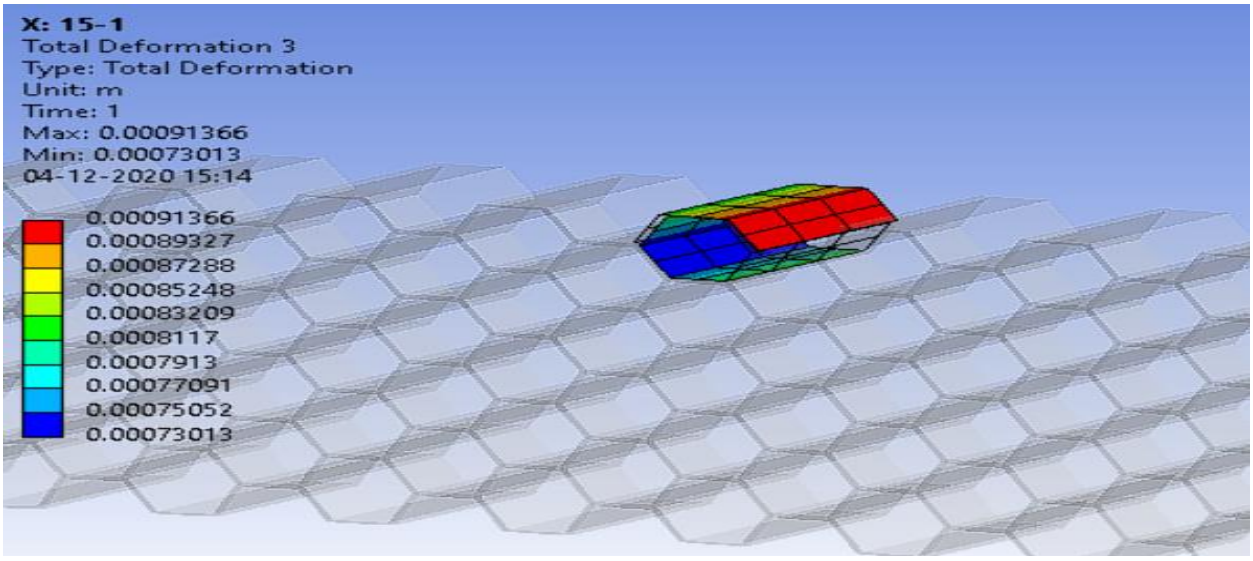

Figure 53 Mid-Cell deformation of regular Horizontal cell-orientation Honeycomb Structure (15,1)

- Minimum Deformation-7.3013e-004 m
- Maximum Deformation - 9.1366e-004 m
- Average Deformation- 8.269e-004 m

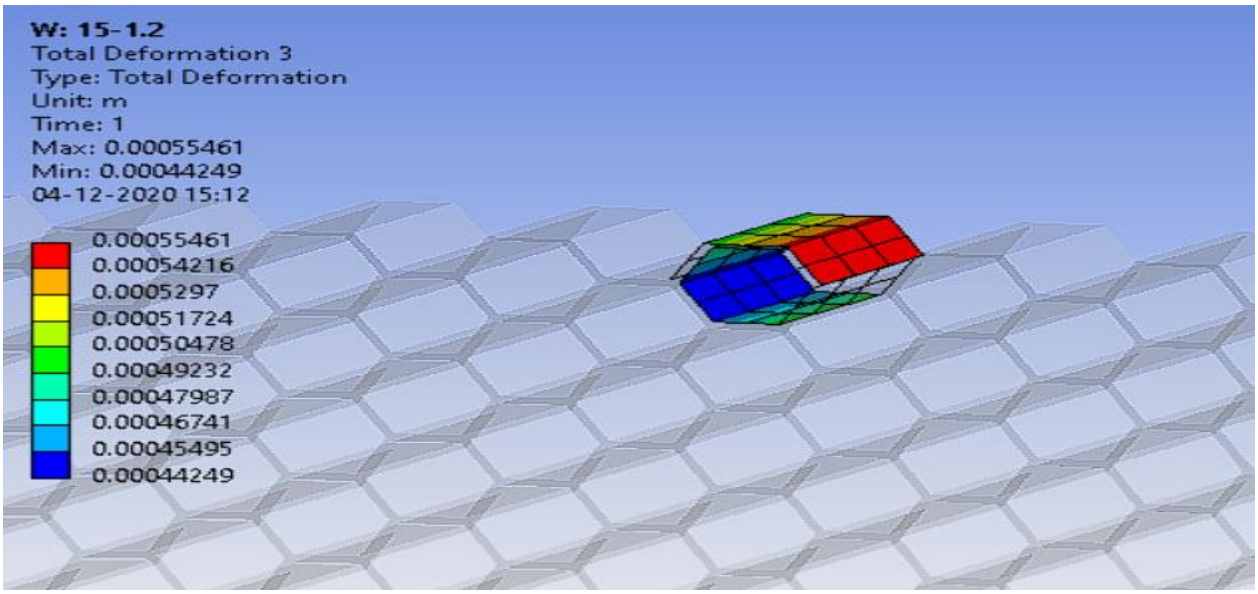

Figure 54 Mid-Cell deformation of regular Horizontal cell-orientation Honeycomb Structure (15,1.2)

- Minimum Deformation-4.4249e-004 m
- Maximum Deformation - 5.5461e-004 m
- Average Deformation- 5.032e-004 m

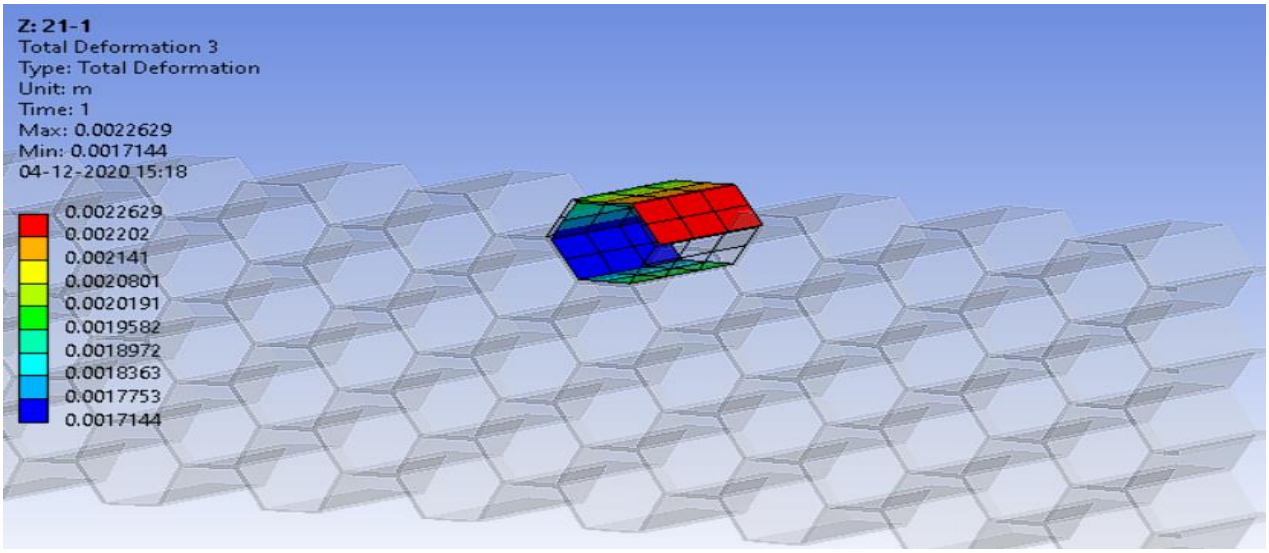

Figure 55 Mid-Cell deformation of regular Horizontal cell-orientation Honeycomb Structure (21,1)

- Minimum Deformation- 1.7144e-003 m
- Maximum Deformation-2.2629e-003 m
- Average Deformation- 2.0138e-003 m

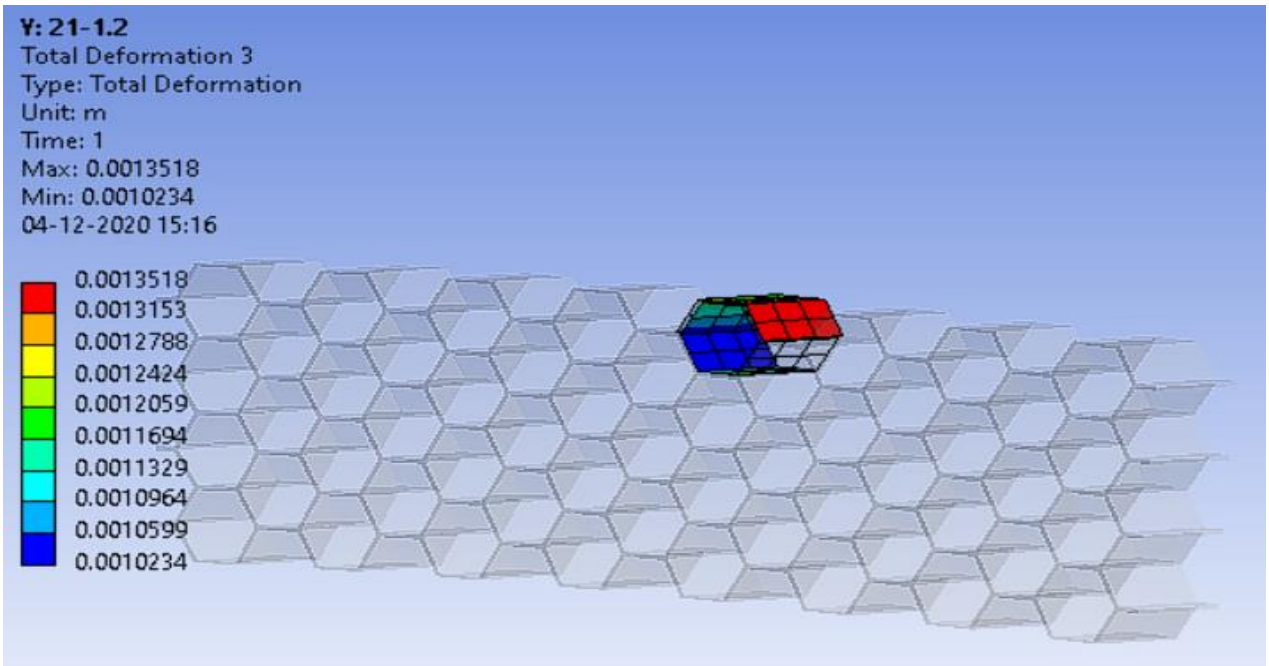

Figure 56 Mid-Cell deformation of regular Horizontal cell-orientation Honeycomb Structure (21,1.2)

- Minimum Deformation- 1.0234e-003 m
- Maximum Deformation-1.3518e-003 m
- Average Deformation- 1.2022e-003 m

Chapter 4
Design of Gradient Honeycomb Structure

- **Vertical cell orientation**

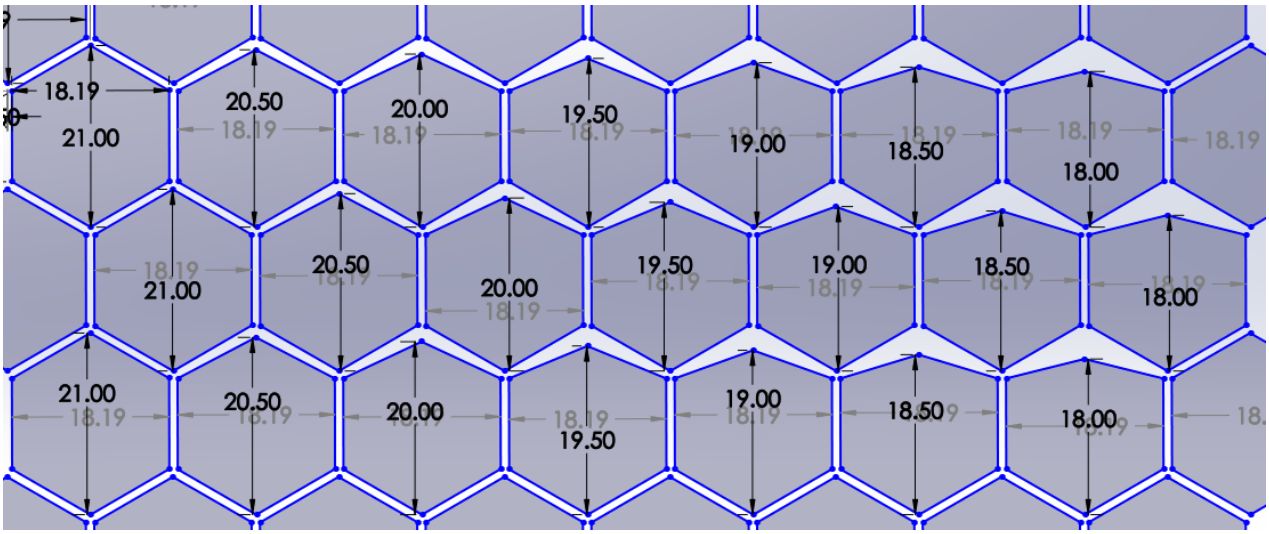

Figure 57 Cell dimensions of Vertical cell oriented Gradient Honeycomb Structure.

- The total length and width of structure are 127.33 mm and 52.5mm respectively. The thickness of whole structure is 30mm.
- Along the length, diagonal length of hexagonal cell is decreased uniformly by 0.5mm by keeping cell size constant i.e., 21mm.

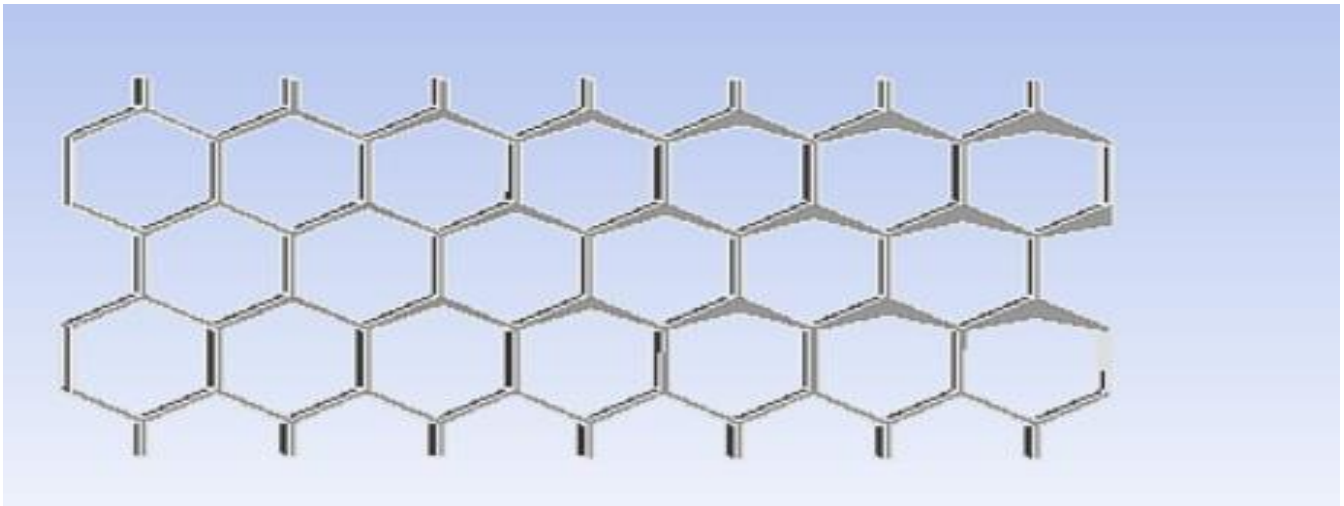

Figure 58 Vertical cell oriented Gradient Honeycomb Structure

- **Horizontal cell orientation**

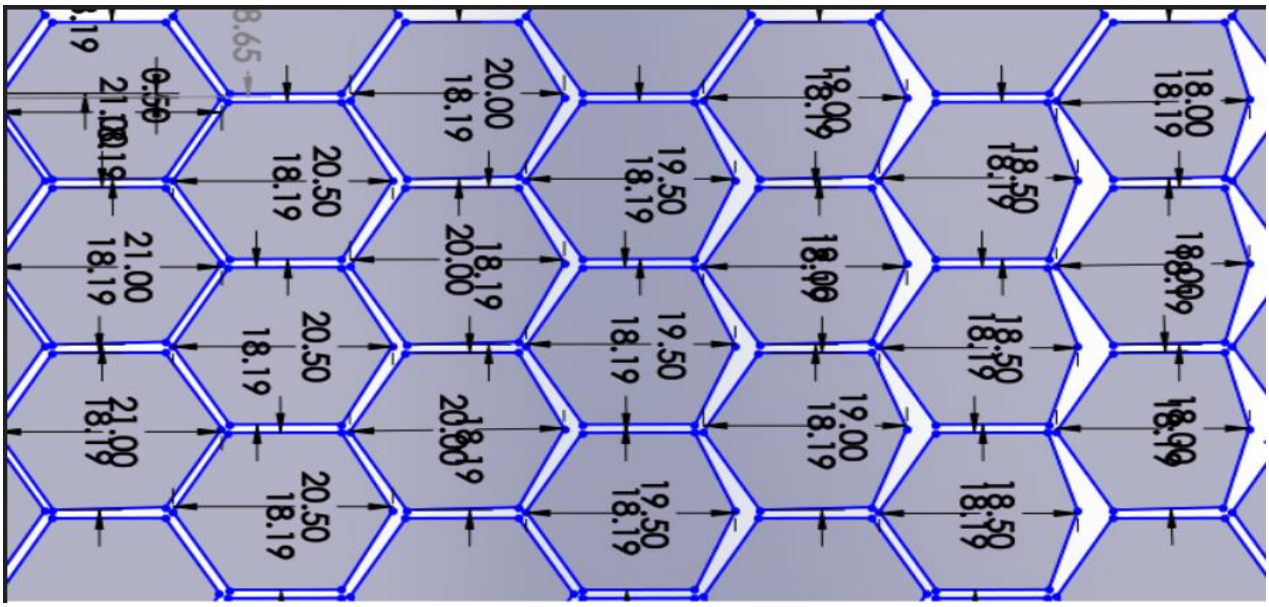

Figure 59 Cell dimensions of Horizontal cell oriented Gradient Honeycomb Structure.

