

# **A Numerical Approach to Buckling Behaviour of Auxetic Sandwich Structures**

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## **ABSTRACT**

Auxetic polymeric materials are a type of material that has a negative Poisson ratio (NPR). When elongated, they become wider, and when squeezed, they become narrower. Auxetic behaviour is a scale-independent property that can be achieved at various structural levels ranging from molecular to macroscopic. When compared to conventional materials, auxetic polymeric materials exhibit several distinct characteristics due to the NPR effect. A variety of auxetic polymeric materials have been designed and manufactured in recent years for a wide range of applications. However, there are still difficult issues that prevent auxetic materials from being used more widely. This article provides an update on recent developments in this field. Previous works on auxetics are thoroughly reviewed, including various auxetic cellular models, naturally observed auxetic behavior, various desirable auxetic properties, and potential applications. The focus is on the geometrical structures and models, design optimization as well as the specific properties and applications of the developed auxetic polymeric materials. Design optimization was achieved using different methods like a genetic algorithm (GA) and design topology. ANSYS R2 2021 (Complete ANSYS workbench Environment) would be used to model and simulate the buckling behaviour of auxetic structures and the critical buckling load will be determined. Different material properties would be simulated to make a comparison of the buckling behaviour of those materials. The thickness would also be altered to see the effect of the thickness of the auxetic cores on buckling behaviour. Stress and strain of the composite structure would be obtained for the results.

**Keywords:** Auxetic, Poisson's Ratio, Simulation, Stress, Strain, Modelling, Buckling

## ÖZ

Auxetic polimerik malzemeler, negatif Poisson oranına (NPR) sahip bir malzeme türüdür. Uzatıldıklarında genişler ve sıkıştırıldıklarında daralırlar. Yardımcı davranış, molekülerden makroskopik olana kadar çeşitli yapısal seviyelerde elde edilebilen ölçekten bağımsız bir özelliktir. Geleneksel malzemelerle karşılaştırıldığında, yardımcı polimerik malzemeler NPR etkisinden dolayı birkaç farklı özellik sergiler. Son yıllarda çok çeşitli uygulamalar için çeşitli yardımcı polimerik malzemeler tasarlanmış ve üretilmiştir. Ancak yine de auxetic malzemelerin daha yaygın olarak kullanılmasını engelleyen zor sorunlar bulunmaktadır. Bu makale, bu alandaki son gelişmeler hakkında bir güncelleme sağlar. Çeşitli auxetic hücresel modeller, doğal olarak gözlemlenen auxetic davranış, çeşitli arzu edilen auxetic özellikler ve potansiyel uygulamalar dahil olmak üzere, auxetics üzerine önceki çalışmalar kapsamlı bir şekilde gözden geçirilmiştir. Odak noktası, geometrik yapılar ve modeller, tasarım optimizasyonu ve ayrıca geliştirilen yardımcı polimerik malzemelerin spesifik özellikleri ve uygulamalarıdır. Tasarım optimizasyonu, genetik algoritma (GA) ve tasarım topolojisi gibi farklı yöntemler kullanılarak sağlandı. Yardımcı yapıların burkulma davranışını modellemek ve simüle etmek için ANSYS R2 2021 (Complete ANSYS workbench Environment) kullanılacak ve kritik burkulma yükü belirlenecektir. Bu malzemelerin burkulma davranışlarının bir karşılaştırmasını yapmak için farklı malzeme özellikleri simüle edilecektir. Yardımcı çekirdeklerin kalınlığının burkulma davranışı üzerindeki etkisini görmek için kalınlık da değiştirilecektir. Sonuçlar için kompozit yapının gerilmesi ve gerilmesi elde edilecektir.

**Anahtar Kelimeler:** Auxetic, Poisson Oranı, Simülasyon, Gerilim, Gerinim, Modelleme, Burkulma

# **DEDICATION**

**TO MERCIFUL GOD AND MY FAMILY**

## **ACKNOWLEDGEMENT**

I would like to thank the almighty God for my ability to perform this task on time despite all the challenges faced. He filled me with peace and rest even when things seemed to be going too fast.

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I also want to send my thanks and regards to my parents for their never-ending support. They provided for me financially and morally. They ensured I had success and I am indebted to them.

Lastly, I want to thank my friends most especially Emmanuel Onyibo that encouraged me along the way and made crucial efforts in this study. They were also factors that pushed me and gave me the drive to do my work well.

## **PREFACE**

My love for mechanical engineering came from my high school where I figured I wanted to know how things worked. I picked an interest in cars and how they functioned which led to me studying mechanical engineering at the university.

As time passed I found out I loved simulation exercises where I could simulate real-life problems on a computer to yield results. That way you do not have to be in a real-world situation to get a result but it can be solved in the comfort of your home or workplace. Softwares like ABAQUS, ANSYS, Solidworks, MATLAB, etc. have been deployed for simulation works during my years of study.

# TABLE OF CONTENTS

|                                                          |      |
|----------------------------------------------------------|------|
| ABSTRACT.....                                            | iii  |
| ÖZ .....                                                 | v    |
| DEDICATION .....                                         | vii  |
| ACKNOWLEDGEMENT .....                                    | viii |
| PREFACE .....                                            | ix   |
| LIST OF TABLES .....                                     | xiii |
| LIST OF FIGURES .....                                    | xv   |
| LIST OF SYMBOLS AND ABBREVIATIONS .....                  | xx   |
| 1 INTRODUCTION .....                                     | 1    |
| 1.1 Auxetics History and Current Status .....            | 1    |
| 1.2 Definition of the Problem.....                       | 5    |
| 1.3 Need for Research (Motivation).....                  | 5    |
| 1.4 Objectives of this Study .....                       | 6    |
| 2 LITERATURE REVIEW.....                                 | 7    |
| 2.1 History of Research Done on Auxetic Structures ..... | 7    |
| 2.2 Properties Common to Auxetic Structures .....        | 10   |
| 2.3 Negative Poisson’s Ratio.....                        | 13   |
| 2.4 Applications of Auxetic Structures .....             | 15   |
| 2.4.1 Auxetics in Biomedical Field .....                 | 15   |
| 2.4.2 Auxetics in Piezoelectric Sensors .....            | 16   |
| 2.4.3 Auxetics in Filters.....                           | 16   |
| 2.4.4 Auxetics in Antennas .....                         | 17   |
| 2.4.5 Auxetcs in Textile Industry.....                   | 17   |

|                                                                                                             |    |
|-------------------------------------------------------------------------------------------------------------|----|
| 2.5 Types of Auxetic Structures .....                                                                       | 19 |
| 2.5.1 Auxetic Cellular Solids .....                                                                         | 19 |
| 2.5.2 Micro Porous Auxetic Polymers .....                                                                   | 21 |
| 2.5.3 Molecular Auxetic Structures .....                                                                    | 22 |
| 3 METHODOLOGY .....                                                                                         | 24 |
| 3.1 Design and Modelling of Auxetic Structures .....                                                        | 24 |
| 3.2 Design Parameters of Aluminium Auxetic Panel .....                                                      | 28 |
| 3.3 Meshing of Finite Element .....                                                                         | 31 |
| 4 RESULTS AND DISCUSSION .....                                                                              | 33 |
| 4.1 Overview of the Study Results .....                                                                     | 33 |
| 4.2 Generation of Material Properties from Auxetic Unit Cell Structure .....                                | 34 |
| 4.2.1 Comparison of Mechanical Properties of an Proposed Model with 15mm, 20mm and 25mm Thickness .....     | 34 |
| 4.2.2 Comparison of Mechanical Properties of an Proposed Model with 65°, 70° and 75° Angle .....            | 35 |
| 4.2.3 Comparison of Mechanical Properties of a Proposed CFRP Model with 15mm, 20mm and 25mm Thickness ..... | 36 |
| 4.2.4 Comparison of Mechanical Properties of a Proposed CFRP Model with 65°, 70° and 75° Angle .....        | 37 |
| 4.2.5 Comparison of Mechanical Properties of Proposed Model And CFRP Model with 15mm Thickness .....        | 38 |
| 4.3 Eigen Value Buckling Analysis .....                                                                     | 39 |
| 4.3.1 Buckling Modes Of Proposed Model with 15mm Thickness .....                                            | 40 |
| 4.3.2 Buckling Modes Of Proposed Model with 20mm Thickness .....                                            | 42 |
| 4.3.3 Buckling Modes Of Proposed Model with 25mm Thickness .....                                            | 44 |

|                                                                                                                         |    |
|-------------------------------------------------------------------------------------------------------------------------|----|
| 4.3.4 Buckling Modes of Proposed Model with a 65° Angle.....                                                            | 46 |
| 4.3.5 Buckling Modes of Proposed Model with a 70° Angle.....                                                            | 48 |
| 4.3.6 Buckling Modes of Proposed Model with a 75° Angle.....                                                            | 50 |
| 4.3.7 Buckling Modes Of Proposed CFRP Model with 15mm Thickness.....                                                    | 52 |
| 4.3.8 Buckling Modes Of Proposed CFRP Model with 20mm Thickness.....                                                    | 54 |
| 4.3.9 Buckling Modes Of Proposed CFRP Model with 25mm Thickness.....                                                    | 56 |
| 4.3.10 Buckling Modes of Proposed CFRP Model with a 65° Angle.....                                                      | 58 |
| 4.3.11 Buckling Modes of Proposed CFRP Model with a 70° Angle.....                                                      | 60 |
| 4.3.12 Buckling Modes of Proposed CFRP Model with a 75° Angle.....                                                      | 62 |
| 4.3.13 Comparison of Buckling Loads of Proposed 15mm Model to Proposed<br>15mm CFRP Model.....                          | 65 |
| 4.3.14 Comparison Of Buckling Loads Of Proposed 70° Model to Proposed 70°<br>CFRP Model.....                            | 66 |
| 4.4 Stress and Strain Analysis and Comparison.....                                                                      | 67 |
| 4.4.1 Stress And Strain For 15mm, 20mm And 25mm Thickness Proposed<br>Model.....                                        | 67 |
| 4.4.2 Stress And Strain For 65°, 70°Mm And 75° Thickness Proposed Model.                                                | 69 |
| 4.4.3 Stress And Strain For 15mm, 20mm And 25mm Proposed CFRP Model                                                     | 71 |
| 4.4.4 Stress And Strain For 65°, 70°Mm And 75° Angle of Proposed CFRP<br>Model.....                                     | 74 |
| 4.4.5 Comparison Between The Stress And Strain Components Of Proposed<br>Model And CFRP Model with 15mm Thickness ..... | 76 |
| 5 CONCLUSION.....                                                                                                       | 78 |
| REFERENCES.....                                                                                                         | 80 |