- The total length and width of structure are 107.25 mm and 60.6mm respectively. The thickness of whole structure is 30mm.
- Along the length, diagonal length of hexagonal cell is decreased uniformly by 0.5mm by keeping cell size constant i.e., 21mm.

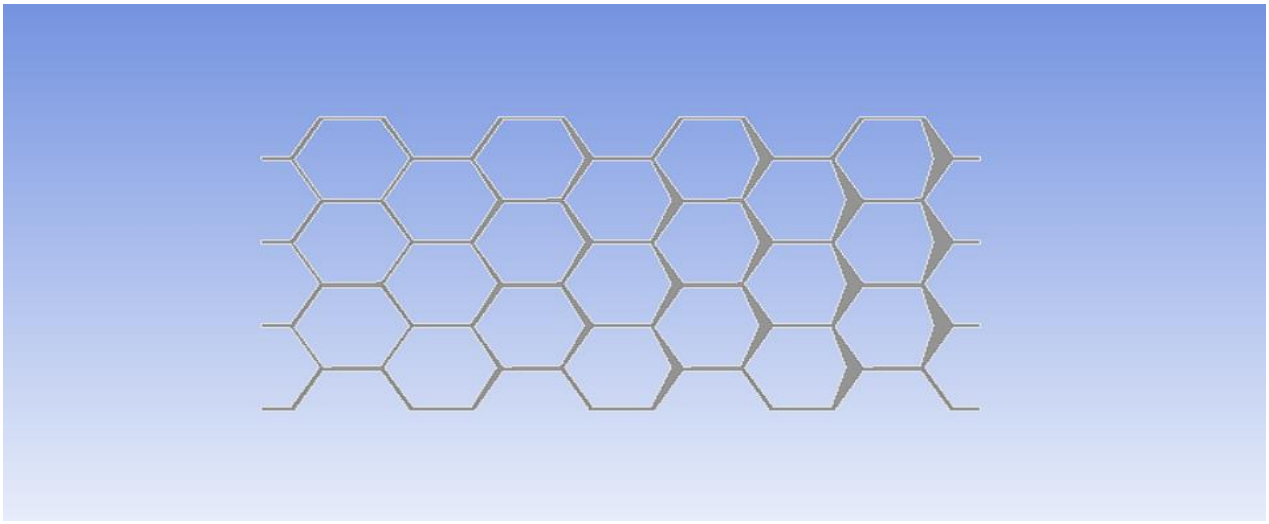

Figure 60 Horizontal cell oriented Gradient Honeycomb Structure

Deformation of Gradient Honeycomb structure (Vertical and Horizontal cell orientation).

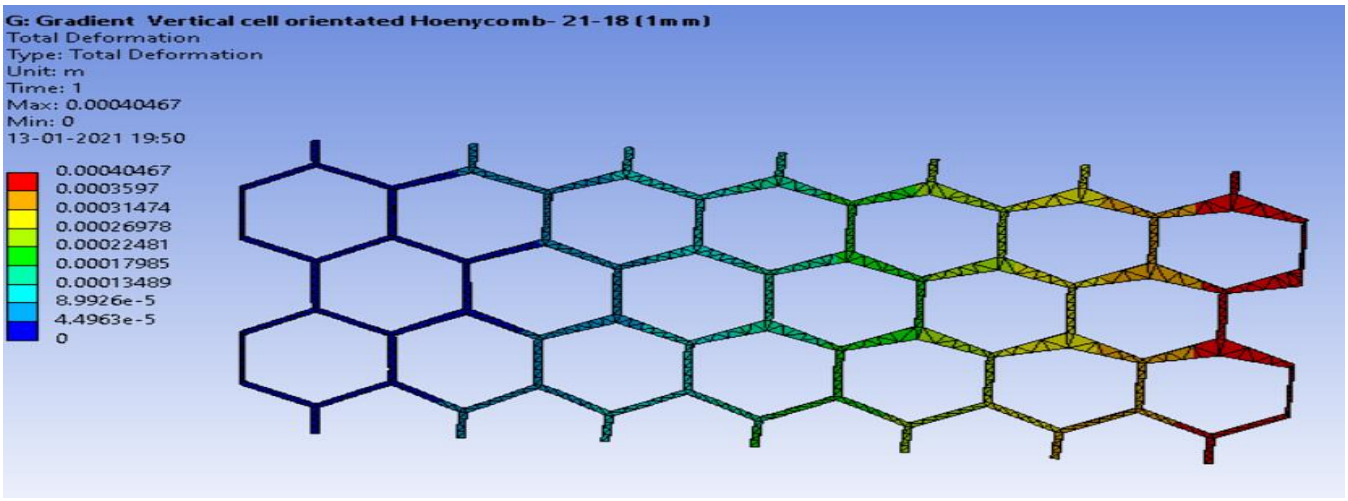

Figure 61 Total Deformation of Gradient Honeycomb Structure (Vertical cell orientation)

- Maximum Deformation=0.00040467m
- Average deformation= 0.00016616m
- Minimum Deformation =0m

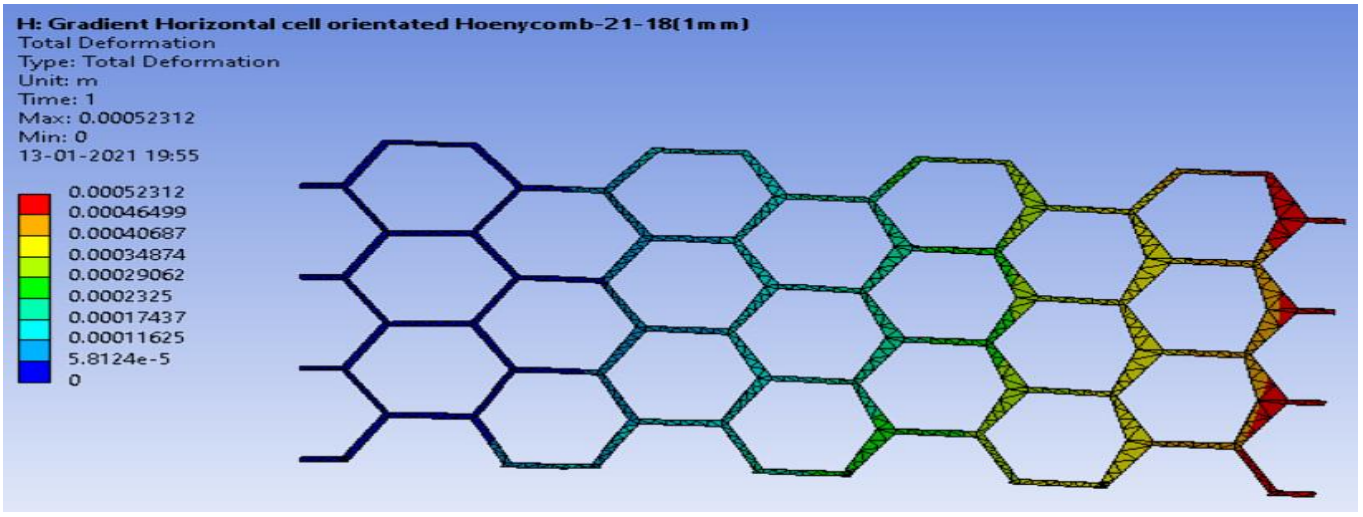

Figure 62 Total Deformation of Gradient Honeycomb Structure (Horizontal cell orientation)

- Maximum Deformation=0.00052312
- Average deformation=0.00020044
- Minimum Deformation =0m

End cell Deformation in Gradient Honeycomb Structures

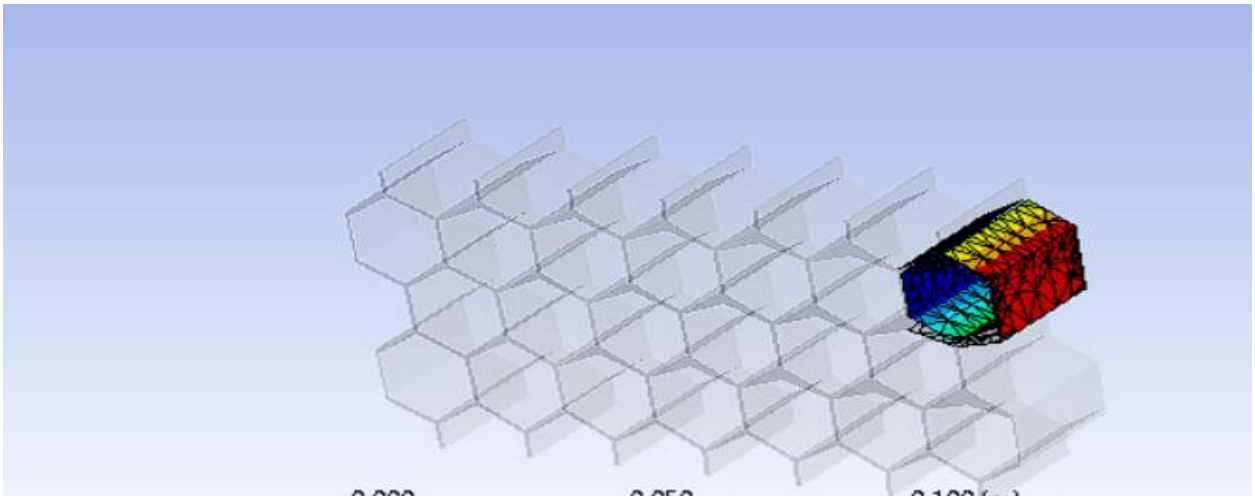

Figure 63 End cell Deformation of Gradient Honeycomb Structure (Vertical cell orientation)

- Maximum Deformation=0.00040467m
- Average deformation=0.00037639m
- Minimum Deformation =0.00033413m

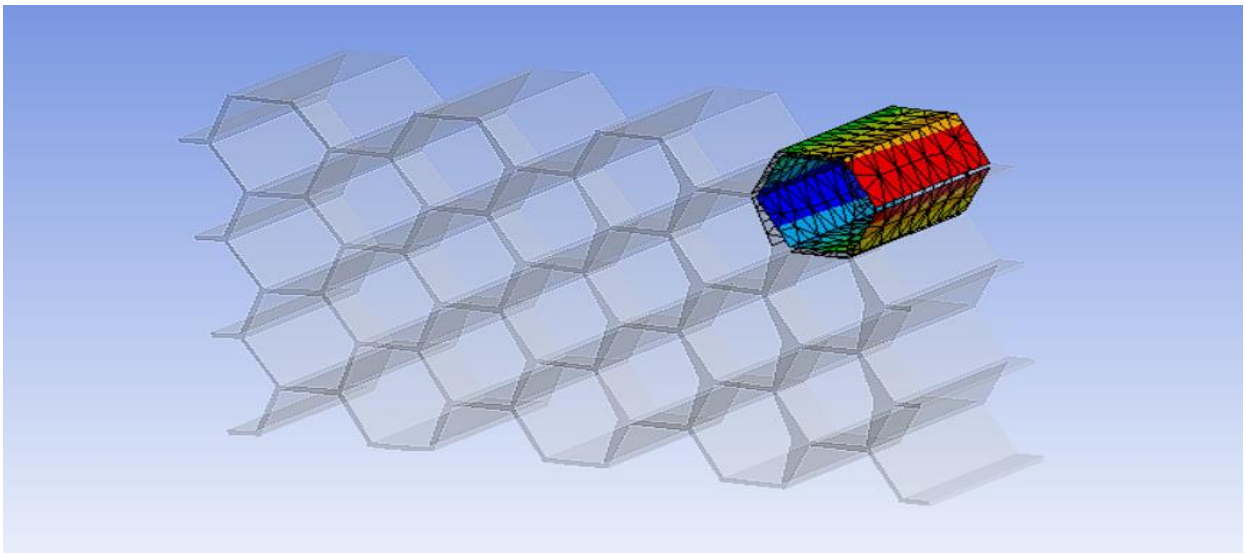

Figure 64 End cell Deformation of Gradient Honeycomb Structure (Horizontal cell orientation)

- Maximum Deformation=0.00049291m
- Average deformation= 0.00043414m
- Minimum Deformation =0.0003787m

Mid-cell Deformation in Gradient Honeycomb Structures

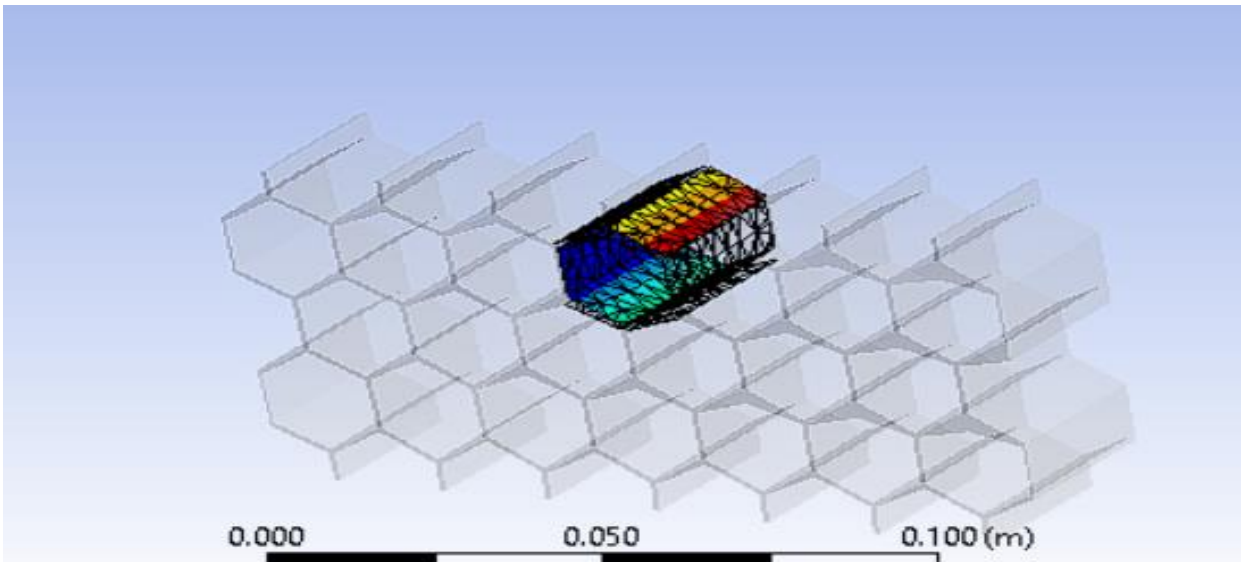

Figure 65 Mid-cell Deformation of Gradient Honeycomb Structure (Vertical cell orientation)

- Maximum Deformation=0.00018976m
- Average deformation=0.00015174m
- Minimum Deformation =0.0001115m

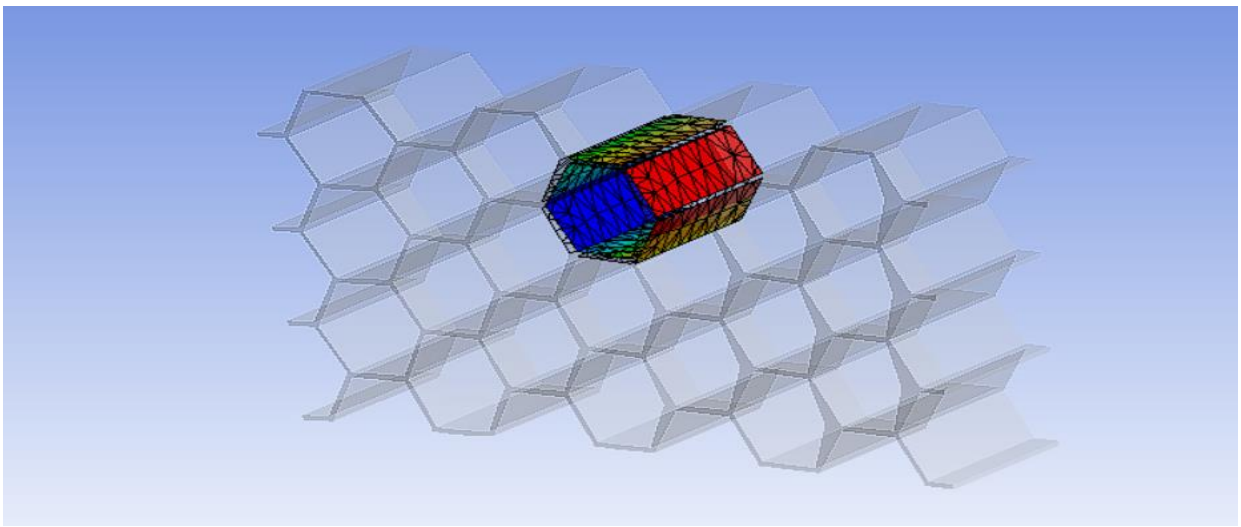

Figure 66 Mid-cell Deformation of Gradient Honeycomb Structure (Horizontal cell orientation)

- Maximum Deformation=0.00022795m
- Average deformation=0.00017764m
- Minimum Deformation =0.00012406m

Modal Analysis of Gradient Honeycomb Structure

- **Vertical cell orientation**

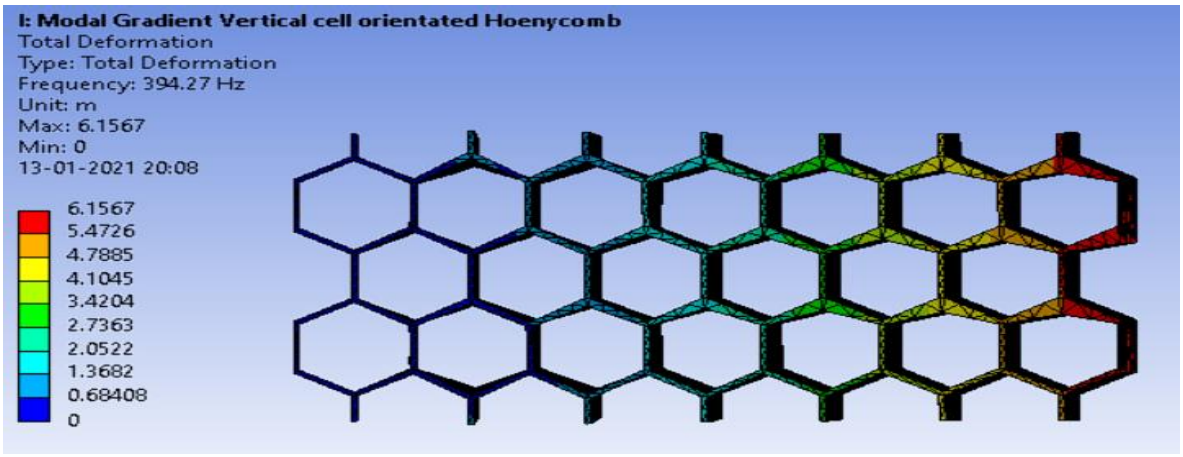

Figure 67 First modal shape deformation of gradient Honeycomb Structure (Vertical cell orientation)

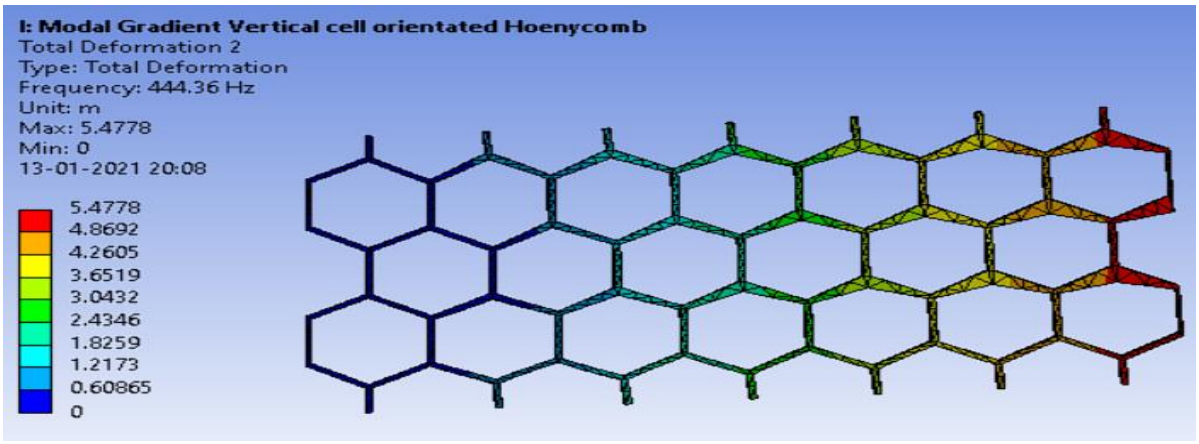

Figure 68 Second modal shape deformation of gradient Honeycomb Structure (Vertical cell orientation)

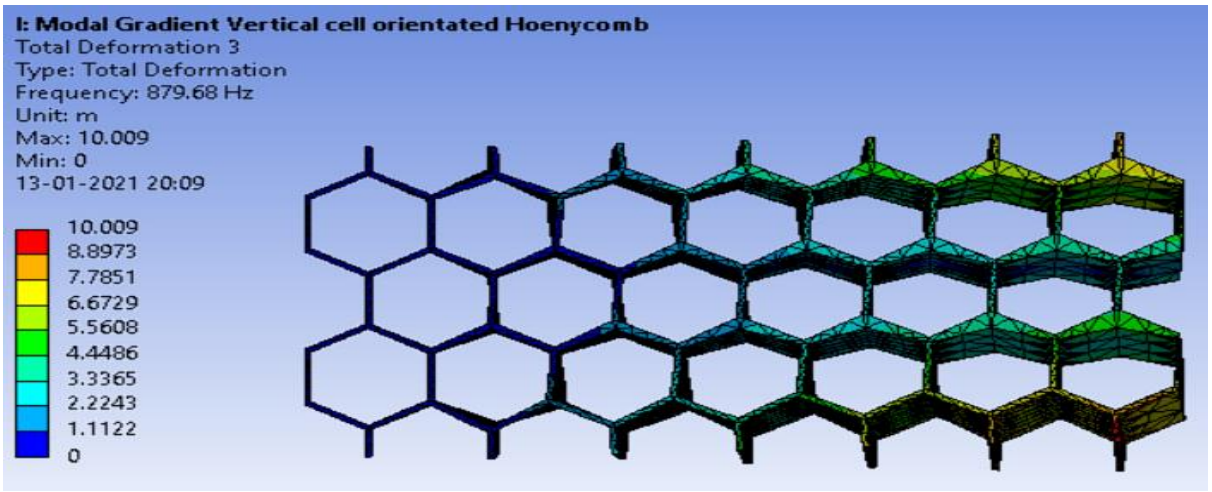

Figure 69 Third modal shape deformation of gradient Honeycomb Structure (Vertical cell orientation)

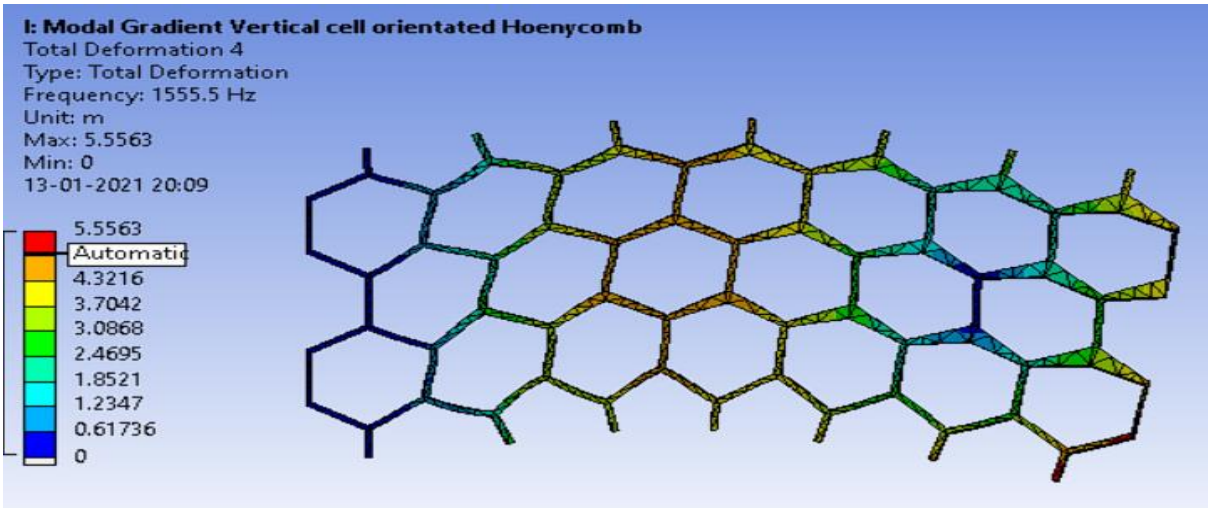

Figure 70 Fourth modal shape deformation of gradient Honeycomb Structure (Vertical cell orientation)

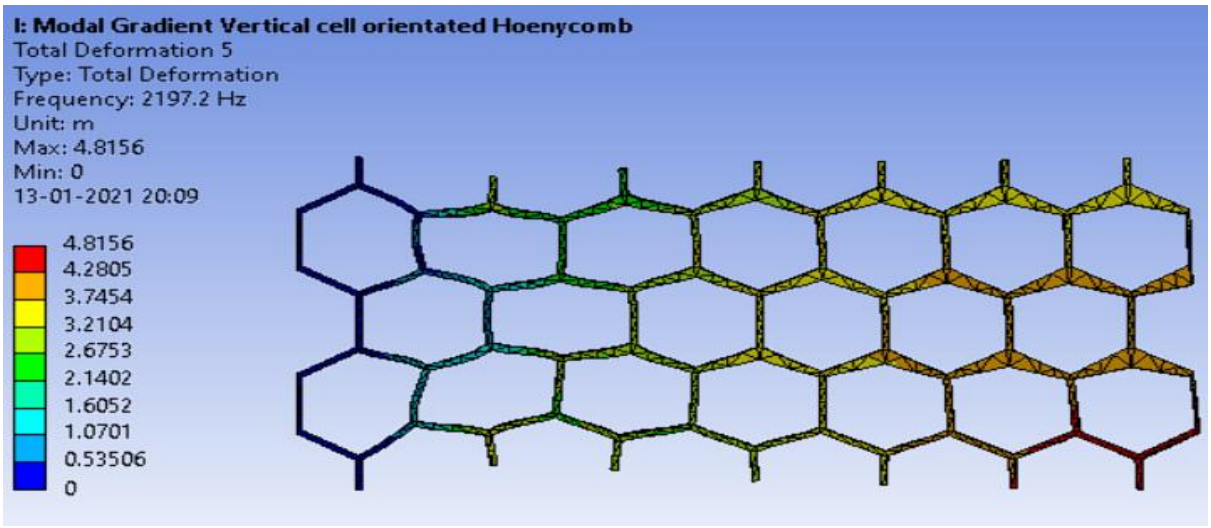

Figure 71 Fifth modal shape deformation of gradient Honeycomb Structure (Vertical cell orientation)

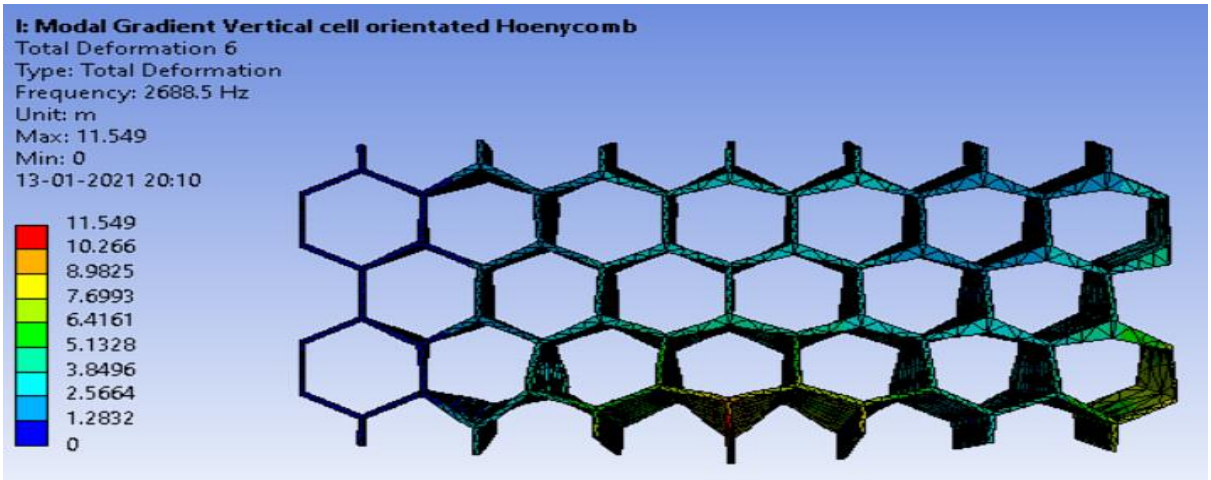

Figure 72 Sixth modal shape deformation of gradient Honeycomb Structure (Vertical cell orientation)

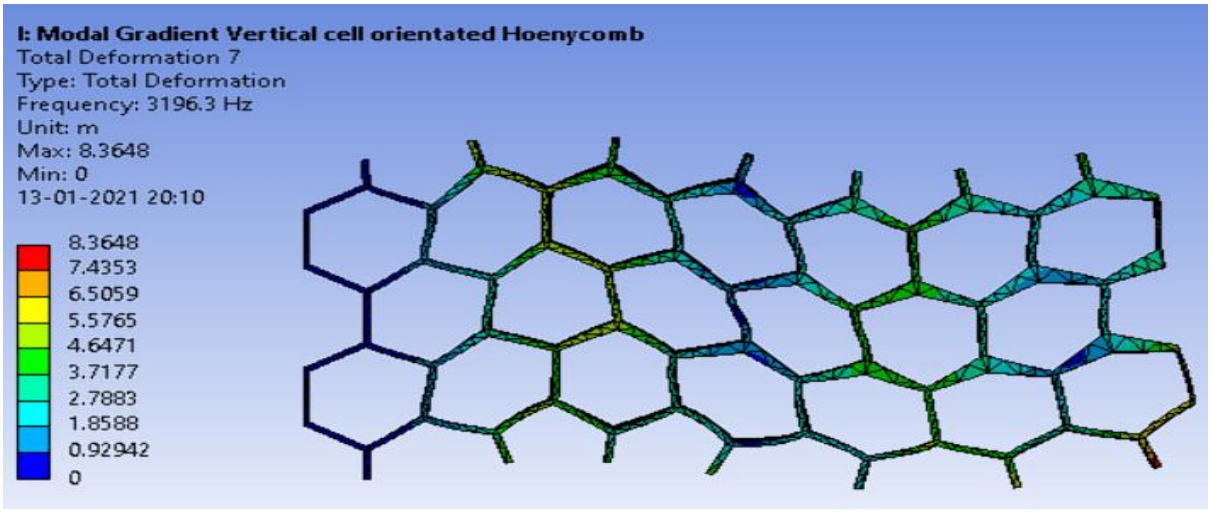

Figure 73 Seventh modal shape deformation of gradient Honeycomb Structure (Vertical cell orientation)

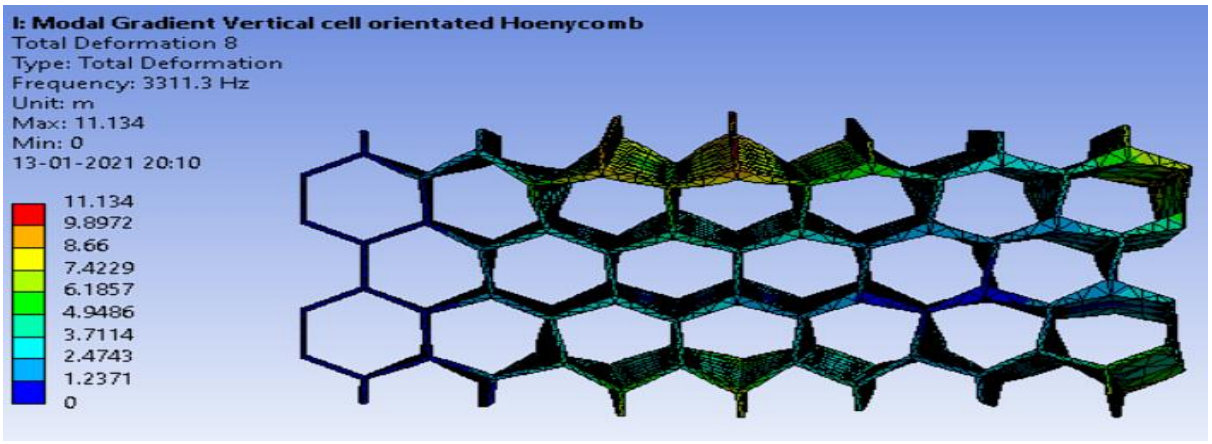

Figure 74 Eight modal shape deformation of gradient Honeycomb Structure (Vertical cell orientation)