## LIST OF TABLES

|                                                                                                   |    |
|---------------------------------------------------------------------------------------------------|----|
| Table 1: Dimensions of the re-entrant structure unit cell.....                                    | 29 |
| Table 2: Mechanical properties of aluminium alloy 2024 .....                                      | 30 |
| Table 3: Mechanical properties of proposed model with 15mm, 20mm and 25mm<br>thickness.....       | 34 |
| Table 4: Mechanical properties of proposed model with angles of 65°, 70° and 75°                  | 36 |
| Table 5: Mechanical properties of proposed CFRP model with 15mm, 20mm and 25<br>mm thickness..... | 37 |
| Table 6: Mechanical properties of proposed CFRP model with angles of 65°, 70° and<br>75° .....    | 38 |
| Table 7: Mechanical properties of proposed model and CFRP model with 15mm<br>thickness.....       | 39 |
| Table 8: Eigenvalues corresponding to their modes .....                                           | 41 |
| Table 9: Eigenvalues corresponding to their modes .....                                           | 43 |
| Table 10: Eigenvalues corresponding to their modes .....                                          | 45 |
| Table 11: Eigenvalues corresponding to their modes .....                                          | 47 |
| Table 12: Eigenvalues corresponding to their modes .....                                          | 49 |
| Table 13: Eigenvalues corresponding to their modes .....                                          | 51 |
| Table 14: Eigenvalues corresponding to their modes .....                                          | 54 |
| Table 15: Eigenvalues corresponding to their modes .....                                          | 56 |
| Table 16: Eigenvalues corresponding to their modes .....                                          | 58 |
| Table 17: Eigenvalues corresponding to their modes .....                                          | 60 |
| Table 18: Eigenvalues corresponding to their modes .....                                          | 62 |
| Table 19: Eigenvalues corresponding to their modes .....                                          | 64 |

|                                                                                                                                       |    |
|---------------------------------------------------------------------------------------------------------------------------------------|----|
| Table 20: Comparison of stress-strain components of a sandwich structure with aluminium alloy and CFRP core with 15mm thickness ..... | 64 |
| Table 21: Stress-strain table of 15mm, 20mm and 25mm of aluminium alloy core..                                                        | 69 |
| Table 22: Stress-strain table of 65°, 70° and 75° of aluminium alloy re-entrant cell                                                  | 71 |
| Table 23: Stress-strain table of 15mm, 20mm and 25mm CFRP core.....                                                                   | 73 |
| Table 24: Stress-strain table of 65°, 70° and 75° of CFRP re-entrant cell .....                                                       | 75 |
| Table 25: Comparison of stress-strain components of a sandwich structure with aluminium alloy and CFRP core with 15mm thickness.....  | 76 |
| Table 26: Result comparison.....                                                                                                      | 78 |

# LIST OF FIGURES

|                                                                                                                                                                         |    |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 1: Loading of a conventional and auxetic honeycomb construction in the Y-direction [11].....                                                                     | 2  |
| Figure 2: Several auxetic structure patterns [3] .....                                                                                                                  | 3  |
| Figure 3: Conventional cylindrical foam compared to auxetic cylindrical foam [25].                                                                                      | 5  |
| Figure 4: Database from scopus showing documents done by year using the word “auxetic structures” scopus sources [26].....                                              | 7  |
| Figure 5: Database from scopus showing documents done by year using the word “auxetic structures” and “optimization”. scopus sources [26] .....                         | 8  |
| Figure 6: Database from scopus showing documents done by year using the word “auxetic structures”, “optimization” and “genetic algorithm”. scopus sources [26] ..       | 8  |
| Figure 7: Database from scopus for published papers by country using the keywords “auxetic structures”, “optimization”, and “genetic algorithm”. scopus sources [26] .. | 9  |
| Figure 8: Indentation resistance of non-auxetic and auxetic materials. [43], [44].....                                                                                  | 12 |
| Figure 9: Synclastic nature of auxetic structures [43].....                                                                                                             | 13 |
| Figure 10: 2D re-entrant bow tie shape and its deformed shape [52] .....                                                                                                | 14 |
| Figure 11: 3D re-entrant bow tie shape and its deformed shape [52] .....                                                                                                | 14 |
| Figure 12: Dilator using an auxetic end sheath [43], [44].....                                                                                                          | 16 |
| Figure 13: Auxetic piezoelectric sensor [54] .....                                                                                                                      | 16 |
| Figure 14: Particulate defouling abilities of (a) nonauxetic honeycomb membrane filters and (b) filters with auxetic membranes [55] .....                               | 17 |
| Figure 15: Auxetic yarn (a) auxetic helical yarn with harder core (b) auxetic helical yarn with soft core [60] .....                                                    | 18 |
| Figure 16: Auxetic woven fabric [61] .....                                                                                                                              | 18 |

|                                                                                                                                                                                    |    |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 17: Re-entrant unit cell [42].....                                                                                                                                          | 20 |
| Figure 18: Classification of cellular auxetic structures [64]. ....                                                                                                                | 20 |
| Figure 19: (a) undeformed (b) deformed missing rib structure [66].....                                                                                                             | 21 |
| Figure 20: (a) undeformed (b) deformed rotating rectangles [68], [69] .....                                                                                                        | 21 |
| Figure 21: Microporous PTFE going through tensile loading in the x-direction, the tension in the fibrils causing transverse displacement of nodes and lateral expansion [42]. .... | 22 |
| Figure 22: The arrangement of laterally attached rods in the main chain liquid crystalline polymer [42] .....                                                                      | 23 |
| Figure 23: Model for 3D re-entrant cell (a) full tetrahedral mesh (b) beam element (c) beam element [8].....                                                                       | 28 |
| Figure 24: Unit re-entrant cell and dimensions.....                                                                                                                                | 29 |
| Figure 25: Force exerted for buckling analysis.....                                                                                                                                | 30 |
| Figure 26: Applied force for stress-strain analysis .....                                                                                                                          | 30 |
| Figure 27: Finite element analysis mesh.....                                                                                                                                       | 32 |
| Figure 28: Buckling mode 1 of proposed model with 15mm thickness .....                                                                                                             | 40 |
| Figure 29: Buckling mode 3 of proposed model with 15mm thickness .....                                                                                                             | 40 |
| Figure 30: Buckling mode 6 of proposed model with 15mm thickness .....                                                                                                             | 41 |
| Figure 31: Buckling mode 9 of proposed model of 15mm thickness .....                                                                                                               | 41 |
| Figure 32: Buckling mode 1 of proposed model with 20mm thickness .....                                                                                                             | 42 |
| Figure 33: Buckling mode 3 of proposed model with 20mm thickness .....                                                                                                             | 42 |
| Figure 34: Buckling mode 6 of proposed model with 20mm thickness .....                                                                                                             | 43 |
| Figure 35: Buckling mode 9 of proposed model with 20mm thickness .....                                                                                                             | 43 |
| Figure 36: Buckling mode 1 of proposed model with 25mm thickness .....                                                                                                             | 44 |
| Figure 37: Buckling mode 3 of proposed model with 25mm thickness .....                                                                                                             | 44 |

|                                                                                  |    |
|----------------------------------------------------------------------------------|----|
| Figure 38: Buckling mode 6 of proposed model with 25mm thickness .....           | 45 |
| Figure 39: Buckling mode 9 of proposed model with 25mm thickness .....           | 45 |
| Figure 40: Buckling mode 1 of proposed model with an angle of $65^{\circ}$ ..... | 46 |
| Figure 41: Buckling mode 3 of proposed model with an angle of $65^{\circ}$ ..... | 46 |
| Figure 42: Buckling mode 6 of proposed model with an angle of $65^{\circ}$ ..... | 47 |
| Figure 43: Buckling mode 9 of proposed model with an angle of $65^{\circ}$ ..... | 47 |
| Figure 44: Buckling mode 1 of proposed model with an angle of $70^{\circ}$ ..... | 48 |
| Figure 45: Buckling mode 3 of proposed model with an angle of $70^{\circ}$ ..... | 48 |
| Figure 46: Buckling mode 6 of proposed model with an angle of $70^{\circ}$ ..... | 49 |
| Figure 47: Buckling mode 9 of proposed model with an angle of $70^{\circ}$ ..... | 49 |
| Figure 48: Buckling mode 1 of proposed model with an angle of $75^{\circ}$ ..... | 50 |
| Figure 49: Buckling mode 3 of proposed model with an angle of $75^{\circ}$ ..... | 50 |
| Figure 50: Buckling mode 6 of proposed model with an angle of $75^{\circ}$ ..... | 51 |
| Figure 51: Buckling mode 9 of proposed model with an angle of $75^{\circ}$ ..... | 51 |
| Figure 52: Buckling mode 1 of proposed model with 15mm thickness .....           | 52 |
| Figure 53: Buckling mode 3 of proposed model with 15mm thickness .....           | 53 |
| Figure 54: Buckling mode 6 of proposed model with 15mm thickness .....           | 53 |
| Figure 55: Buckling mode 9 of proposed model with 15mm thickness .....           | 53 |
| Figure 56: Buckling mode 1 of proposed model with 20mm thickness .....           | 54 |
| Figure 57: Buckling mode 3 of proposed model with 20mm thickness .....           | 55 |
| Figure 58: Buckling mode 6 of proposed model with 20mm thickness .....           | 55 |
| Figure 59: Buckling mode 9 of proposed model with 20mm thickness .....           | 55 |
| Figure 60: Buckling mode 1 of proposed model with 25mm thickness .....           | 56 |
| Figure 61: Buckling mode 3 of proposed model with 25mm thickness .....           | 57 |
| Figure 62: Buckling mode 6 of proposed model with 25mm thickness .....           | 57 |