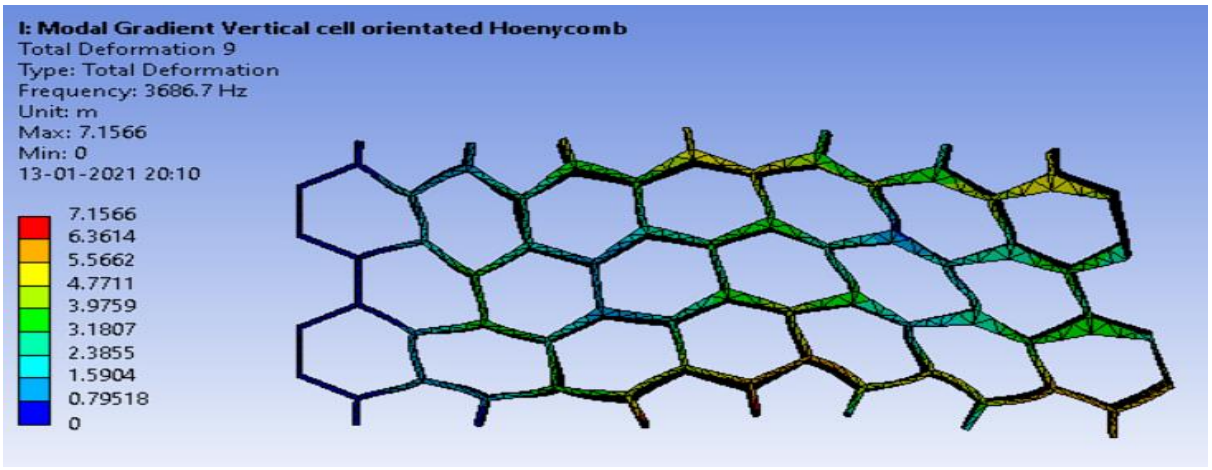

Figure 75 Ninth modal shape deformation of gradient Honeycomb Structure (Vertical cell orientation)

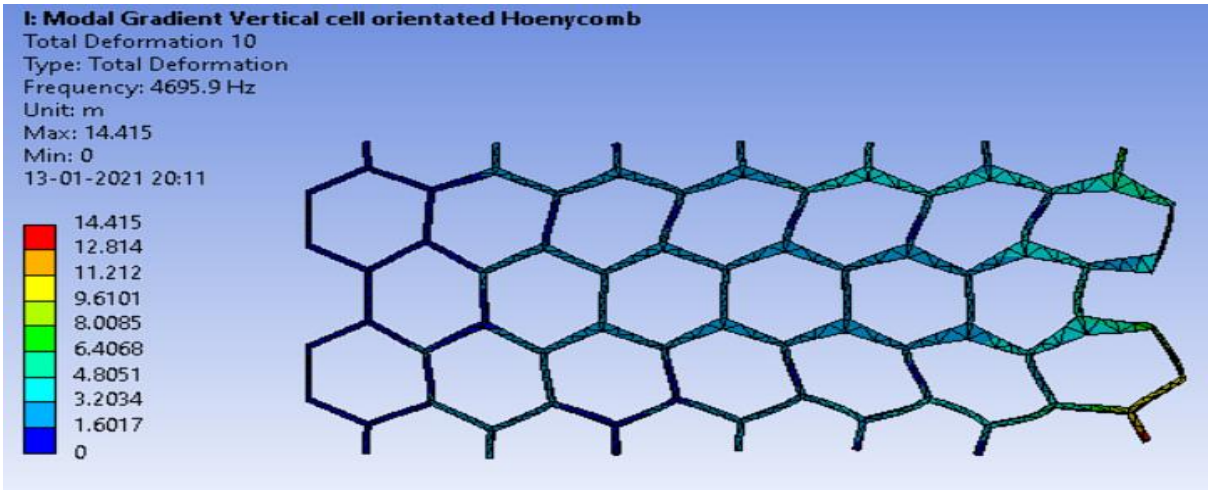

Figure 76 Tenth modal shape deformation of gradient Honeycomb Structure (Vertical cell orientation)

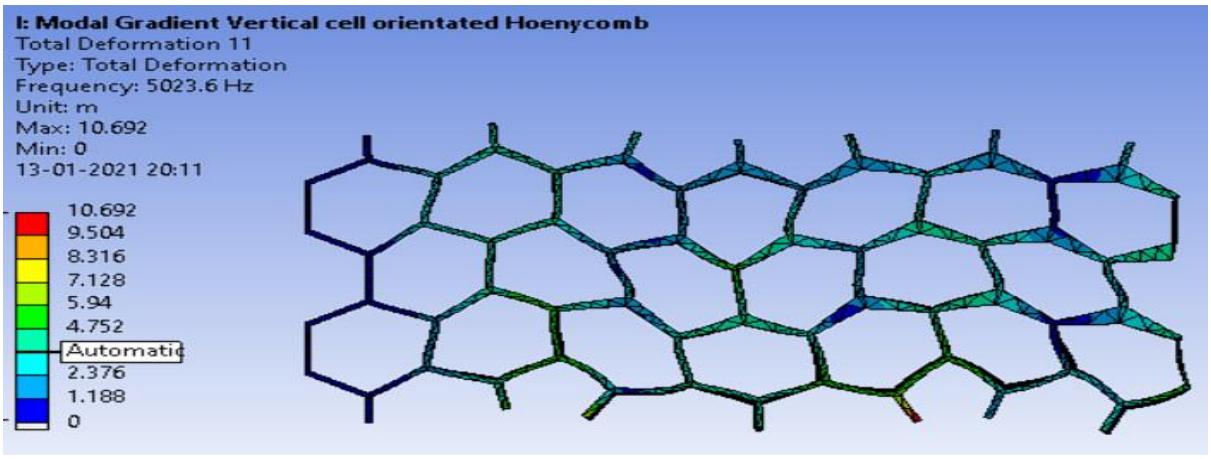

Figure 77 Eleventh modal shape deformation of gradient Honeycomb Structure (Vertical cell orientation)

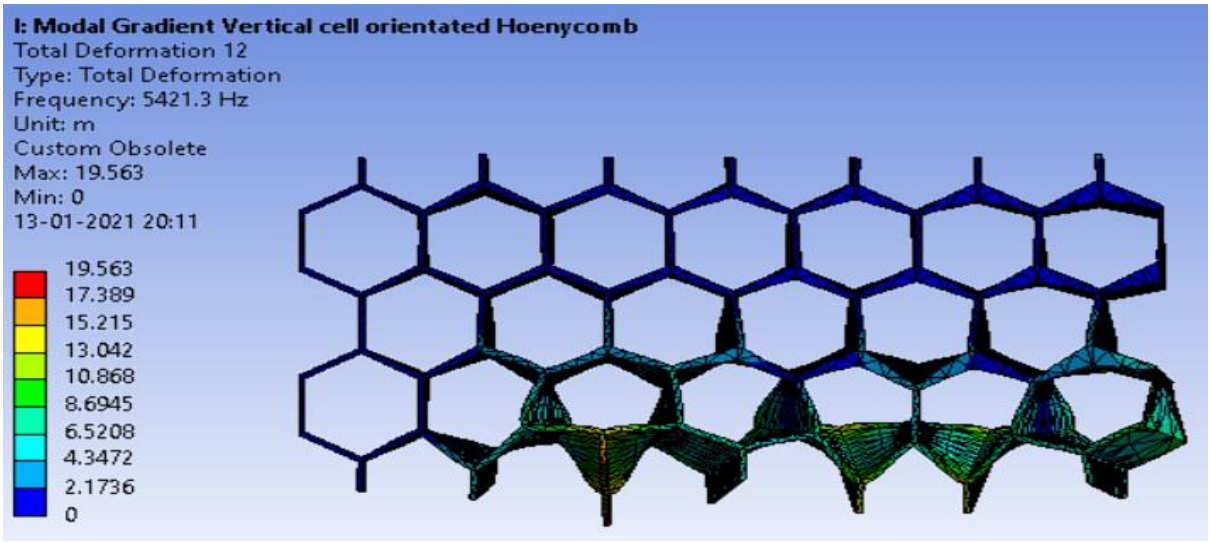

Figure 78 Twelfth modal shape deformation of gradient Honeycomb Structure (Vertical cell orientation)

- **Horizontal Cell orientation**

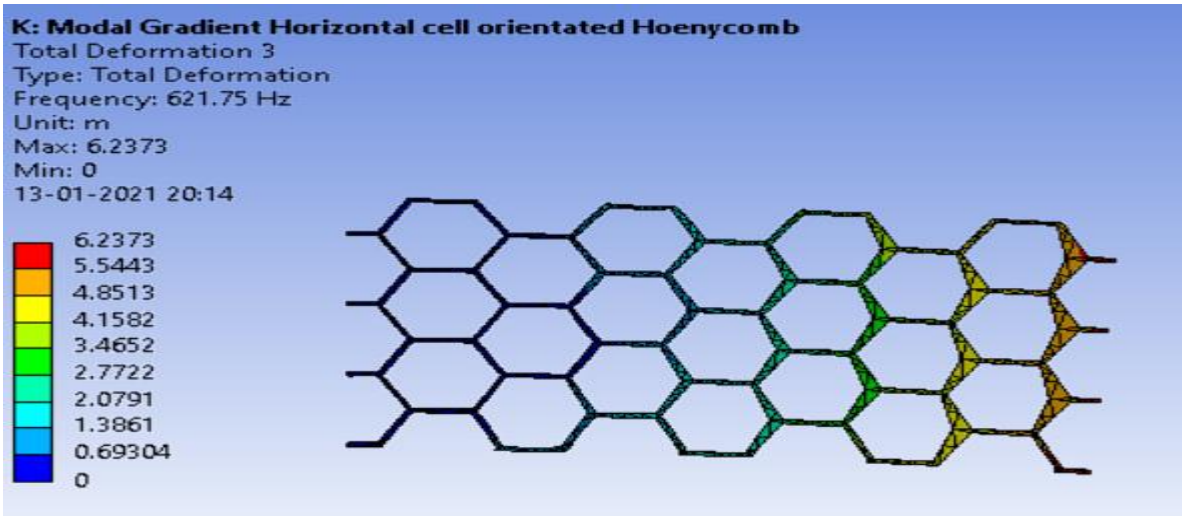

Figure 79 First modal shape deformation of gradient Honeycomb Structure (Horizontal cell orientation)

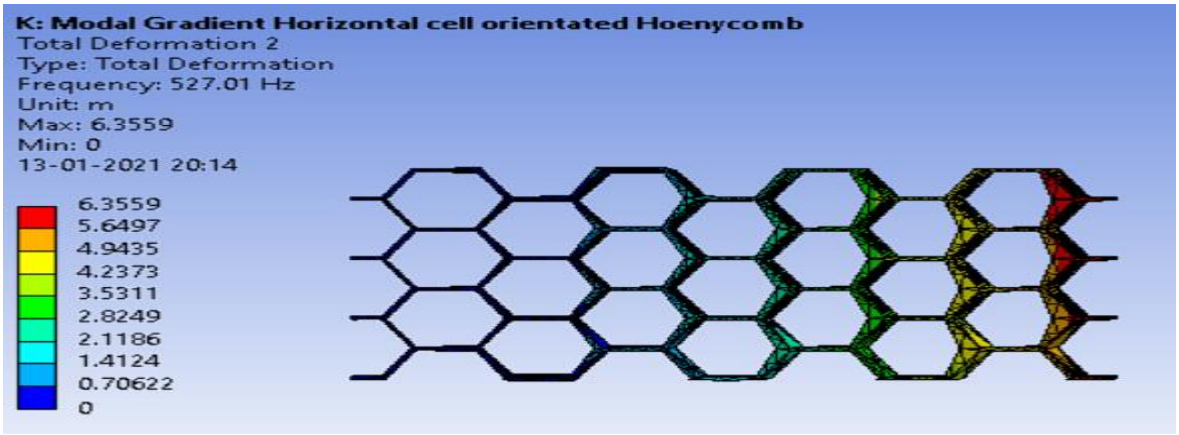

Figure 80 Second modal shape deformation of gradient Honeycomb Structure (Horizontal cell orientation)

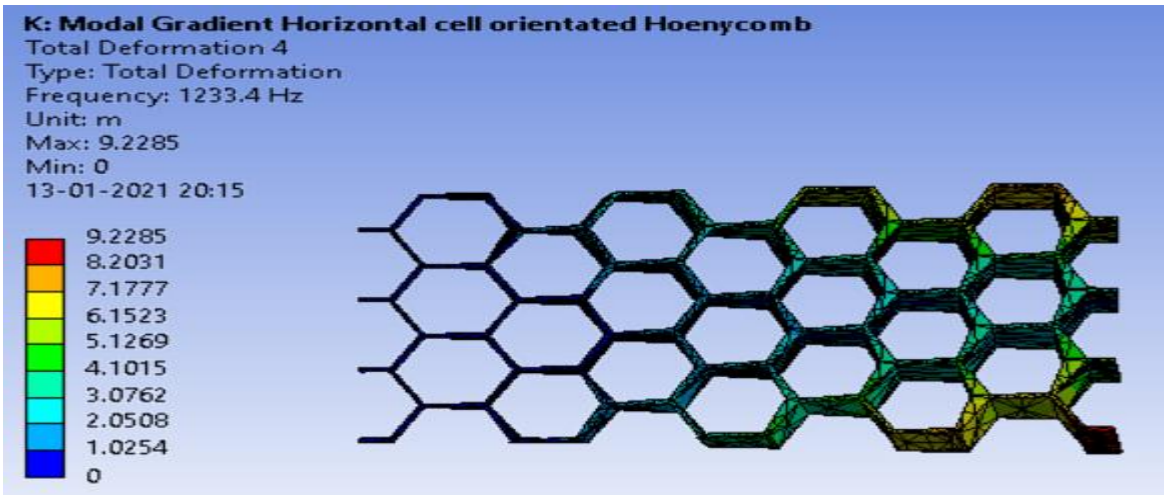

Figure 81 Third modal shape deformation of gradient Honeycomb Structure (Horizontal cell orientation)

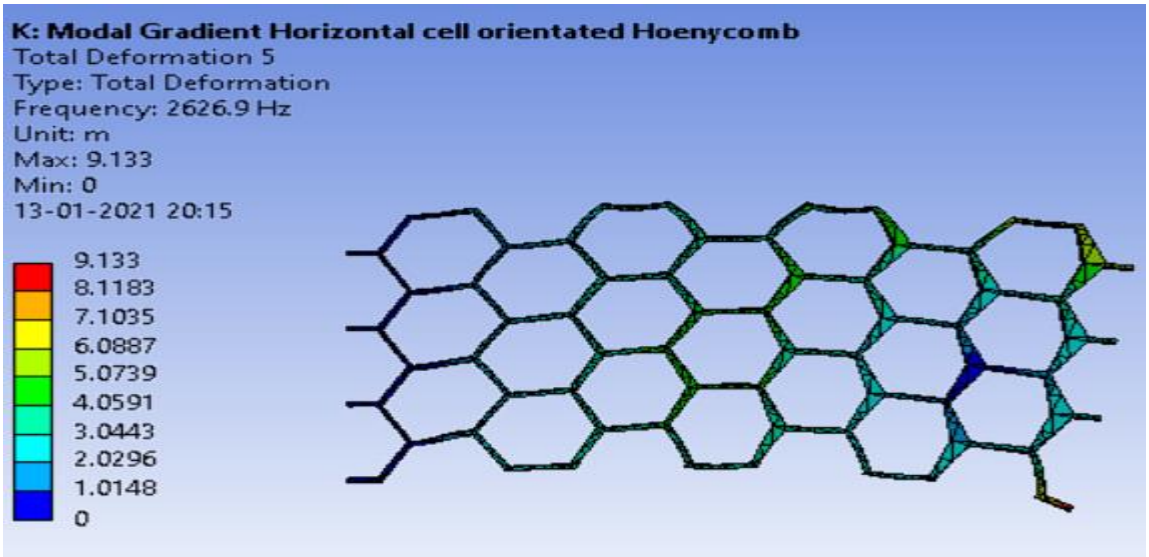

Figure 82 Fourth modal shape deformation of gradient Honeycomb Structure (Horizontal cell orientation)

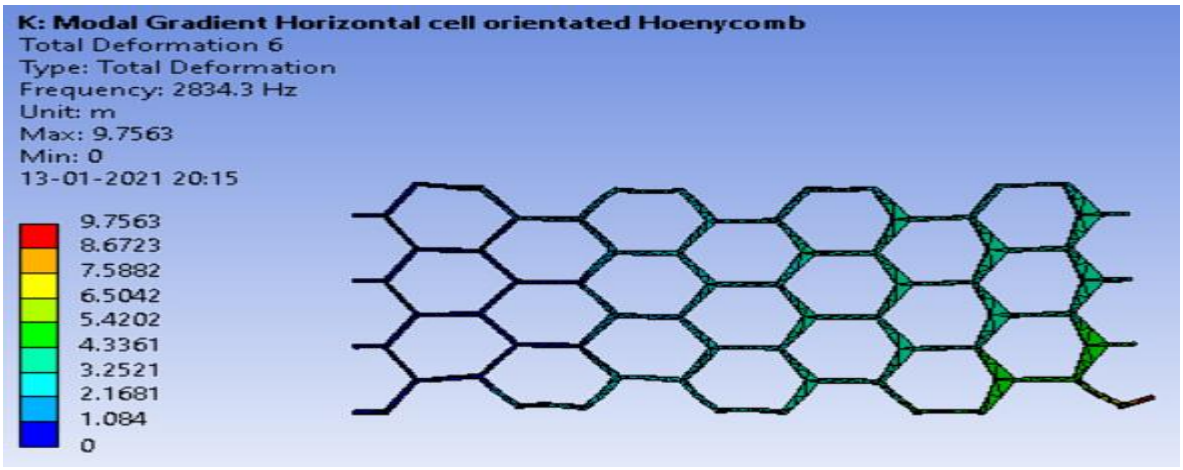

Figure 83 Fifth modal shape deformation of gradient Honeycomb Structure (Horizontal cell orientation)