|                                                                                                                                                              |    |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 63: Buckling mode 9 of proposed model with 25mm thickness .....                                                                                       | 57 |
| Figure 64: Buckling mode 1 of proposed model with an angle of $65^{\circ}$ .....                                                                             | 58 |
| Figure 65: Buckling mode 3 of proposed model with an angle of $65^{\circ}$ .....                                                                             | 59 |
| Figure 66: Buckling mode 6 of proposed model with an angle of $65^{\circ}$ .....                                                                             | 59 |
| Figure 67: Buckling mode 9 of proposed model with an angle of $65^{\circ}$ .....                                                                             | 59 |
| Figure 68: Buckling mode 1 of proposed model with an angle of $70^{\circ}$ .....                                                                             | 60 |
| Figure 69: Buckling mode 3 of proposed model with an angle of $70^{\circ}$ .....                                                                             | 61 |
| Figure 70: Buckling mode 6 of proposed model with an angle of $70^{\circ}$ .....                                                                             | 61 |
| Figure 71: Buckling mode 9 of proposed model with an angle of $70^{\circ}$ .....                                                                             | 61 |
| Figure 72: Buckling mode 1 of proposed model with an angle of $75^{\circ}$ .....                                                                             | 62 |
| Figure 73: Buckling mode 3 of proposed model with an angle of $75^{\circ}$ .....                                                                             | 63 |
| Figure 74: Buckling mode 6 of proposed model with an angle of $75^{\circ}$ .....                                                                             | 63 |
| Figure 75: Buckling mode 9 of proposed model with an angle of $75^{\circ}$ .....                                                                             | 63 |
| Figure 76: Eigenvalue comparison of 15mm aluminum alloy auxetic re-entrant core<br>and 15mm CFRP auxetic re-entrant core. ....                               | 65 |
| Figure 77: Eigenvalue comparison of $70^{\circ}$ angled aluminum alloy auxetic re-entrant<br>core and $70^{\circ}$ angled CFRP auxetic re-entrant core. .... | 66 |
| Figure 78: Stress component of proposed model with thickness of 15mm .....                                                                                   | 67 |
| Figure 79: Stress component of proposed model with thickness of 20mm .....                                                                                   | 67 |
| Figure 80: Stress component of proposed model with thickness of 25mm .....                                                                                   | 68 |
| Figure 81: Strain component of proposed model with thickness of 15mm .....                                                                                   | 68 |
| Figure 82: Strain component of proposed model with thickness of 20mm .....                                                                                   | 68 |
| Figure 83: Strain component of proposed model with thickness of 25mm .....                                                                                   | 69 |
| Figure 84: Stress component of proposed model with a re-entrant angle of $65^{\circ}$ .....                                                                  | 69 |
| Figure 85: Stress component of proposed model with a re-entrant angle of $70^{\circ}$ .....                                                                  | 70 |

|                                                                                             |    |
|---------------------------------------------------------------------------------------------|----|
| Figure 86: Stress component of proposed model with a re-entrant angle of $75^{\circ}$ ..... | 70 |
| Figure 87: Strain component of proposed model with a re-entrant angle of $65^{\circ}$ ..... | 70 |
| Figure 88: Strain component of proposed model with a re-entrant angle of $70^{\circ}$ ..... | 70 |
| Figure 89: Strain component of proposed model with a re-entrant angle of $75^{\circ}$ ..... | 71 |
| Figure 90: Stress component of proposed model with thickness of 15mm .....                  | 71 |
| Figure 91: Stress component of proposed model with thickness of 20mm .....                  | 72 |
| Figure 92: Stress component of proposed model with thickness of 20mm .....                  | 72 |
| Figure 93: Strain component of proposed model with thickness of 15mm .....                  | 72 |
| Figure 94: Strain component of proposed model with thickness of 20mm .....                  | 73 |
| Figure 95: Strain component of proposed model with thickness of 25mm .....                  | 73 |
| Figure 96: Stress component of proposed model with re-entrant angle of $65^{\circ}$ .....   | 74 |
| Figure 97: Stress component of proposed model with re-entrant angle of $70^{\circ}$ .....   | 74 |
| Figure 98: Stress component of proposed model with re-entrant angle of $75^{\circ}$ .....   | 74 |
| Figure 99: Strain component of proposed model with re-entrant angle of $65^{\circ}$ .....   | 74 |
| Figure 100: Strain component of proposed model with re-entrant angle of $70^{\circ}$ .....  | 75 |
| Figure 101: Strain component of proposed model with re-entrant angle of $75^{\circ}$ .....  | 75 |
| Figure 102: Stress component of proposed model with thicknesses 15mm, 20mm and 25mm. ....   | 76 |
| Figure 103: Strain component of proposed model with thicknesses 15mm, 20mm and 25mm. ....   | 77 |

## LIST OF SYMBOLS AND ABBREVIATIONS

|           |                               |
|-----------|-------------------------------|
| %         | Percentage                    |
| °C        | Degree Celsius                |
| cm        | Centimeters                   |
| E         | Young's Modulus               |
| GPa       | Gigapascal                    |
| I         | Inertia                       |
| K         | Global Stiffness Matrix       |
| K0        | Element Stiffness Matrix      |
| m         | Meters                        |
| M         | Moment                        |
| mm        | Millimeters                   |
| MPa       | Megapascal                    |
| N         | Force                         |
| Pa        | Pascal                        |
| U         | Strain Energy                 |
| Uout      | Transverse Displacement       |
| Xe        | Design Variable               |
| Xmin      | Lower Density Bound           |
| $\gamma$  | Hertzian Indentation Constant |
| $\lambda$ | Eigenvalue                    |
| $\nu$     | Poisson's Ratio               |
| $\sigma$  | Critical Buckling Load        |
| $\phi$    | Fraction of Design Space      |

|            |                                  |
|------------|----------------------------------|
| $\epsilon$ | Strain                           |
| 2D         | 2 Dimensional                    |
| 3D         | 3 Dimensional                    |
| CFRP       | Carbon Fiber Reinforced Plastics |
| NPR        | Negative Poisson's Ratio         |
| PP         | Polypropylene                    |
| PTFE       | Polytetrafluoroethylene          |

# Chapter 1

## INTRODUCTION

### 1.1 Auxetics History and Current Status

In recent decades, the study of materials with uncharacteristic behaviours has been studied by scientists and engineers to achieve innovative applications [1] in the aircraft, automotive, and sports industries [2]. These sectors require high-performance materials to meet high engineering specifications. These specifications are; high strength, stiffness low cost, resistance to corrosion, etc. That is where auxetic materials come in. Materials that exhibit unexpected behaviour when mechanical loads and strains are applied to them are known as auxetic materials, structures, and textiles (or "Auxetics," which refers to all of them). [3], [4][5]. Auxetic bodies are made up of a pattern of identical microstructures that repeats itself [6]. These structures possess superior and unusual properties in aspects of density [7], energy absorption [8], static modulus, etc.

They are materials with a negative Poisson's ratio also known as auxetics meaning when stretched longitudinally, it becomes larger in one or more of the perpendicular width-wise directions and vice versa [2], [9]. The term "Auxetic" stems from the Greek word auxetikos which means "that which tends to increase" and it is based on the Greek word auxesis which is a noun that means "increase" [10]. The key to auxetic behaviour is a negative Poisson's ratio, which is provided by the precise geometric arrangement and mechanical deformation of auxetic materials'

microstructures. Negative Poisson's ratio causes structures/materials to behave in an unconventional manner as the structures expand when in tension and compress when in compression as seen in Figure 1.

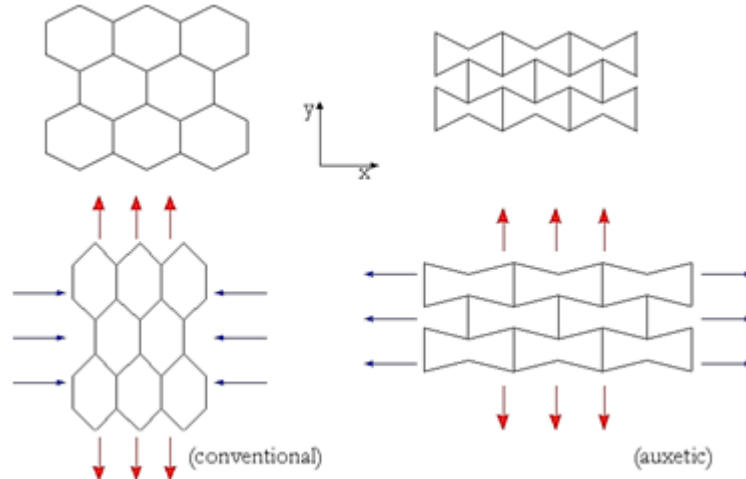


Figure 1: Loading of a conventional and auxetic honeycomb construction in the Y-direction [11]

Prior to this, it was believed that negative Poisson's ratio values were impossible. [12]. Researchers have concentrated on examining auxetic materials' characteristics and uses as well as finding novel materials with negative Poisson ratios and developing new methods for making them since the discovery of auxetic materials. [13]. The initial concept for auxetic research was a framework structure with a negative Poisson's ratio [14]. Auxetic materials have been seen naturally in the year 1882, by performing studies on the twisting and bending of mineral rods, iron pyrite monocrystals were discovered. [15]. This study first proved the existence of auxetics in nature. Its Poisson's ratio was estimated to be  $-\frac{1}{7}$  [16]. Since that point, other cases of naturally occurring auxetics have been discovered such as polymorphic silicones [17], zeolites [18], and silicates [19]. There was an attempt to synthesize auxetics due to its scarcity in nature and the difficulties in assigning a specific

application to them [20]. This goal was achieved for the first time in 1987 when the first auxetic foam was manufactured [21]. This was accomplished by analyzing the material's internal structure and examining how it deforms when loaded [22]. Lakes [21] first described a re-entrant foam structure that demonstrates NPR in 1987. After four years, Evans et al. [23] named items containing NPR "auxetics" or "auxetic materials" to shorten the lengthy explanation of "NPR." Others use structural techniques and design shapes to achieve the auxetic effect by changing the base cell of the material given in the types of auxetic structures in this paper, i.e. auxetic cellular solids. Some methods have been proposed to find new auxetic materials that depend on turning non auxetic materials into foams. Figure 2 shows different patterns in which auxetic structures are configured.

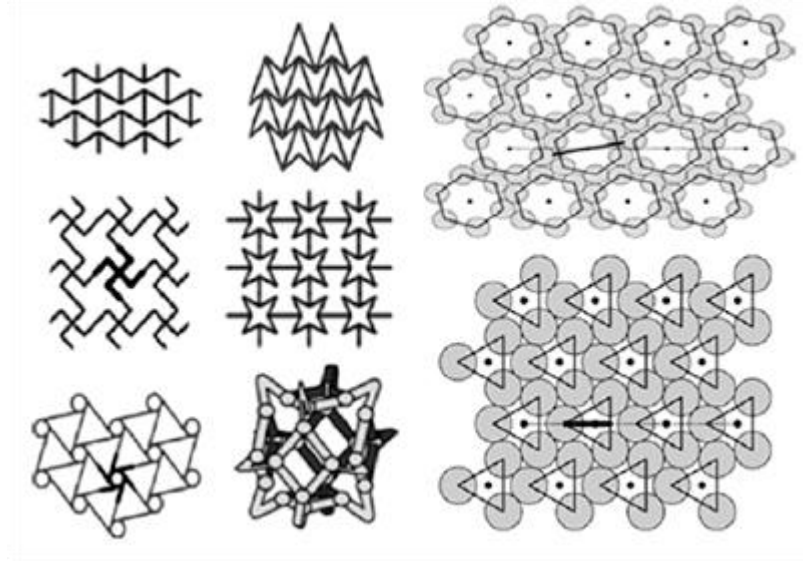


Figure 2: Several auxetic structure patterns [3]

In this paper, we will have an in-depth review of auxetic structures and then develop a simulation of the buckling effects on auxetic structures using ANSYS R2 2021 software. The 3D model will comprise a re-entrant auxetic structure. The auxetic structure is made of aluminum alloy.

Materials with a negative Poisson's ratio are referred to as auxetics. The Poisson's ratio, which relates how a material deforms in one direction when it is actively deformed in a direction that is perpendicular to the first one by the application of mechanical stress or strain, is defined as the negative ratio of transverse (or lateral) to longitudinal (or axial) strain (eqn 1):

$$\nu = - \frac{\varepsilon_{lateral}}{\varepsilon_{axial}} \quad (1)$$

A certain material can be made to have that effect by changing its internal (micro) structure and getting it to work properly with the way the material deforms under load. This is achieved by methods of changing and geometrically refining it. When the material is mechanically transformed, the proper deformation modes and mechanisms are acquired. These ultimately lead to a deformation behaviour that defies reason, exhibiting features like thickening when stretched, thinning when compressed, volume expansion upon stretching, etc. This effect can be seen in Figure 1. In the case of auxetic polymeric foams, where the internal structure created during the foaming process, when carefully managed, results in auxetic behaviour and possesses the following characteristics: When compared to their aspect ratio in their centre part, cell ribs are thicker at the joints. Great concavity is visible in open cells percentage of newly generated cells with certain characteristics. This enables the peculiar "rotation of stiff units" mechanism that, in the case of foams [24], gives rise to the auxetic behaviour. When compared to traditional PU foam as seen in Figure 3, auxetic foams were discovered to be much more able to diffuse energy upon impact.

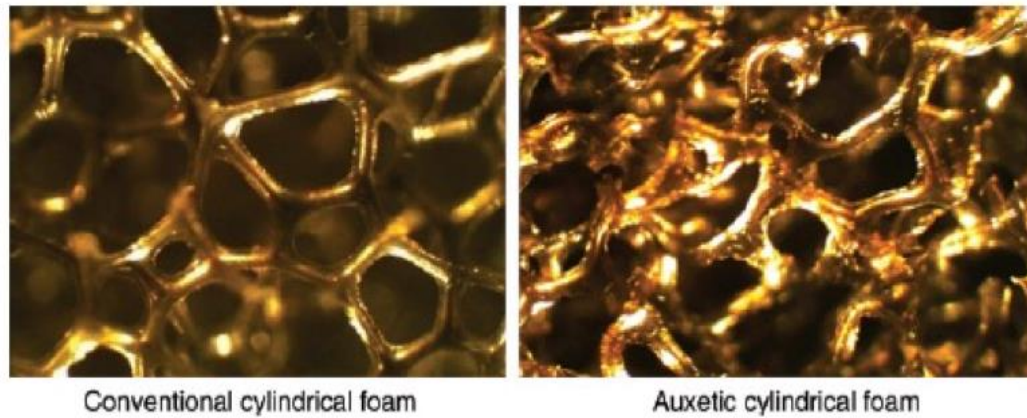


Figure 3: Conventional cylindrical foam compared to auxetic cylindrical foam [25]

## 1.2 Definition of the Problem

Auxetic structures are fairly used in the manufacturing industry to manufacture several parts, especially in the aerospace industry. Auxetic structures due to their negative Poisson's ratio provide good mechanical properties (indentation resistance, fracture toughness, increased plain strain fracture resistance) for manufacturing. Buckling of structures is a major issue in several industries; the buckling test of auxetic structures can provide a good test to show its behaviour under buckling.

## 1.3 Need for Research (Motivation)

Buckling occurs in structures as long as it is fixed on one end and a certain force is exerted at the other. Buckling is a mode of failure under compression according to Britannica. The buckling behaviour of auxetic structures has rarely been discussed/researched. Auxetic structures are used in the manufacturing of some components in the aerospace and automobile industries. These components undergo constant pressure hence the need to investigate the behaviour under these loadings.

## **1.4 Objectives of this Study**

- I. The main goal of this research is to simulate the buckling behaviours of Auxetic structures under compressive loads to derive the Eigenvalues which make these structures buckle under a certain load. The simulation is to be done using ANSYS R2 2021 software.
- II. Different material properties which would be assigned to the Auxetic structure would be simulated and their Eigen values would be compared.
- III. The thicknesses of the structures would be altered to simulate the buckling behaviour and the Eigenvalues under the compressed load compared to the starting thickness.

## Chapter 2

### LITERATURE REVIEW

#### 2.1 History of Research Done on Auxetic Structures

The database gotten for the literature review was gotten from Scopus as well as Google scholar. From the data gotten from Scopus, there have been several papers that have dived into the topic of auxetic structures (that being around the 1666 mark). Figure 4 shown below graphically represents the scope of research done on auxetic structures. As seen in the figure below, there was a high publication of research done on auxetic structures in the year 2021.

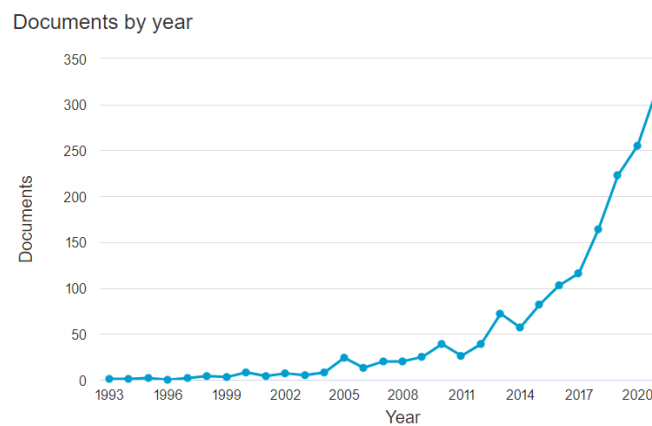


Figure 4: Database from scopus showing documents done by year using the word “auxetic structures” scopus sources [26]

But before that, there was a steady increase in interest dating back from 1993 to 2021. Then when the search was limited to “optimization”, the search results were reduced to 441 documents. From the graph of the refined result, the slope was similar to the previous one as shown in figure 5.

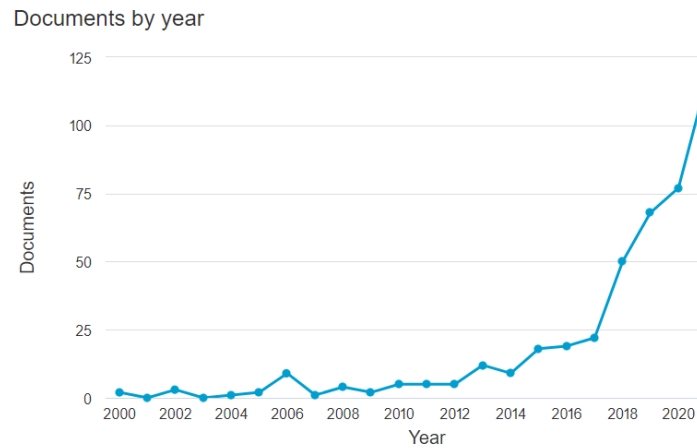


Figure 5: Database from scopus showing documents done by year using the word “auxetic structures” and “optimization”. scopus sources [26]

Refining the search parameters to “genetic algorithm” we get a total of 44 articles related to the optimization of auxetic structures using genetic algorithms (GA). The research done on this differs from the previous graphs shown as seen in figure 6. Dating from 2002-2017 the number of research done was in the range of 0-2, but the research done shot up to 10 in 2018. Research had a dip in the year 2019 which had only 4 researches done. It then had a gradual increase from 2020-2021 with 2021 having the largest amount of documentation [11].

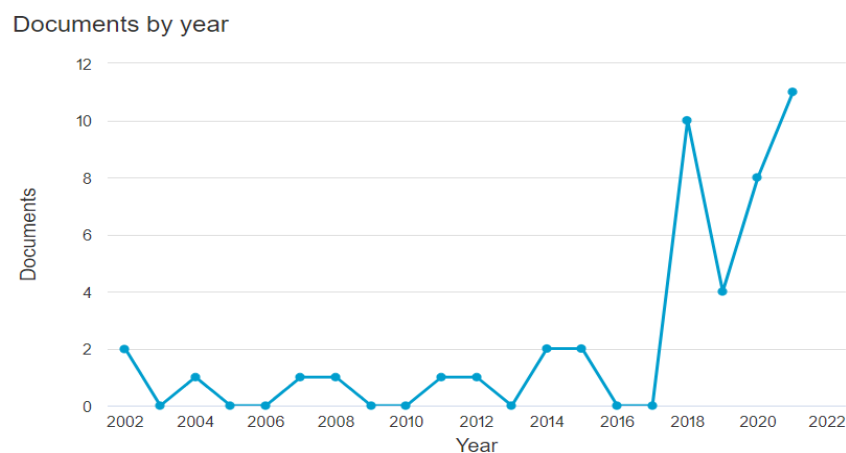


Figure 6: Database from scopus showing documents done by year using the word “auxetic structures”, “optimization” and “genetic algorithm”. scopus sources [26]

Figure 7 shows documents done by territory and it shows China has the most publications with 28, the USA is second with 10, the United Kingdom is third with 6 documents, and then the rest follow.