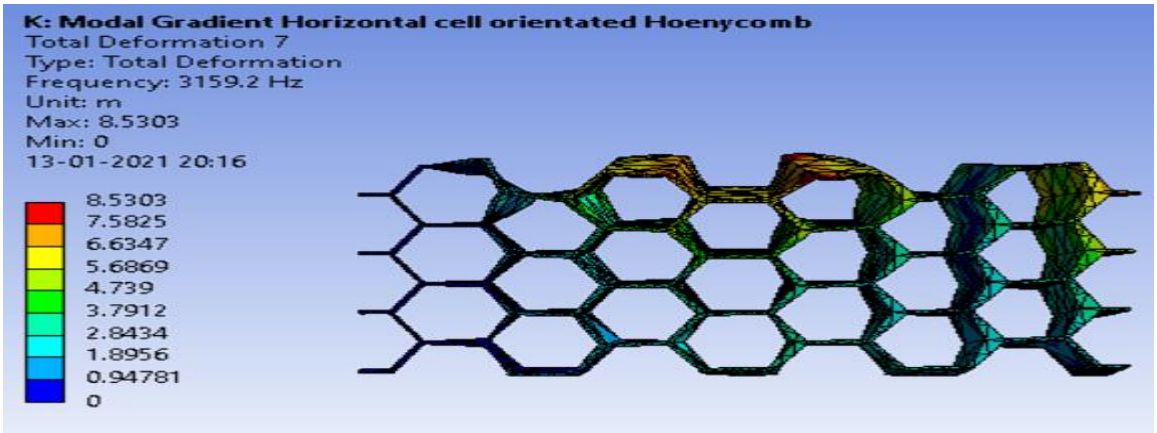

Figure 84 Sixth modal shape deformation of gradient Honeycomb Structure (Horizontal cell orientation

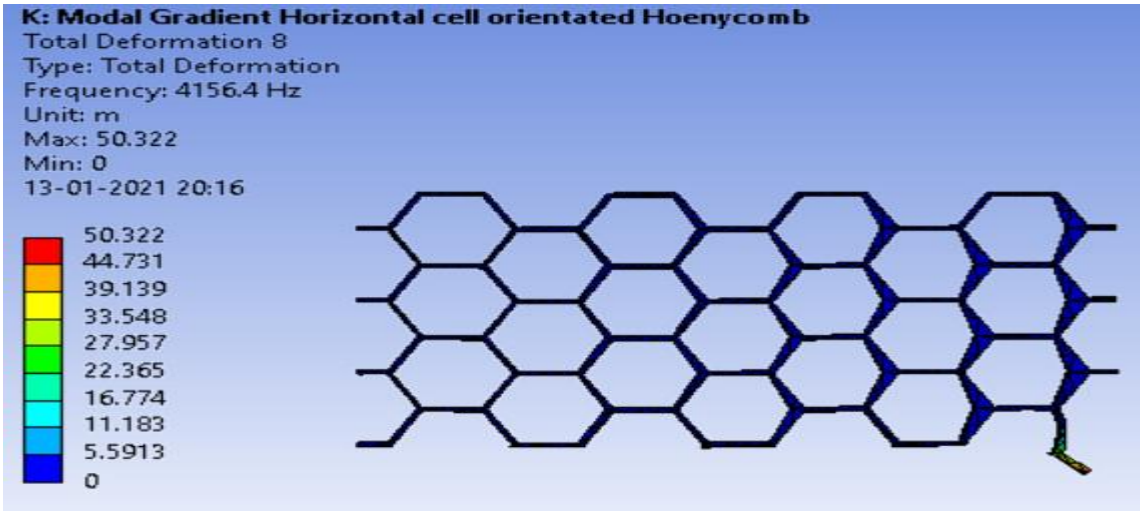

Figure 85 Seventh modal shape deformation of gradient Honeycomb Structure (Horizontal cell orientation)

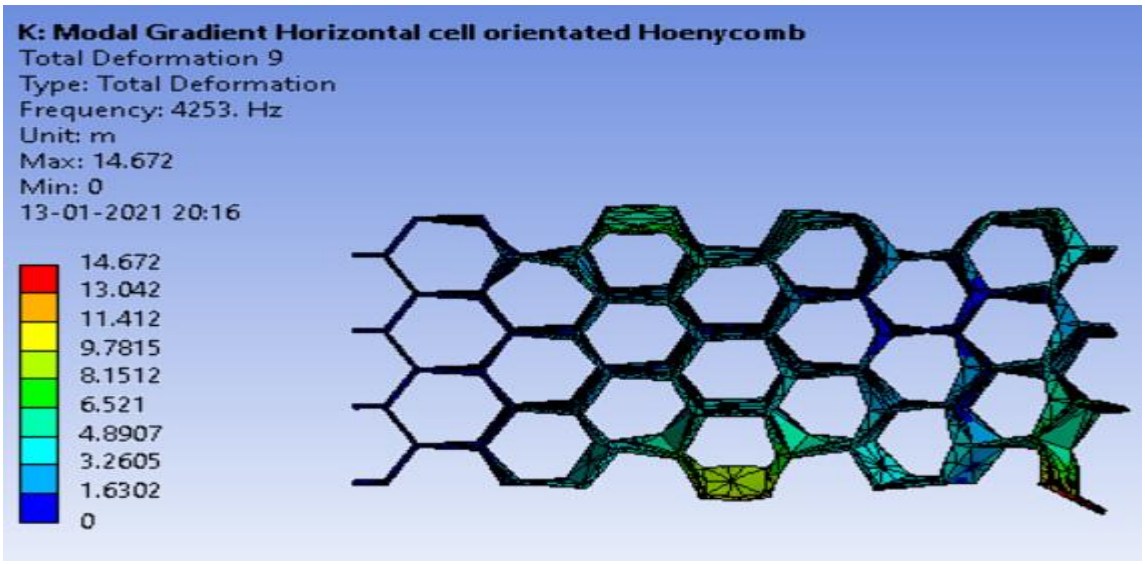

Figure 86 Eighth modal shape deformation of gradient Honeycomb Structure (Horizontal cell orientation)

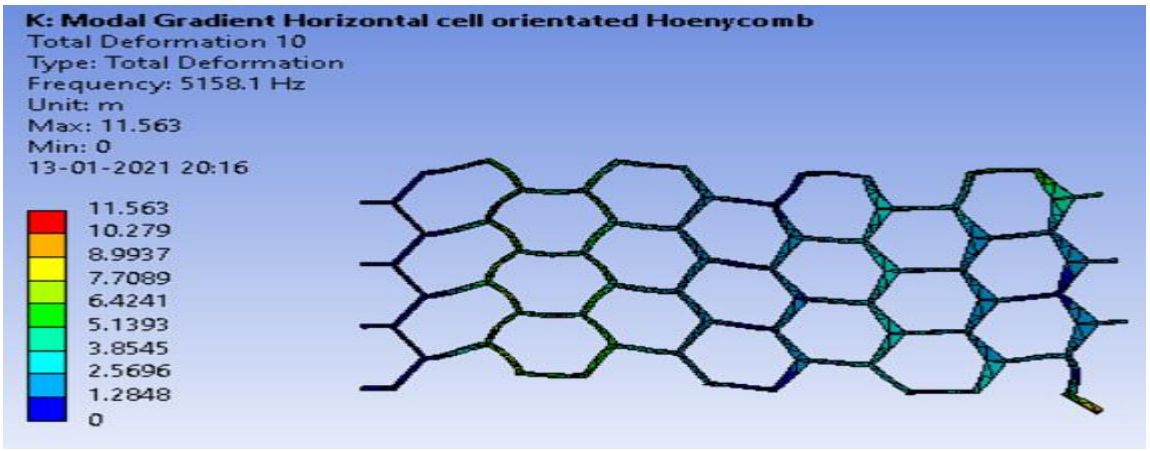

Figure 87 Ninth modal shape deformation of gradient Honeycomb Structure (Horizontal cell orientation)

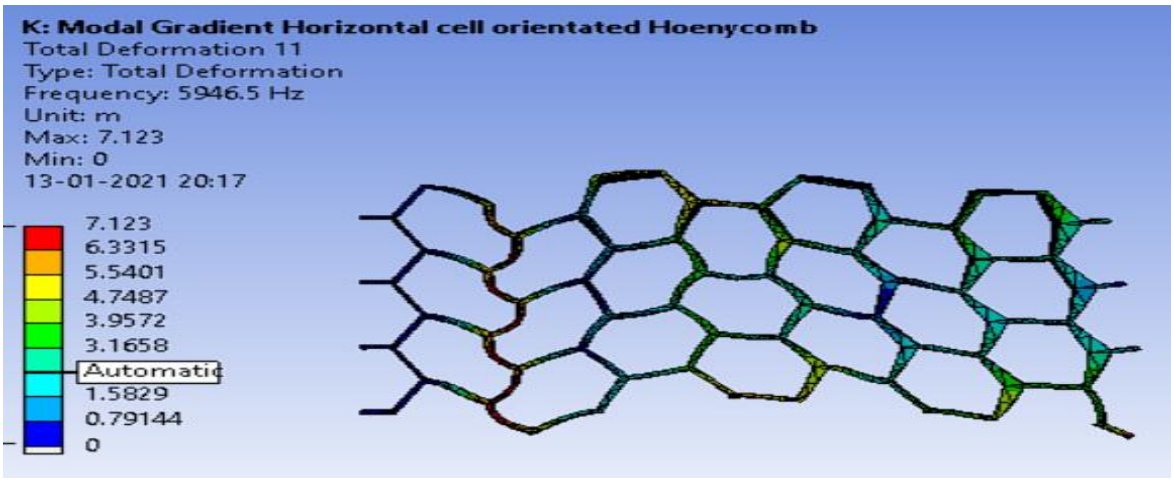

Figure 88 Tenth modal shape deformation of gradient Honeycomb Structure (Horizontal cell orientation)

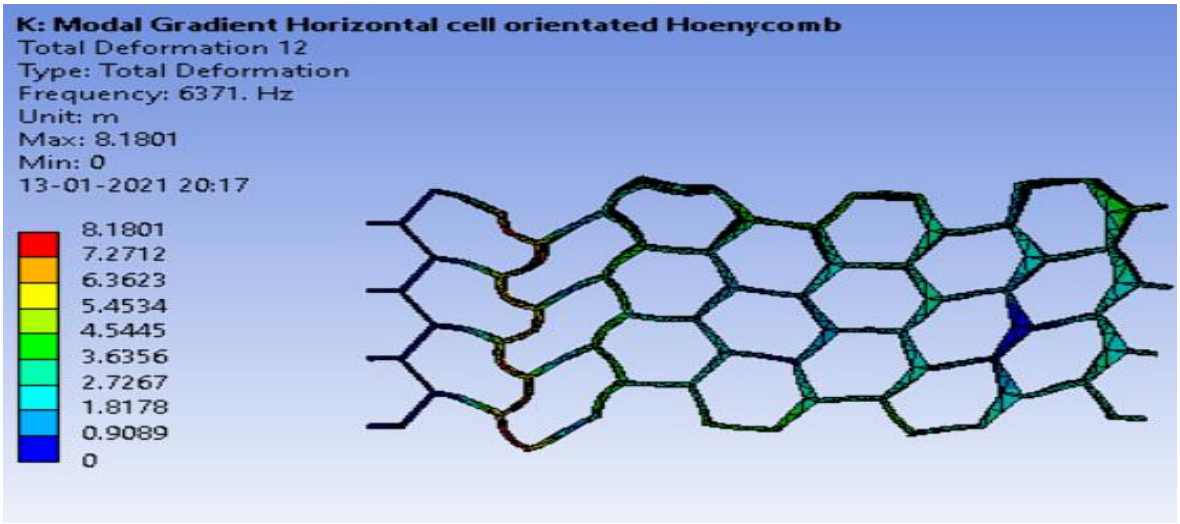

Figure 89 Eleventh modal shape deformation of gradient Honeycomb Structure (Horizontal cell orientation)

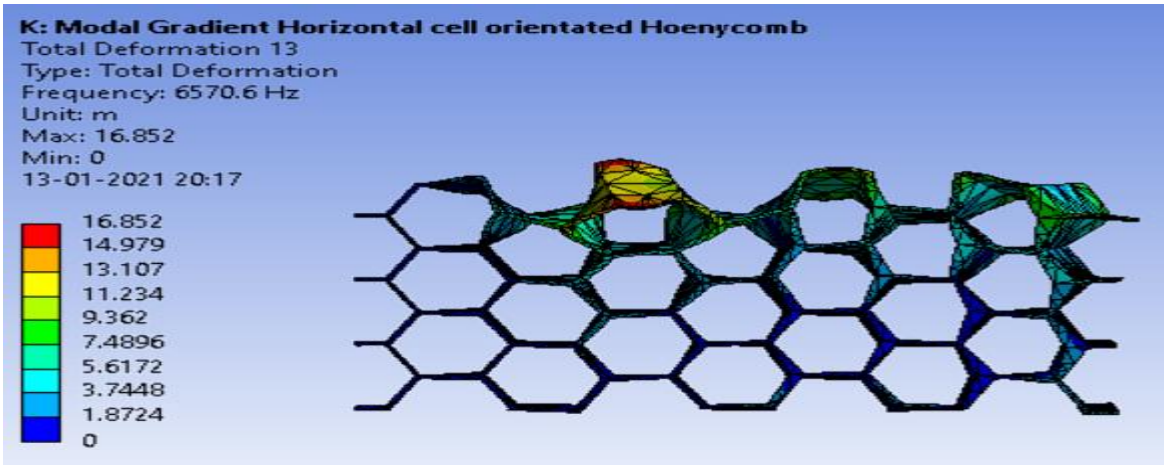

Figure 90 Twelfth modal shape deformation of gradient Honeycomb Structure (Horizontal cell orientation

Vertical Cell Orientation			Horizontal Cell Orientation	
Mode	**Frequency (HZ)**	**Type of Mode**	**Mode**	**Frequency (HZ)**
1	399.27	Bending	1	527.01
2	444.36	Bending	2	621.75
3	879.68	Bending	3	1233.4
4	1555.5	Bending +Torsion	4	2626.9
5	2197.5	Bending +Torsion	5	2834.3
6	2688.5	Bending	6	3159.2
7	3196.3	Bending	7	4156.4
8	3311.3	Bending + Torsion	8	4253
9	3686.7	Bending + Torsion	9	5458.1
10	4695.9	Bending + Torsion	10	5946.5
11	5023.6	Bending	11	6371
12	5421.3	Bending	12	6570.6

Table 3 Types of mode and frequency table for gradient Honeycomb structures

- Modal analysis is a technique to study the dynamic characteristics of a structure under vibrational excitation. Natural frequencies, mode shapes and mode vectors of a structure can be determined using modal analysis.

- The modal shape represents the way a structure can deflect. Modal shape for lowest frequency indicates the lower energy state.
- Therefore, if you provide very little input to a system it will deflect as mode shape 1. If you continue increasing energy input it will show two, three or next modal shape depending on the energy. The higher modal shapes require very high energy state which a structure or system may not face in its entire life.