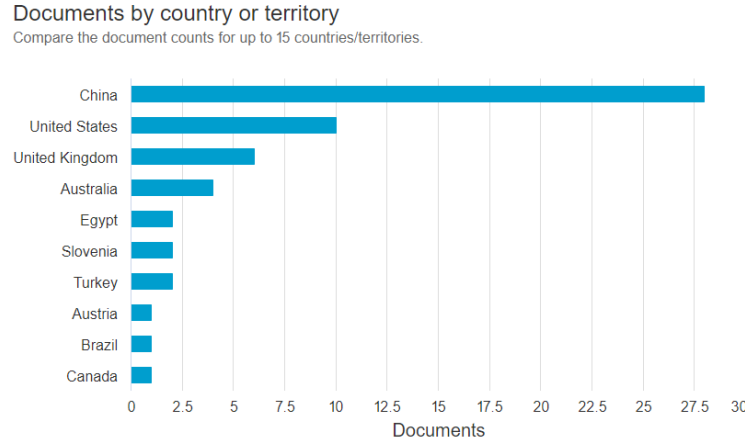


Figure 7: Database from scopus for published papers by country using the keywords “auxetic structures”, “optimization”, and “genetic algorithm”. scopus sources [26]

Out of those 44 articles, the article was done by Zhang. X.Y et al [27] have the most citing at 4. They made research on auxetic structures combined tubular structure with tunable stiffness and they were aiming to improve the bearing capacity and stability by length design of the central column [28]. The next most cited article was done by Tan et al [29] working on the Crashworthiness design and multi-objective optimization of a novel auxetic hierarchical honeycomb crash box with a citing of 3. This paper investigates the crushing performance of an auxetic hierarchical crash box [29]. Research has been done by various researchers on the historical development of auxetic materials. The possibility that Poisson's ratio could take negative values, predicted by Saint-Venant in 1848 [30] for anisotropic continua, resulted in materials with the counterintuitive property of expanding laterally when stretched' on the atomic scale [31]. According to Fung [32], the thermodynamic restrictions imposed on the constitutive law of elastic solids based on

the mathematical theory of elasticity gave the limits of the Poisson's ratio as  $-1 \leq \nu \leq 0.5$  for isotropic solids. In a footnote, Landau and Lifshitz [33] stated that the Poisson's ratio being between 0 and 1/2 only in practice but not thermodynamically necessary is a cautious hint at the possibility of solids with a negative Poisson's ratio. A resurgence of negative In the 1980s, there was more evidence for Poisson's ratio materials, either through experimental measurement or computational simulation. Among these studies are -quartz (Kittinger et al.) [34], and re-entrant hexagonal honeycombs (Gibson et al.) [35]. 3D isotropic structures made of rods, hinges, and springs that keep their shape, i.e.  $\nu = 1$  (Almgren)[36], hexagonal molecules in a 2D lattice (Wojciechowski [37], Wojciechowski, and Branka [37], [38]), and cellular materials (Lakes [12], [21], Caddock and Evans [39]). Some research has been done on the buckling behaviour of auxetic structures. Ming Hui Fu, Yu Chen et al talked about the buckling strength of an enhanced in-plane stiffness of a novel auxetic honeycomb [40]. The in-plane mechanical properties, buckling strength, and Poisson's ratio were calculated in their study. Teik Cheng Lim also wrote an article on the buckling and vibration of circular auxetic plates [41]. The article checks the elastic stability and vibration characteristics of circular plates made from auxetic materials. Nicholas Karnesis and Gaetano Burriesci wrote an article on the uniaxial and buckling mechanical response of auxetic cellular tubes, the study showed how auxetic tubular structures can help in the resistance to kinking which is a phenomenon where a material forms a sharp twist or curve (this generally affects tubular structures).

## **2.2 Properties Common to Auxetic Structures**

Auxetic structures have characteristics specific to them when compared to regular structures. Classical elasticity theory predicts when materials are auxetic; certain

mechanical qualities, including shear modulus, indentation resistance, fracture toughness, and plane strain fracture resistance, have been improved. [42].

Auxetic structures are interesting due to their novel behaviour under deformation and they can be used to enhance other structures as a result of having a negative Poisson's ratio ( $\nu$ ). Regular structures tend to flow away from the impact point in a lateral direction which results in density reduction and also a reduction in the structural indentation resistance. For auxetic structures, during impact, they flow into the direction of the impact due to the lateral shrinkage with the longitudinal contraction. This causes the auxetic structure to be denser under impact in both the longitudinal and transverse directions as seen in figure 6, leading to increased resistance to indentation[43], [44]. The principle of elasticity justifies an increase in indentation resistance [45]. The indentation resistance of a material is proportional to its hardness. ( $H$ ). The equation can be denoted by equation (2) below [46]:

$$H \propto \left[ \frac{E}{(1-\nu^2)} \right]^\gamma \quad (2)$$

- Where  $E$  is Young's modulus,
- $\nu$  is the Poisson's ratio of the base materials and
- $\gamma$  is the constant that, depending on whether there is a uniform pressure distribution or a Hertzian indentation, takes on the value of 1 or 2/3.

Auxetic structures have high indentation resistance; High shear stiffness and the feature that auxetic materials travel to the places where an impact is transmitted, increasing the density of these areas, are the two main causes of this feature. Many studies on materials with re-entrant unit cells, polymeric and metallic foams, and

composite sandwich panels [46], [47] have been conducted. Figure 8 shows the schematic of how molecules move on auxetic structures and non-auxetic structures.

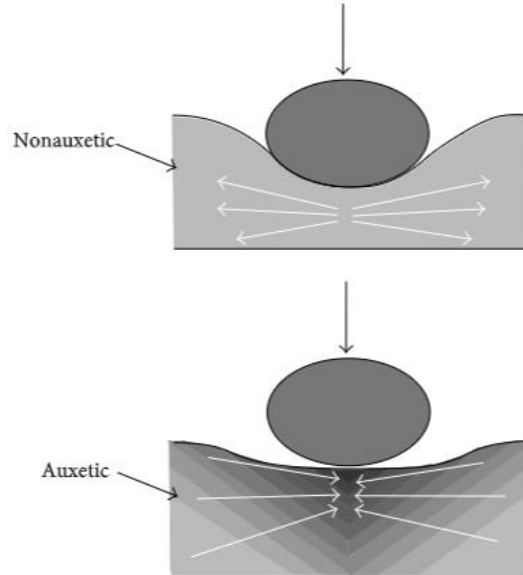


Figure 8: Indentation resistance of non-auxetic and auxetic materials. [43], [44]

Auxetic structures have a high fracture toughness; According to studies, auxetic materials require more energy to develop cracks, and their toughness might alter when the Poisson's ratio changes, with the material becoming very tough if the Poisson's ratio approaches -1 [48]. Auxetic structures have a synclastic curvature in bending; when a bending load is applied to two opposite sides of an auxetic surface, it undergoes synclastic deformation. This characteristic permits the creation of structures with a range of shapes using a limited number of machining operations, preventing material waste and hence lowering manufacturing costs. This characteristic is most common in structures with re-entrant unit cells. Figure 9 shows the schematic of an auxetic foam having a synclastic curvature when bent.

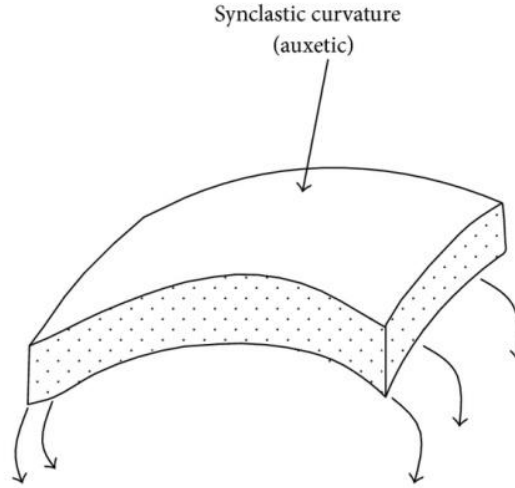


Figure 9: Synclastic nature of auxetic structures [43]

Also, auxetic materials have the properties of being wider when stretched and narrower when being squashed. This is a result of their negative Poisson ratio. A negative Poisson's ratio gives structures enhanced properties such as increased shear stiffness, energy absorption, etc. These enhancements make auxetic structures superior to normal structures for some practical applications [18]. Auxetic structures possess attractive acoustic properties. Auxetic structures have enhanced acoustic absorption for frequencies up to 1600 Hz compared to conventional structures [49].

### 2.3 Negative Poisson's Ratio

Poisson's Ratio was named after Simeon Dennis Poisson (21 June 1787–25 April 1842)[50], a mathematical genius born in Pithiviers, France. It is defined as the ratio of transverse contraction strain to longitudinal extension strain in the direction of stretching force application. Four constants are used to describe a material's elastic behaviour: Shear modulus ( $G$ ), Young's modulus ( $E$ ), bulk modulus ( $K$ ), and then Poisson's ratio ( $\nu$ ). For isotropic materials, the four constants for isotropic materials are interdependent. The Poisson's ratio for stable materials should not be lower than -1 or more than 0.5 because the shear modulus and bulk modulus require positive

values. This means that Poisson's ratio should be within the range of  $-1 < \nu < 0.5$  in 3D and the range of  $-1 < \nu < 1$  in 2D [51]. The negative Poisson's ratio is given by equation(1).

Auxetic behavior is found in a very small number of material formations. An iconic ground structure for auxetic materials is the re-entrant structure. It's made up of V-shaped components that are repeated. These units open up when they are in tension (stretched) and then closed while being compressed. There is just a common shape of the base cell for the re-entrant structure which is the bow tie shape.