Boundary Conditions

- Honeycomb Structure is fixed at one end and 100N force is applied on the other end of structure.
- Total deformation of structure and cell deformation of different cells in different columns were found out in ANSYS.
- Element type- Linear tetrahedral
- All the simulations are performed at ambient temperature (22 °C)
- Sphere material Properties:

Structural Steel

Fatigue Data at zero mean stress comes from 1998 ASME BPV Code, Section 8, Div 2, Table 5-110.1

Density	7850 kg/m³

Structural

Isotropic Elasticity

Derive from	Young's Modulus and Poisson's Ratio
Young's Modulus	2e+11 Pa
Poisson's Ratio	0.3
Bulk Modulus	1.6667e+11 Pa
Shear Modulus	7.6923e+10 Pa
Isotropic Secant Coefficient of Thermal Expansion	1.2e-05 1/°C
Compressive Ultimate Strength	0 Pa
Compressive Yield Strength	2.5e+08 Pa

- Honeycomb Structure material properties:

Aluminum

Density	2710 kg/m³

Structural

Isotropic Elasticity

Derive from	Young's Modulus and Poisson's Ratio
Young's Modulus	6.8e+10 Pa
Poisson's Ratio	0.32
Bulk Modulus	6.2963e+10 Pa
Shear Modulus	2.5758e+10 Pa

Deformation of Gradient Honeycomb Structure at impact loads

- **Vertical cell orientation**

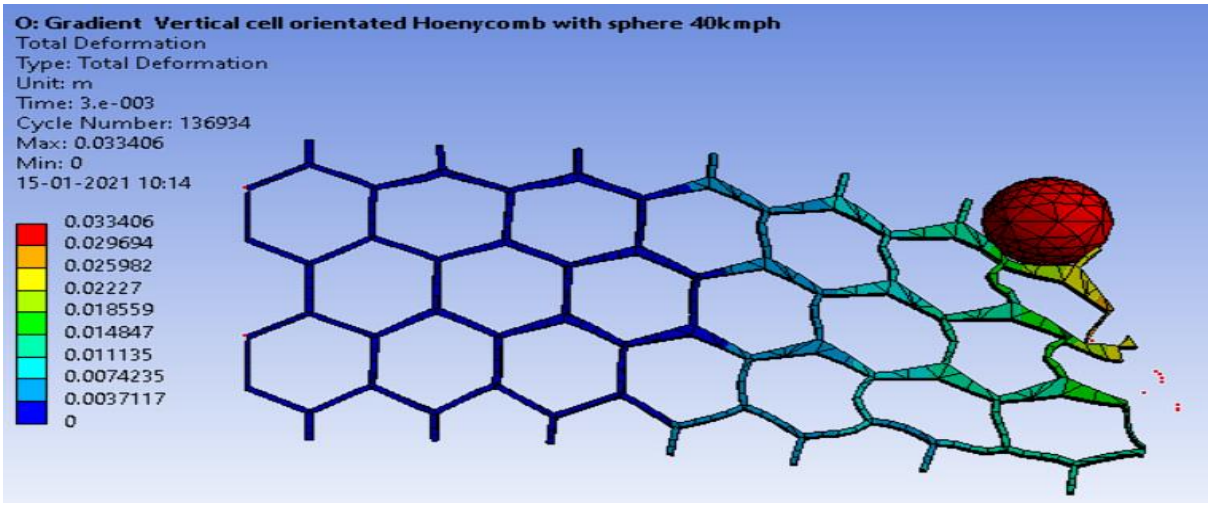

Figure 91 Total Deformation of Honeycomb Gradient (Vertical cell orientation) when impacted with a sphere with 40KMPH

- Minimum Deformation-0m
- Maximum Deformation-3.3406e-002 m
- Average Deformation-8.1439e-003 m

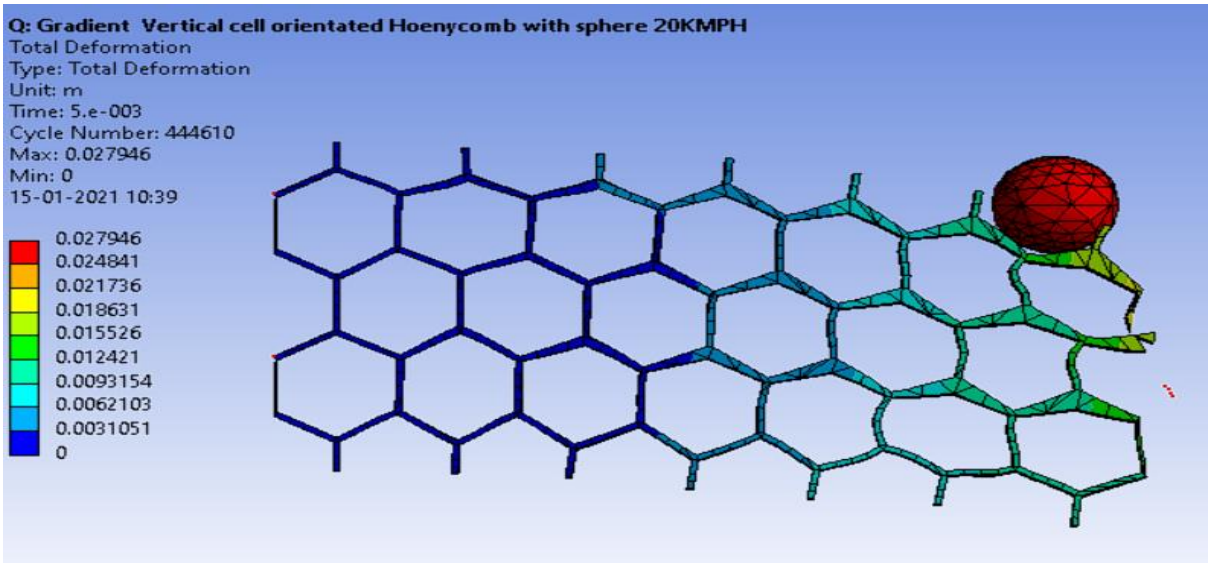

Figure 92 Total Deformation of Honeycomb Gradient (Vertical cell orientation) when impacted with a sphere with 20KMPH

- Minimum Deformation-0m

- Maximum Deformation-2.7946e-002 m
- Average Deformation-6.983e-003 m

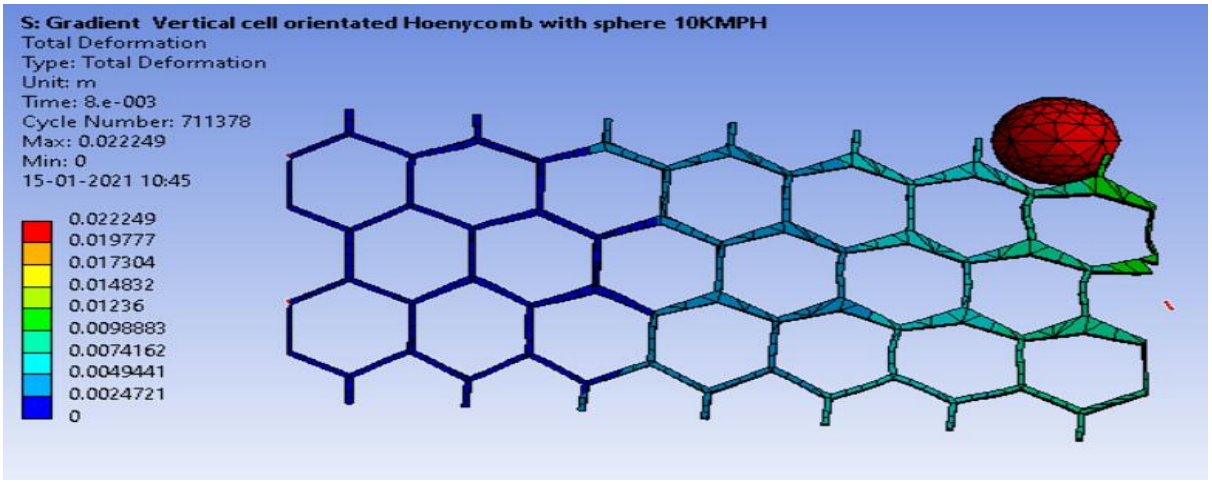

Figure 93 Total Deformation of Honeycomb Gradient (Vertical cell orientation) when impacted with a sphere with 10KMPH

- Minimum Deformation-0m
- Maximum Deformation-2.2249e-002 m
- Average Deformation-5.3843e-003 m

- **Horizontal cell orientation**

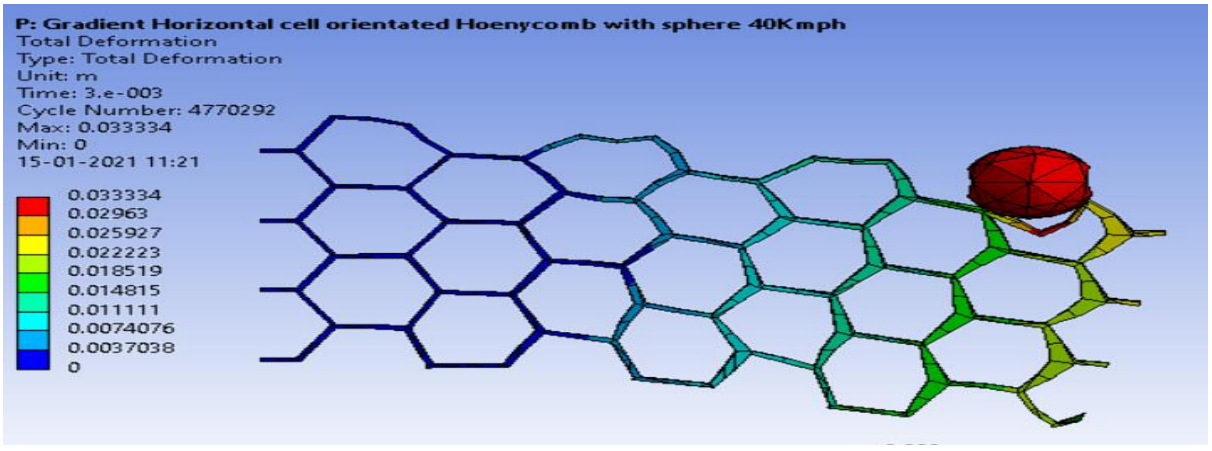

Figure 94 Total Deformation of Honeycomb Gradient (Horizontal cell orientation) when impacted with a sphere with 40KMPH

- Minimum Deformation-0m
- Maximum Deformation-3.3334e-002 m
- Average Deformation-1.2691e-002 m

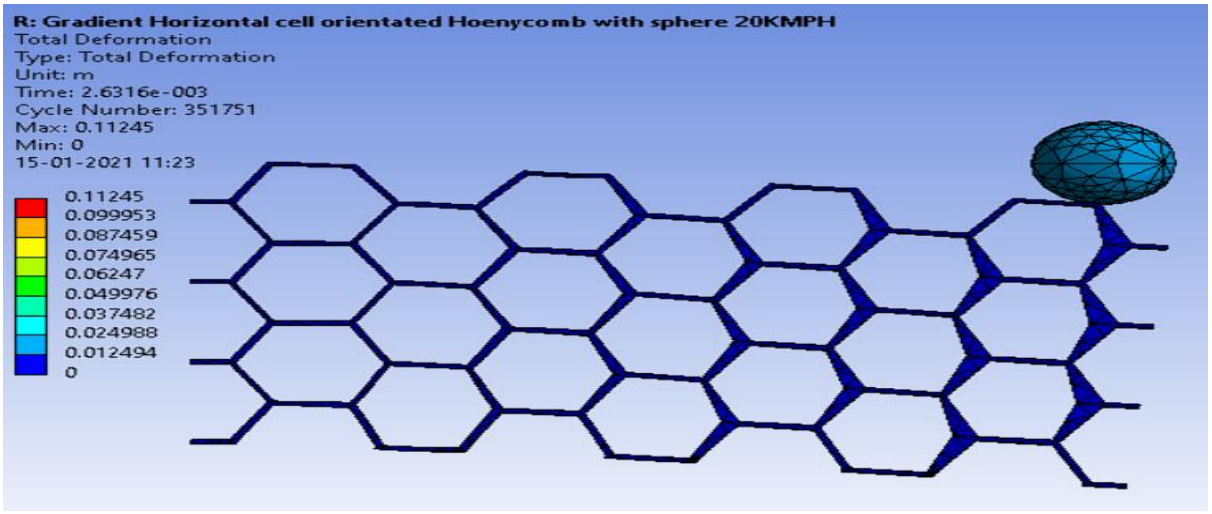

Figure 95 Total Deformation of Honeycomb Gradient (Horizontal cell orientation) when impacted with a sphere with 20KMPH

- Minimum Deformation-0m
- Maximum Deformation-0.11245 m
- Average Deformation-5.4481e-003 m

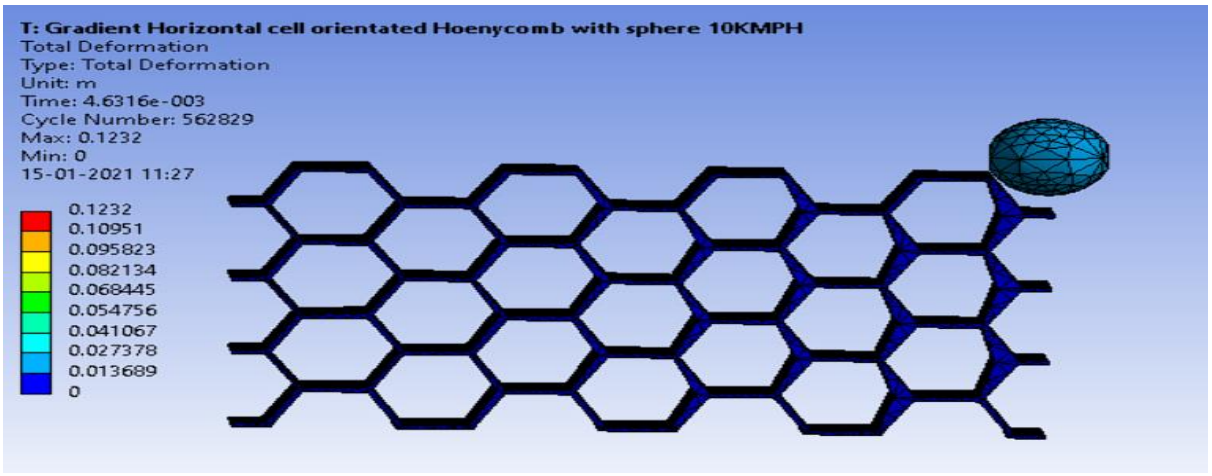

Figure 96 Total Deformation of Honeycomb Gradient (Horizontal cell orientation) when impacted with a sphere with 10KMPH

- Minimum Deformation-0m
- Maximum Deformation-0.1232 m
- Average Deformation-4.2916e-003 m.

Energy absorption of Gradient Honeycomb Structure (Vertical cell orientation and horizontal cell orientation) at impact loads

- **Vertical Cell orientation**

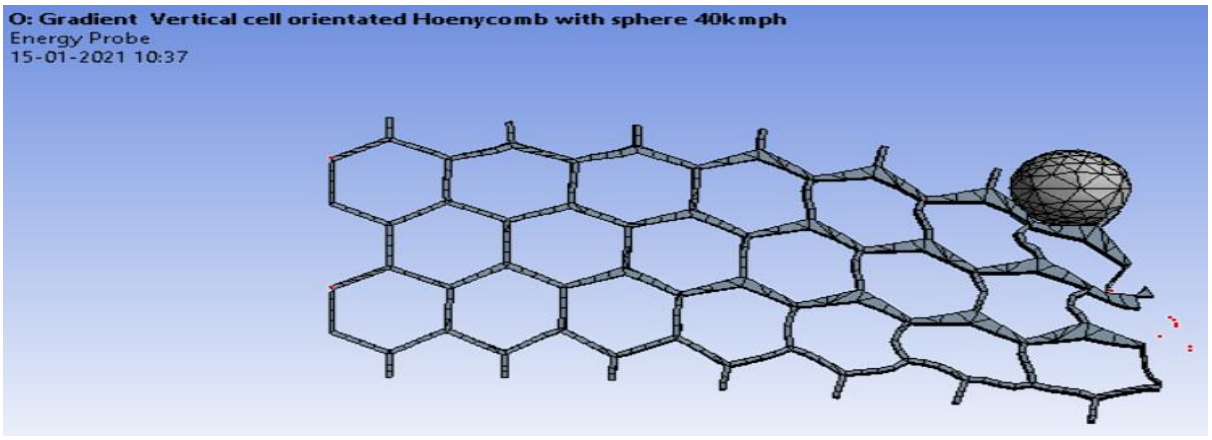

Figure 97 Energy probe of Honeycomb Gradient (Vertical cell orientation) when impacted with a sphere with 40KMPH

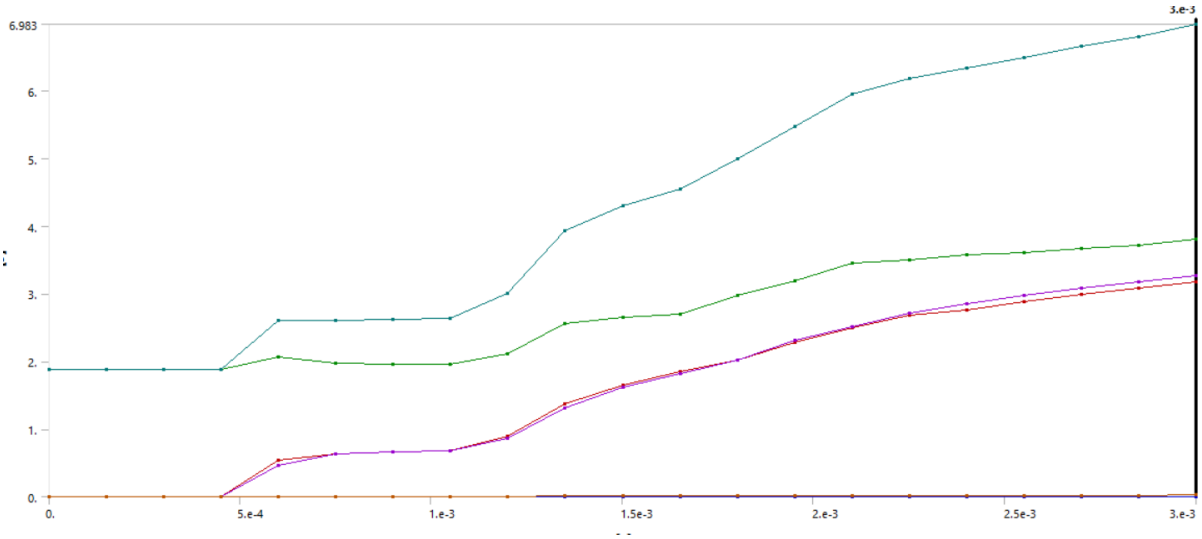

Figure 98 Energy vs time graph of Honeycomb Gradient (Vertical cell orientation) when impacted with a sphere with 40KMPH

- Sphere speed- 11.11mps

- The graph illustrates Kinetic and Internal energy absorbed during the impact. The green line and pink line represent kinetic and internal energy respectively.
- Maximum Kinetic Energy = 3.8042 J, Minimum Kinetic Energy= 1.8878 J
- Maximum Internal Energy = 3.1788 J, Minimum Internal Energy = 0J
- The blue line Indicates total Energy. Maximum total energy is 6.983J

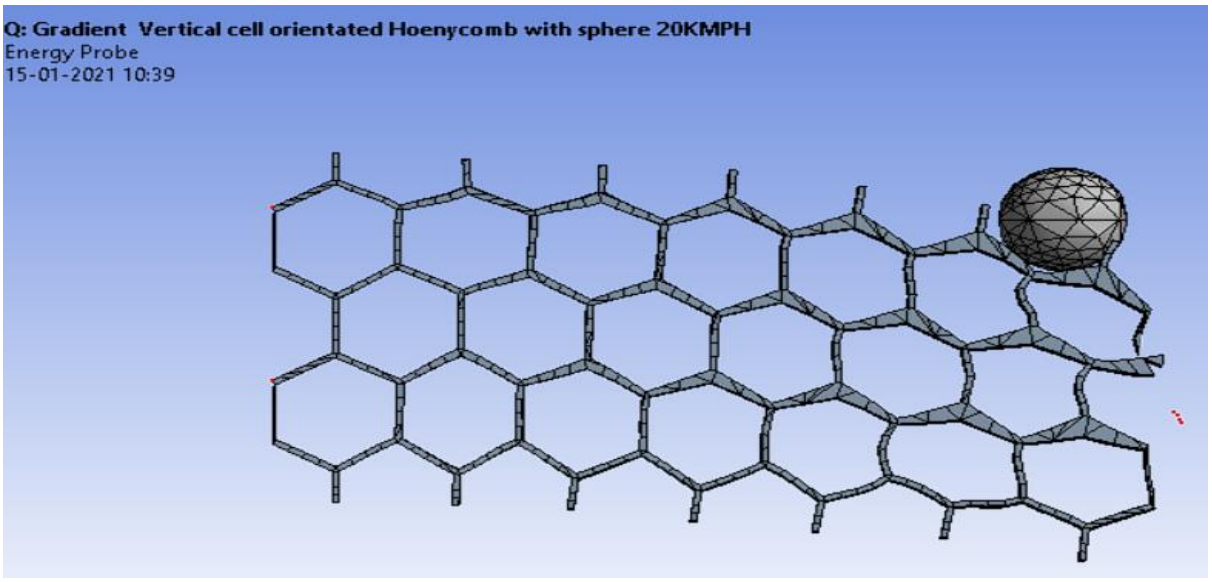

Figure 99 Energy probe of Honeycomb Gradient (Vertical cell orientation) when impacted with a sphere with 20KMPH

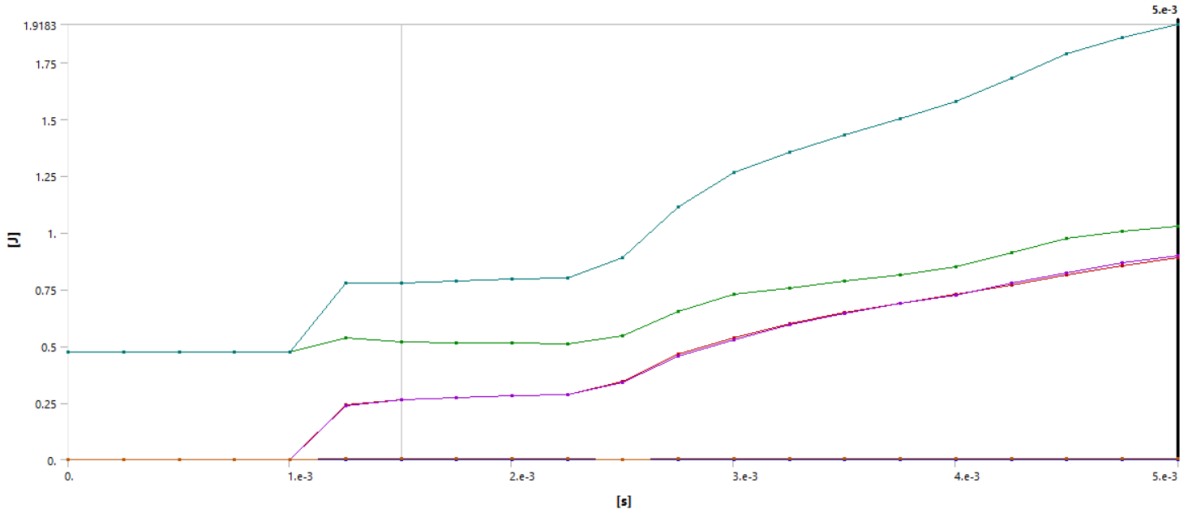

Figure 100 Energy vs time graph of Honeycomb Gradient (Vertical cell orientation) when impacted with a sphere with 20KMPH

- Sphere speed- 5.555mps

- The graph illustrates Kinetic and Internal energy absorbed during the impact. The green line and pink line represent kinetic and internal energy respectively.
- Maximum Kinetic Energy = 1.0296 J, Minimum Kinetic Energy= 0.47204 J
- Maximum Internal Energy = 0.88873 J, Minimum Internal Energy = 0J
- The blue line Indicates total Energy. Maximum total energy is 1.9183 J

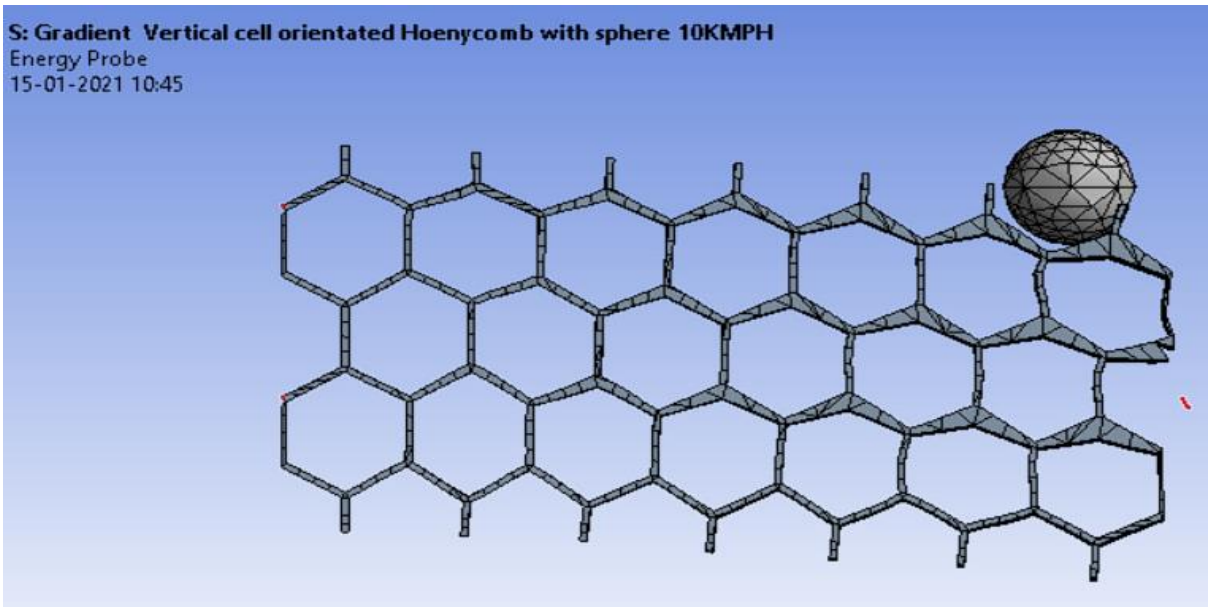

Figure 101 Energy probe of Honeycomb Gradient (Vertical cell orientation) when impacted with a sphere with 10KMPH

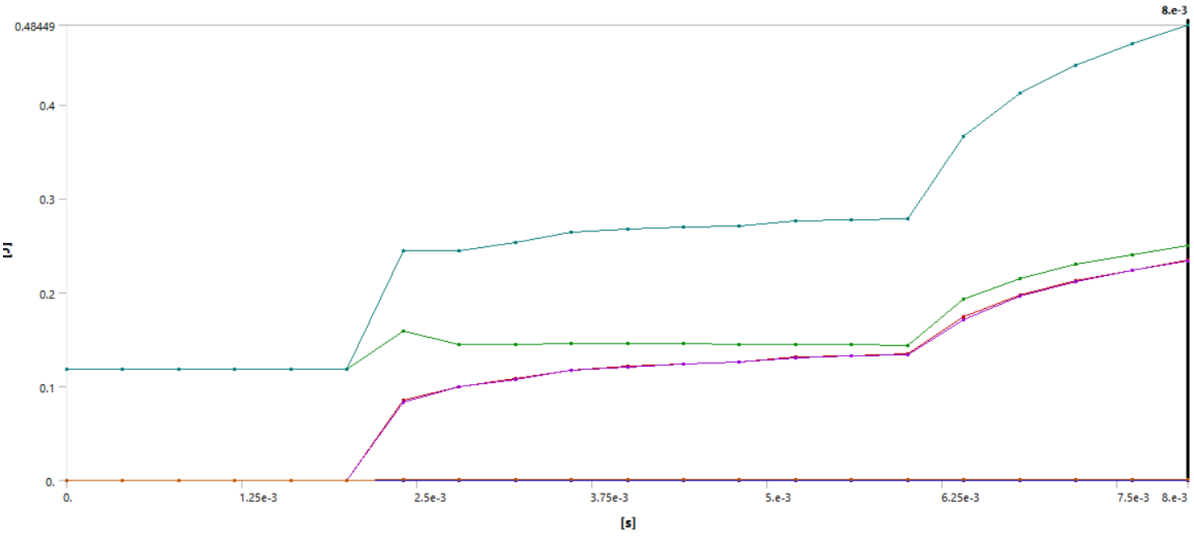

Figure 102 Energy vs time graph of Honeycomb Gradient (Vertical cell orientation) when impacted with a sphere with 10KMPH

- Sphere speed- 2.5557mps
- The graph illustrates Kinetic and Internal energy absorbed during the impact. The green line and pink line represent kinetic and internal energy respectively.
- Maximum Kinetic Energy = 24.784 J, Minimum Kinetic Energy= 0.11849 J
- Maximum Internal Energy = 21.744 J, Minimum Internal Energy = 0J
- The blue line Indicates total Energy. Maximum total energy is 29.026 J

- **Horizontal cell orientation**

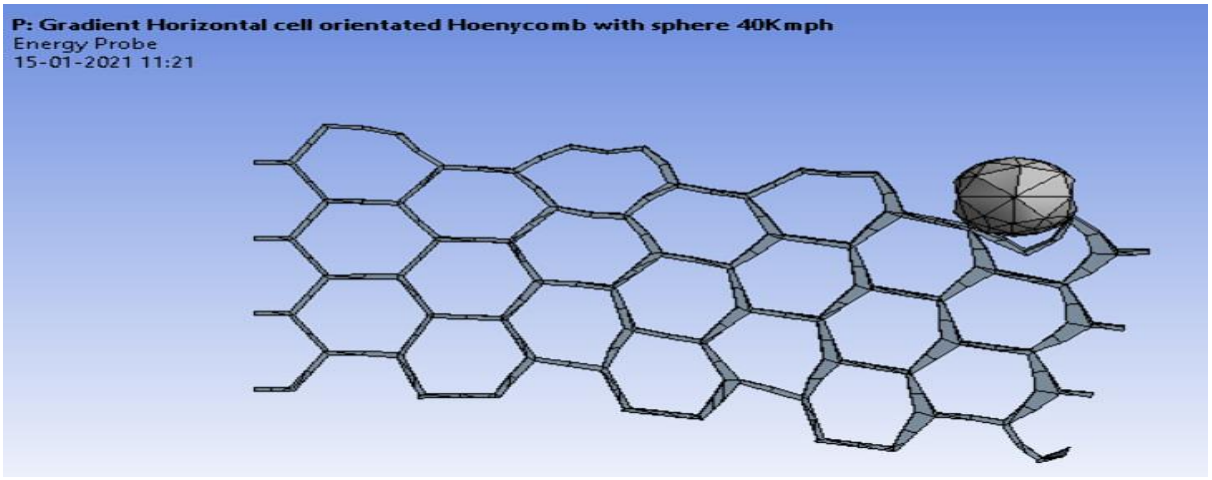

Figure 103 Energy probe of Honeycomb Gradient (Horizontal cell orientation) when impacted with a sphere with 40KMPH

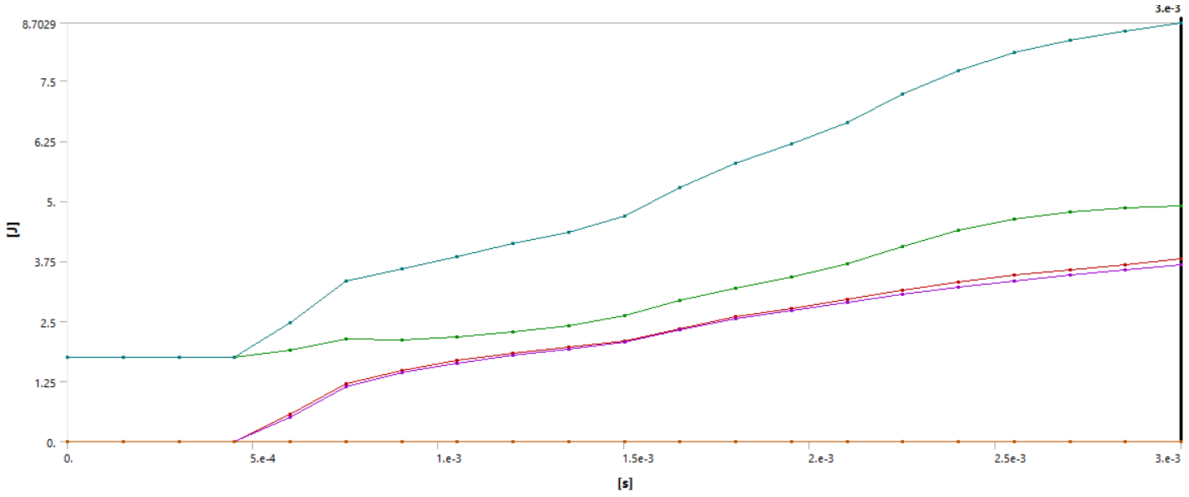

Figure 104 Energy vs time graph of Honeycomb Gradient (Vertical cell orientation) when impacted with a sphere with 40KMPH

- Sphere speed- 11.11mps
- The graph illustrates Kinetic and Internal energy absorbed during the impact. The green line and pink line represent kinetic and internal energy respectively.
- Maximum Kinetic Energy = 4.9037 J, Minimum Kinetic Energy= 1.7479 J
- Maximum Internal Energy = 3.7992 J, Minimum Internal Energy = 0J
- The blue line Indicates total Energy. Maximum total energy is 8.7029J

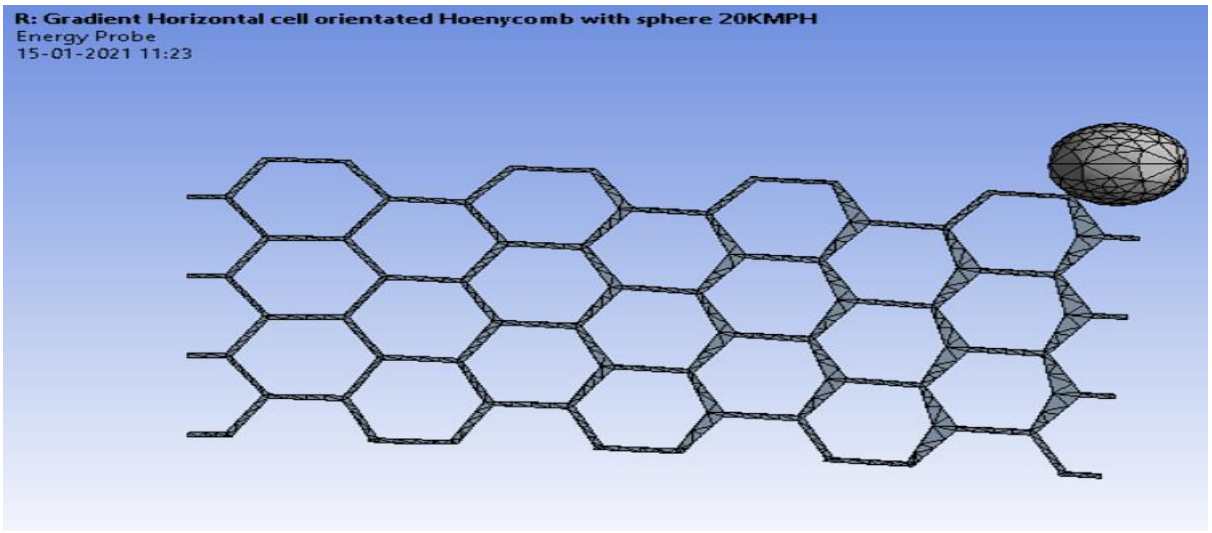

Figure 105 Energy probe of Honeycomb Gradient (Horizontal cell orientation) when impacted with a sphere with 20KMPH