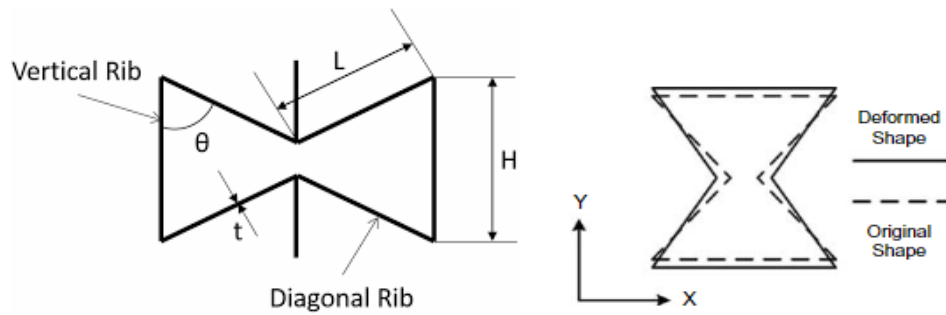


Figure 10: 2D re-entrant bow tie shape and its deformed shape [52]

The same structure also exists for 3D re-entrant structures and their deformation, as seen in figure 11 below. (The dash lines represent the deformation).

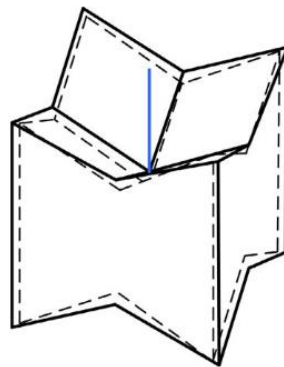


Figure 11: 3D re-entrant bow tie shape and its deformed shape [52]

Love reported negative Poisson's ratios for single-crystalline iron pyrite for the first time in 1944[53]. Negative Poisson's ratios were thought to be impossible to achieve at the time, and twining defects in pyrite crystals were ascribed for the phenomenon. Lakes found the polyurethane (PU) foam with re-entrant structures with a negative Poisson's ratio in 1987. Anti-rubber, auxetic, or dilatational compounds were termed by researchers for their behaviour. Auxetic materials are rare in nature. An auxetic substance that can be found in nature is bone. Williams and Lewis (1982) and Evans (1982) measured the negative Poisson's ratio of bone (1990). A methodology for improving and engineering the microstructure of auxetic materials is presented in this work. It is shown that a wide range of new auxetic materials with variously negative Poisson's ratios could be created using this method. The proposed technology can also be utilized to tailor materials with specified Poisson's ratio values (negative or positive) or other elastic properties.

## **2.4 Applications of Auxetic Structures**

Considering the properties that are unique to auxetic structures due to their negative Poisson's ratio. Potential applications of auxetic structures have been developed even for mechanisms that were thought to be impossible.

### **2.4.1 Auxetics in Biomedical Field**

Auxetic structures are used in the biomedical field to make auxetic microporous and cellular materials. Dilators are used in the opening of the cavity of arteries. The artery is opened by the lateral expansion of a flexible auxetic polytetrafluorethylene (PTFE) sheath which is under tension [54].

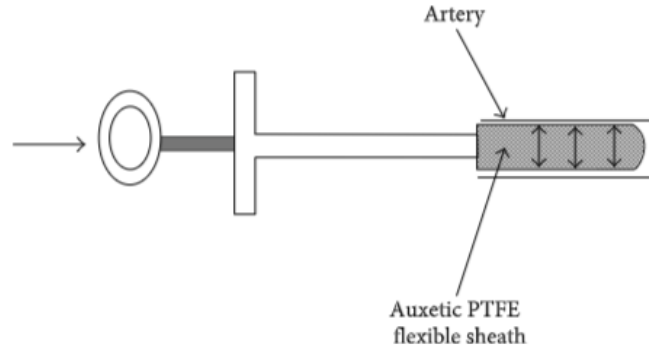


Figure 12: Dilator using an auxetic end sheath [43], [44]

### 2.4.2 Auxetics in Piezoelectric Sensors

Auxetic structures are also used in the manufacturing of piezoelectric sensors [45]. These structures have a low bulk modulus [46] and also the ability to maintain an auxetic matrix that follows the distortion of the piezoelectric rods. It makes the sensors more sensitive to pressure changes. This phenomenon can be seen in figure 13 below.

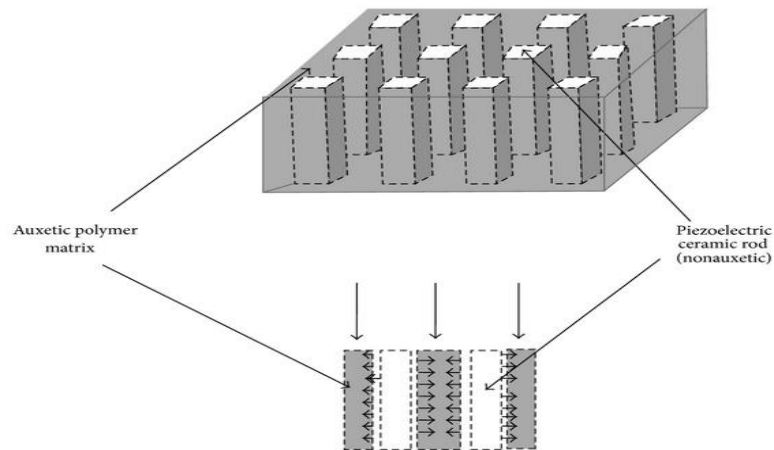


Figure 13: Auxetic piezoelectric sensor [54]

### 2.4.3 Auxetics in Filters

The fluctuating permeability of auxetic structures is one of its characteristics. This quality allows for the production of intelligent filters, which may be produced in a

variety of shapes and sizes to regulate the passage's pressure during filtering [55]. Auxetic honeycomb membrane filter holes open in the lateral direction as well as in the direction of applied tensile load, which makes sure defouling can be made possible [55] as seen in figure 14 below.

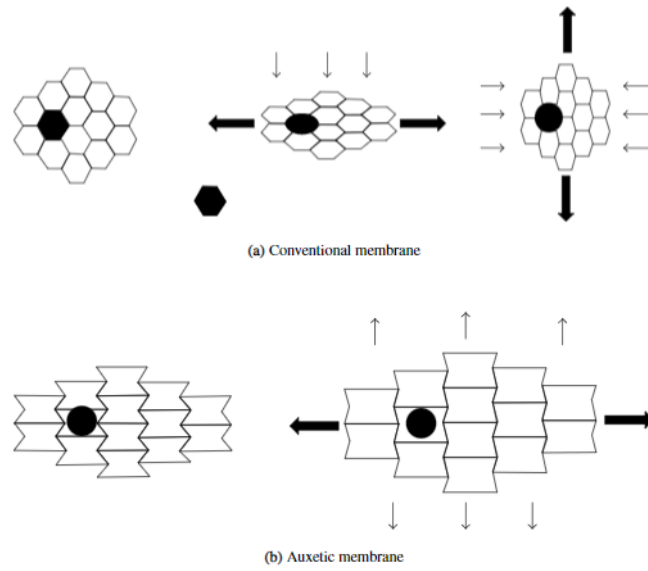


Figure 14: Particulate defouling abilities of (a) nonauxetic honeycomb membrane filters and (b) filters with auxetic membranes [55]

#### 2.4.4 Auxetics in Antennas

Auxetic structures are also used in the manufacturing of chiral-based honeycomb deployable antennas which are used for deep-space missions and make use of the shape memory properties [56]. The antenna is folded while it is being transported into space, and then unfolds itself when it senses the thermal energy of the sun.

#### 2.4.5 Auxetics in Textile Industry

Auxetic structures are also used in the textile industry. In recent years, auxetic textiles, such as auxetic fibres, yarns, and fabrics, have gotten a lot of attention. Using a continuous partial melt extrusion method, Alderson et al.[57] Created auxetic polypropylene (PP) fibres for the first time. The obtained NPR (negative

Poisson's ratio) was 0.6. Auxetic fibres, such as auxetic polyester fibres [58], [59] and nylon fibres [58], were invented and developed following that. Auxetic helical yarn (figure 15a) was created by wrapping two non-auxetic filaments of varying stiffness around a softer core filament [60]. The stiff filament becomes straight when stretched, while the soft core filament wraps around the stiff filament, as seen in (figure 15b). This type of auxetic yarn was used to create woven cloth [61] (figure 16) that might inherit the yarn's auxetic effect.

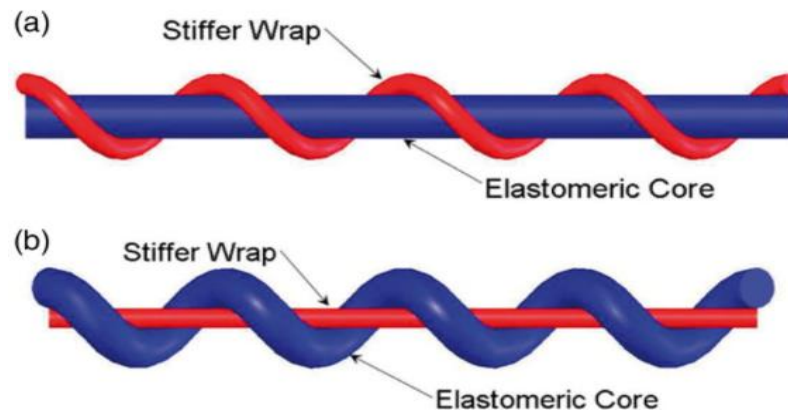


Figure 15: Auxetic yarn (a) auxetic helical yarn with harder core (b) auxetic helical yarn with soft core [60]

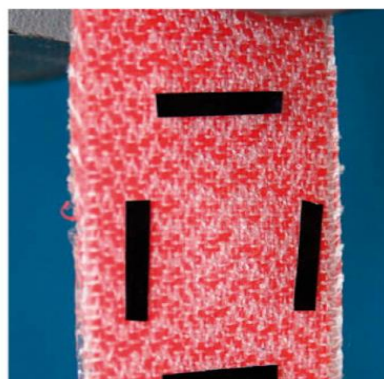


Figure 16: Auxetic woven fabric [61]

## **2.5 Types of Auxetic Structures**

There are different types of auxetic structures each distinct through their differences in structure, mechanism of deformation, and scale. Polyethene foams, polypropylene (PP), laminates, and various rocks with tiny fractures are examples of auxetic structures that have been observed, idealized, synthesized, and predicted. [42].

### **2.5.1 Auxetic Cellular Solids**

First discovered by Lakes in 1987 [21], a re-entrant cell shape was a defined foam structure where the material showed auxeticity. They are made using a one-stage thermomechanical process, which includes tri-axial compression of conventional open-cell foam into a mould. The mould is then heated slightly above the softening point of the foam material, and then it is cooled and relaxed. Cellular materials provide functional characteristics that are unique to themselves such as high stiffness and specific strength, high absorption of mechanical energy, and heat transfer control [62], [63]. To achieve these requirements for application, the properties of the cellular material can be tuned by manipulating the topology and size of the cell. Polyethene foams were transformed into re-entrant microstructures recently through thermomechanical processing giving them the auxetic property. To achieve auxeticity in re-entrant forms the key is in the microarchitecture of the structure as seen in figure 17 below, where the ribs of the auxetic foams' cells come concave when compared with normal foams' convex cell structure [42].

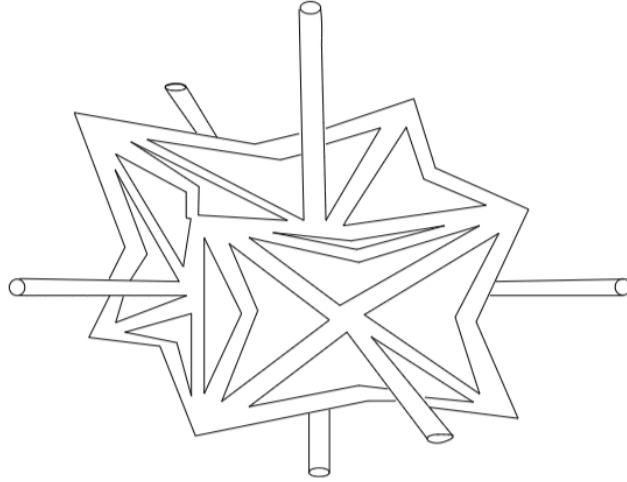


Figure 17: Re-entrant unit cell [42]

Auxetic cellular solids can also be categorized into chiral structures, crumpled and perforated sheets models, semi-rigid structures, etc. as seen in figure 18.

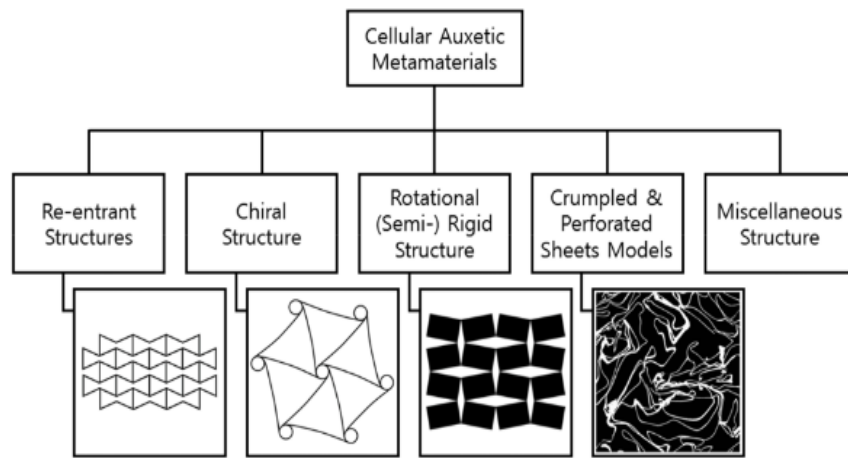


Figure 18: Classification of cellular auxetic structures [64].

Auxetic structure is obtained from conventional honeycomb (intact), where cutting some ribs results in missing rib structure [65]. Exceptional work was done by Gasper et al.[66] where they worked on the experimental testing of two different missing rib structures and two conventional structures as seen in figures 19a and 19b.

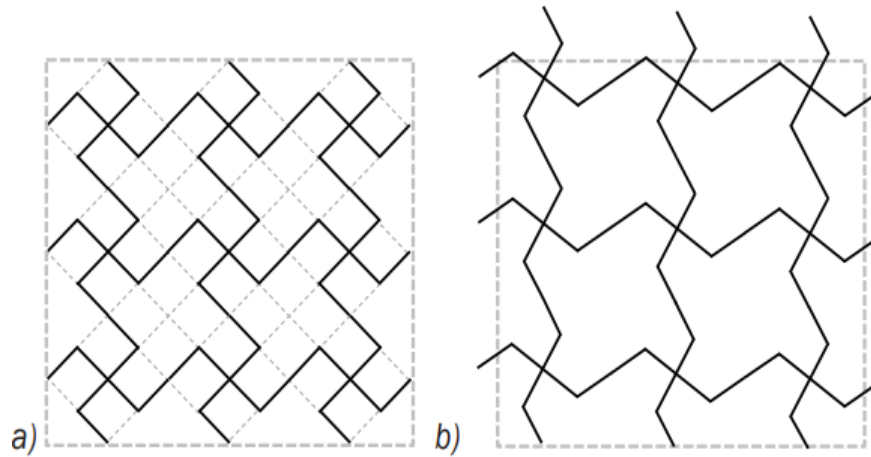


Figure 19: (a) undeformed (b) deformed missing rib structure [66]

Grima and Evans [67] described auxetic structures with rotating units, in which rigid rectangular and triangular cells are hinged together at specified vertices as seen in figure 20. Because of these structures, Poisson's ratio has an analytical value of minus one. Analytical formulas for rotating rectangles [68], [69], and triangles [67] were used to study the auxetic behavior of rotating units.

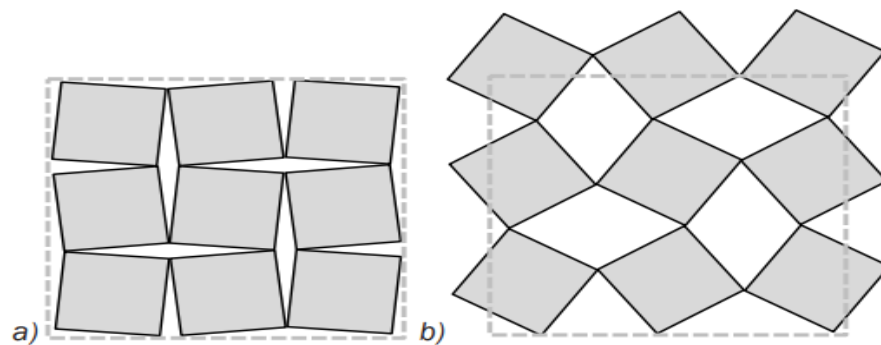


Figure 20: (a) undeformed (b) deformed rotating rectangles [68], [69]

### 2.5.2 Microporous Auxetic Polymers

The microporous PTFE microstructure when subjected to load is mainly composed of an interconnected network of nodules and fibrils that produces auxeticity as seen in figure 21 below.

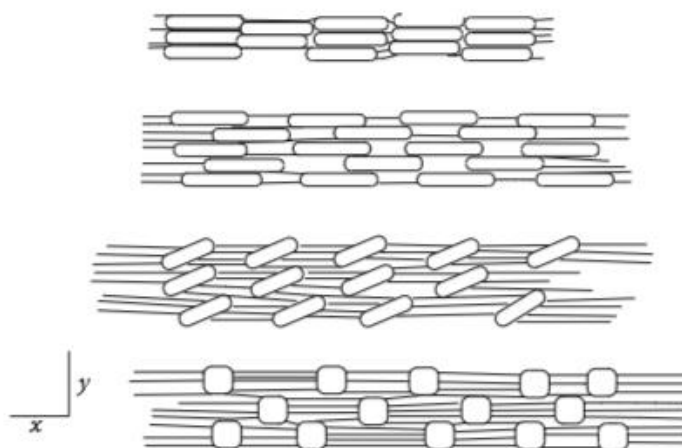


Figure 21: Microporous PTFE going through tensile loading in the x-direction, the tension in the fibrils causing transverse displacement of nodes and lateral expansion [42]

The nodules and fibrils worked together to expand in the transverse direction, while the fibrils pushed the nodules apart. With increasing tensile strain, the value of Poisson's ratio increased, reaching as high as 6 [70] and even 12 [39] in some cases. Sevick et al. [71] discussed how porous membranes grafted with polymers may act as valves and sensors. Densely grafted chains in excellent solvents generate impenetrable layers that swell under shear for both externally and internally grafted chains.

### 2.5.3 Molecular Auxetic Structures

The auxetic molecules are found in polymers with particular inorganic crystals such as zeolites, silicon dioxide, and elemental metals. Figure 22 shows the creation of auxetic molecule [54] using a method based on site-connectivity driven rod reorientation in main-chain liquid crystalline polymers.

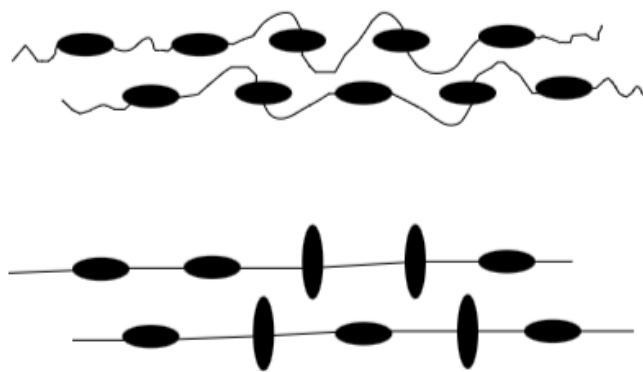


Figure 22: The arrangement of laterally attached rods in the main chain liquid crystalline polymer [42]

When the flexible spacers in the polymer chain are stretched, the laterally attached rods are forced to move from a position roughly parallel to the tensile axis to a position normal to it, pushing the surrounding chains apart [42]. Twisted-chain Auxetic 23odeled23 is created by a soft shear deformation mode for helical polyacetylene chains produced from neighbouring chains in a linked polydiacetylene chain network. [43], [44]. Auxetic microstructures have intrinsic flaws, which are addressed by molecular auxetics. Auxetic characteristics have no scale limitations, hence auxetic materials can be designed at the molecular level. Modifying the molecular structure offers a significant deal of control over the overall auxetic properties by integrating molecular components that make the structure display auxetic activity. These materials will have an edge over natural and microscale auxetics since they already have a variety of customizable mechanical properties [72].