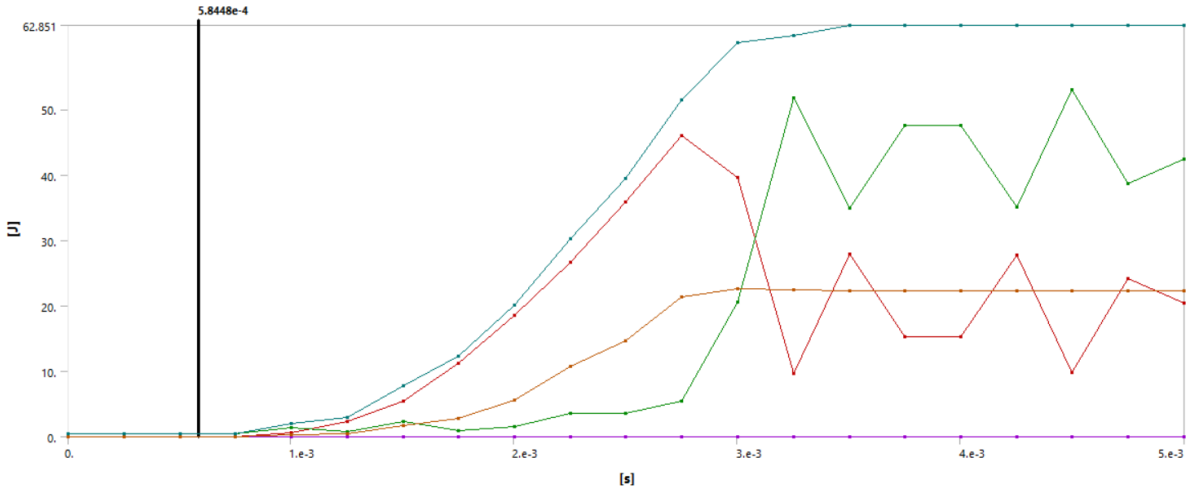

Figure 106 Energy vs time graph of Honeycomb Gradient (Vertical cell orientation) when impacted with a sphere with 20KMPH

- Sphere speed- 5.555mps

- The graph illustrates Kinetic and Internal energy absorbed during the impact. The green line and pink line represent kinetic and internal energy respectively.
- Maximum Kinetic Energy = 52.996 J, Minimum Kinetic Energy= 0.47398 J
- Maximum Internal Energy = 45.936 J, Minimum Internal Energy = 0J
- The blue line Indicates total Energy. Maximum total energy is 62.851 J

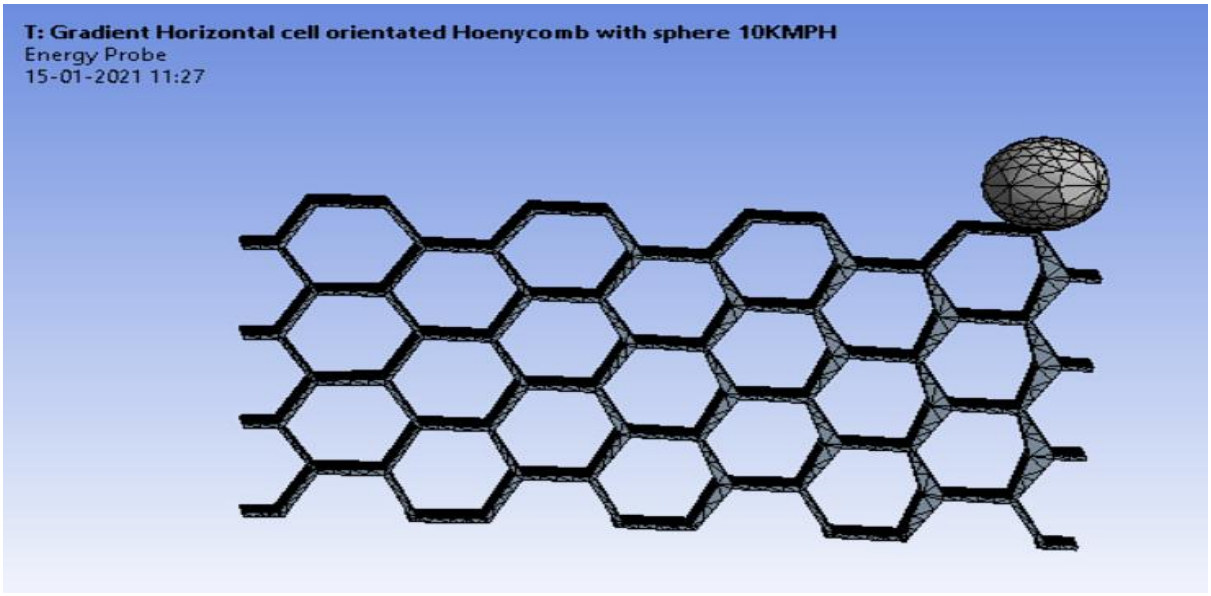

Figure 107 Energy probe of Honeycomb Gradient (Horizontal cell orientation) when impacted with a sphere with 10KMPH

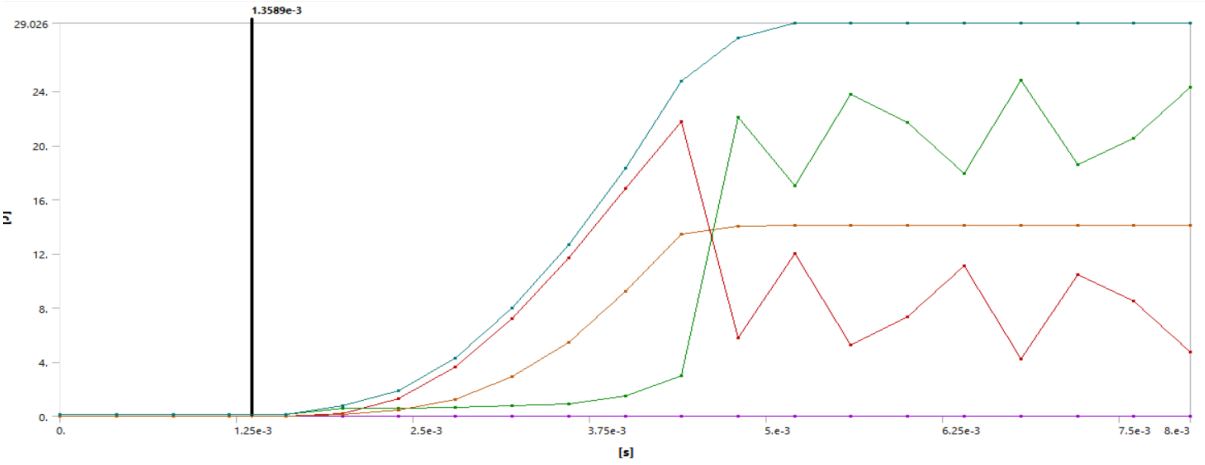

Figure 108 Energy vs time graph of Honeycomb Gradient (Vertical cell orientation) when impacted with a sphere with 10KMPH

- Sphere speed- 2.5557mps

- The graph illustrates Kinetic and Internal energy absorbed during the impact. The green line and pink line represent kinetic and internal energy respectively.
- Maximum Kinetic Energy = 24.784 J, Minimum Kinetic Energy= 0.11849 J
- Maximum Internal Energy = 21.744 J, Minimum Internal Energy = 0J.
- The blue line Indicates total Energy. Maximum total energy is 29.026 J.

Results and Inferences

- As cell's longest diagonal length decreases along rows i.e., each column will have same cell size, the properties such as Honeycomb density, Cells per honeycomb surface area, foil edge area per honeycomb surface area, exposed foil area per honeycomb volume decrease.

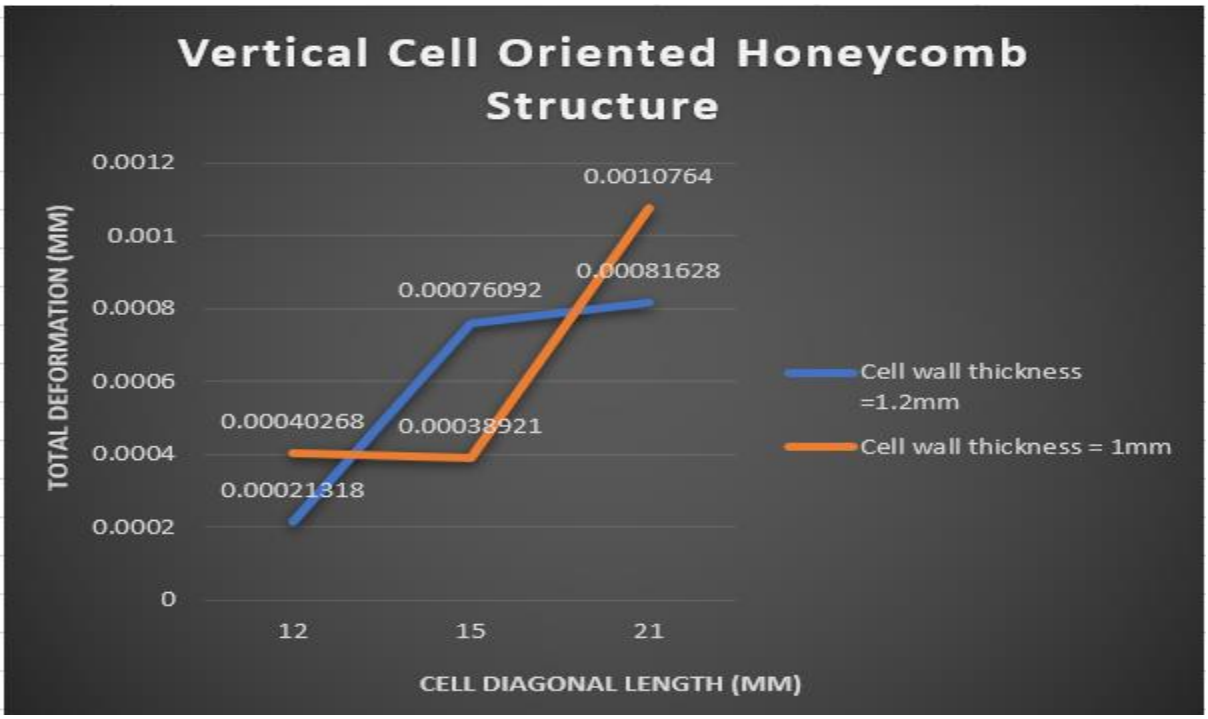

Figure 109 Total Deformation vs Cell diagonal length graph for Vertical Cell Oriented Regular Honeycomb Structure

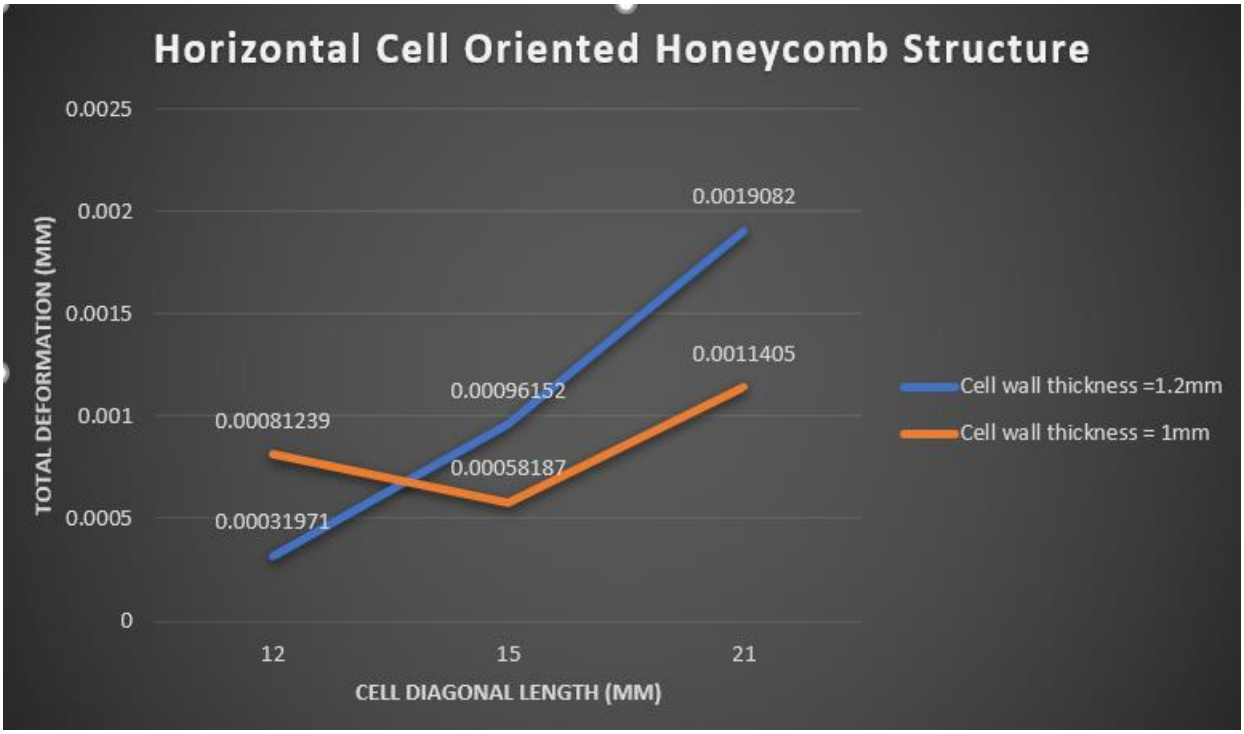

Figure 110 Total Deformation vs Cell diagonal length graph for Vertical Cell Oriented Regular Honeycomb Structure

Observations	Inferences
• As cell diagonal length increased, total deformation also increased.	• For lowest diagonal length in a cell of honeycomb Structure, has high resistance.
• As wall thickness increases, total deformation decreased.	• Cell wall thickness increases moment of inertia which will decrease deflection.
• Except for 15mm,1mm Structure, in which total deformation is lesser than the structure with 15mm and 1.2mm as diagonal length of cell and cell wall thickness respectively.	• This is because of total length of structure, as it is to be maintained approximately 220mm length and 50mm width.

Table 4 Observation vs Inference table of regular honeycomb structues

- For almost all the modes, Vertical call oriented Gradient Honeycomb Structure deforms less than Horizontal cell oriented Gradient Honeycomb Structure.
- But, for all the mode type of Bending +Torsion, Horizontal cell oriented Gradient Honeycomb Structure's maximum deformation is very high.
- The higher modal shapes require very high energy state which a structure or system may not face in its entire life.
- Vertical cell-oriented Honeycomb Structures offer higher bending resistance than Horizontal cell-oriented Honeycomb Structures.
- Gradient Vertical cell-oriented Honeycomb Structures offer higher bending resistance than Gradient Horizontal cell-oriented Honeycomb Structures.
- Maximum deformation occurs at end cell of Honeycomb structure.
- Gradient Honeycomb Structure offers more bending resistance then the regular Honeycomb Structure because of gradual increment in cell wall thickness for a given number of cells.
- Horizontal cell oriented gradient Honeycomb Structure fails at 40 KMPH speed impact load.
- For vertical cell orientated Honeycomb Structure, failure occurs at all the three cases. This is because of resistance offered by Honeycomb cell due to its orientation.
- Horizontal cell-oriented Honeycomb Structure can be used wherever low speed impacts at free end are applied.
- At low speeds Horizontal cell-oriented Honeycomb Structure absorbs more energy than the vertical cell-oriented Honeycomb Structure.

Conclusions and Future works

- Vertical cell-oriented honeycomb structure offers more bending resistance than horizontal cell orientated honeycomb structures.
- Increasing cell diagonal along length increases bending resistance than regular honeycomb structure. (Both for horizontal and vertical cell oriented)
- Compression test on adhesive bonded Honeycomb Sandwiches can also be a future work.
- In future, this can be experimented on cars front exterior as gradient honeycomb structures can sustain impact loading (sudden brakes or speed breaker jerks during drive).

Figure 111 Honeycomb panels assembled in AUDI R7S

- Harmonic Analysis and Random Vibration analysis can be done in future to determine the response of the structure under a steady-state sinusoidal (harmonic) loading at a given frequency and todetermine structure response at random loading respectively

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