## Chapter 3

### METHODOLOGY

#### 3.1 Design and Modelling of Auxetic Structures

Auxetic structures were designed and optimized using the topology optimization method [4], [6], [73], [74], homogenization [50], [75]–[80] and genetic algorithm. According to Kaminakis et al. [6] to create new auxetic structures, topology optimization was applied. The following are the steps [6] that are used in the mathematical formulation of topology optimization:

- (i) The design domain is discretized into finite elements, and each element (e) is given a density design variable ( $X_e$ )
- (ii) The specification of a structure's objective function with appropriate limitations. The goal function can be to reduce overall structure flexibility or to increase transverse displacement ( $U_{out}$ ) [6]. The following equations (equations 2 and 3) [81] can be used to show the formulation of a structural optimization problem that can be put into auxetic structures.

$$\min_{u, X_e} c(X_e) = f^T u$$

$$\text{Or} \tag{3}$$

$$\max_{u, X_e} U_{out}$$

Subject to

$$Ku = f$$

$$\begin{aligned}
\sum_{e=1}^N v_e x_e &\leq \phi V_0 \\
0 < x^{min} &\leq x_e \leq 1 \\
e &= 1, \dots, N
\end{aligned} \tag{4}$$

In equation (3), the objective function is the global flexibility where  $f$ ,  $u$ , and  $x$  represent input load, displacement, and density design variables respectively. In equation (4),  $v_e$  represents the volume of the finite element,  $V_0$  represents the domain volume and  $\phi$  denotes the fraction of design space.  $X^{min}$  represents the lower bound of the density. The global stiffness matrix,  $K$ , is determined by putting element stiffness matrices together as shown in equation (5) below.  $K_0$  is the element stiffness matrix, which has a density of  $X_e = 1$ .

$$K = (\sum_{e=1}^N x_e^v K_0), \rho \geq 3 \tag{5}$$

According to Javadi et al, [13] the Genetic Algorithm (GA) technique was used in addition to FEM to develop and optimise the auxetic structures. Examining auxetic microstructures with previously determined behavioural demands can be treated as an optimization problem to use GA. The benefit of using GA is that it can effectively locate the global optimum because it searches a population of points instead of a single point and allows for the consideration of a combination of continuous and discrete variables. Auxetic microstructures can be created using geometry and size optimization approaches. Geometry coordinates can be regarded as variables in geometry optimization, whereas cross-section size will be regarded as a variable in size optimization. The formulation can be written as seen in equation (6): [13]

$$\begin{aligned}
&\text{find } x \in R_k \\
&\text{minimize } f(x) \\
&\text{subject to } g_i(x) \leq 0, i = 1, 2, 3, \dots, n
\end{aligned}$$

$$x_j^L \leq x_j \leq x_j^U, j = 1, 2, \dots, k \quad (6)$$

- Design variables represents  $x$
- Objective function  $f(x)$  is used to reduce the structures' Poisson's ratio.
- The constraint functions, which could represent node displacement, are denoted by  $g(x)$ .
- $x_j^L$  and  $x_j^U$  show the lower and upper bounds of the design variables (side constraints).

Ribeiro and Körner [82] used finite element Eigenmode analysis on various cellular architectures in another approach to designing and optimizing periodic structures. They discovered that the resonance 26odeled26 of basic structural elements is closely connected to frequency band gaps. As a result, a modal analysis of individual structural elements can be used to estimate the dynamic 26odeled26 of the proper periodic lattice structure. The goal of 26odeled26 auxetic structures is to ease their mechanics and understand their 26odeled26. The auxetic structure is divided into beams, and analytical models [83] are created by calculating the bending moments of each beam using free-body diagrams. The Castigliano principle as seen in equation (7) is then used to measure the deflection of each of the auxetic structure's beam components. This method can also be used to calculate Young's modulus of auxetic materials.

$$\delta = \frac{\partial U}{\partial P} = \sum_i^n \int \frac{M_i}{EI} \frac{\partial M_i}{\partial P} dz \quad (7)$$

- $U$  represents the strain energy,
- $M_i$  represents the bending moment of each beam,
- $E$  represents the Young's Modulus and
- $I$  represent the moment of inertia,

- $n$  is the number of beams in the auxetic structure.

Experiment feedback advocates for the use of either enhanced continuum models [79], [80], [83], [84] or full field finite element simulations capable of accurately describing the geometry [8], [75], [76], [85], [86].

Examples of FEM modeled research, element type selection, application of symmetry and repeated boundary conditions, mesh sensitivity, as well as additional elements like the transformation of a complex structure into a simpler one or the discovery of a representative volume element (RVE) [81]. Evans et al.[87] created a re-entrant 3D dodecahedron analytical and finite element model. In the modeled and analytical study, three-dimensional elastic beam elements were used. In the FE model, periodic boundary conditions were used. Both positive and negative Poisson's ratios can be manufactured by altering the cell geometry in open-cell foams, it was observed. Scarpa et al.[88] performed analytical and FEM modeled of in-plane uniaxial loading done on auxetic honeycombs. The model's inputs were the aspect ratio, relative thickness, and internal cell angle. The FEM model was discretized using 2,508 two-node beam elements, modeled 2,131 nodes. The cross-sectional area of the beam element was rectangular. Poisson's ratio is strongly dependent on the geometrical parameters of the model, according to the study. The numerical modeled of auxetic composite panels was conducted by Imbalzano et al. [8] Blast load/pressure and geometrical specifications for 3D re-entrant cells are model parameters. There were two different FE model types applied. While the second was mesh with a node second-order Timoshenko beam elements, the first was mesh with tetrahedral modified second-order solid elements. Figure 23 below shows the modeled done by Imbalzano et al. [8].

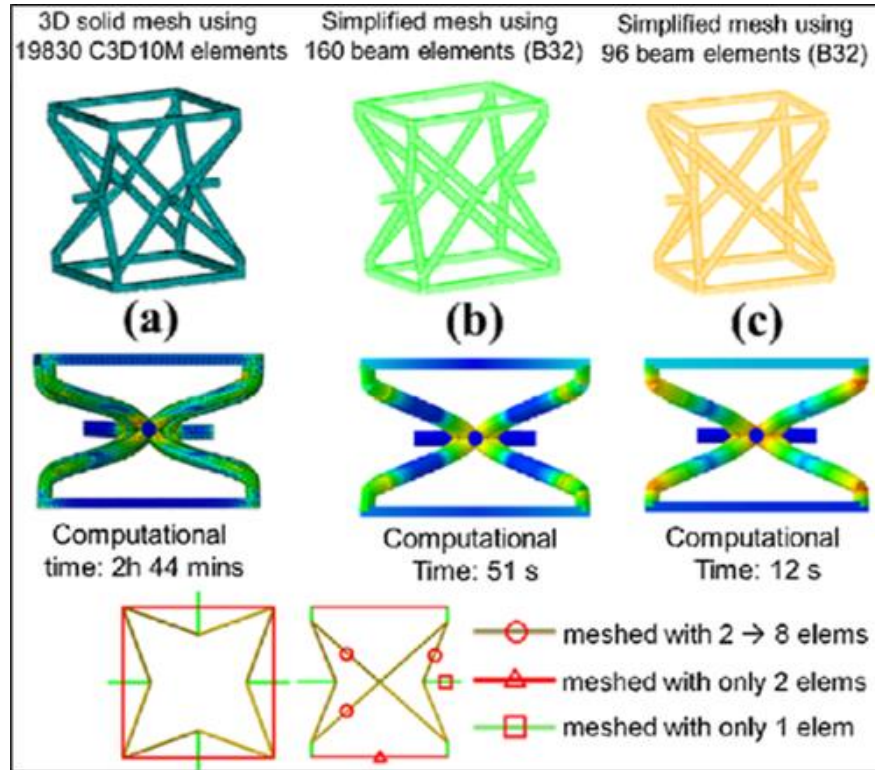


Figure 23: Model for 3D re-entrant cell (a) full tetrahedral mesh (b) beam element (c) beam element [8]

It was found that the time of computation for solving a model with solid elements was much longer than for solving a model with beam elements. Qiao and Chen [86] modeled the quasi-static and dynamic impact on double arrowhead auxetic honeycombs using analytical and FE methods. Four nodes, quadrilateral stress/displacement shell elements with reduced integration, and a large strain formulation were used to mesh the cell walls. It was revealed that re-entrant angles alter the collapse stress for low-velocity impact, but the auxetic effect is ineffectual for high-velocity impact.

### 3.2 Design Parameters of Aluminium Auxetic Panel

The design of Aluminium re-entrant auxetic structures is critical in guaranteeing the structure's integrity while staying within established structural dimensions and materials to handle the given load. Auxetics design factors include in-plane shear,

inter-laminar shear, tensile, and compressive strengths. Mechanical tests or theoretical calculations are used to determine design factors for auxetic structures. A plate is expected to buckle at some critical load ' $N_x$ ' under uniform transverse stress. Geometry, edge conditions, and flexural characteristics all influence buckling loads. Shear buckling can cause thin plates to break before shear failure force. The re-entrant unit cells consist of the following dimensions as seen in Table 1:

Table 1: Dimensions of the re-entrant structure unit cell

| Length of a cell (mm) | Height of a cell (mm) | Angle of re-entrant cell ( $^{\circ}$ ) | Thickness of cell (mm) |
|-----------------------|-----------------------|-----------------------------------------|------------------------|
| 38.5                  | 30                    | 60                                      | 10                     |

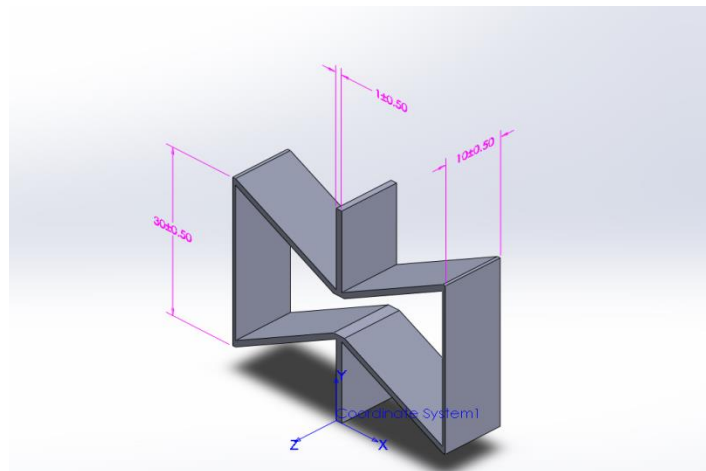


Figure 24: Unit re-entrant cell and dimensions

The load used for the simulation was a force exerted on structure of 1N as seen in Figure 25 below.

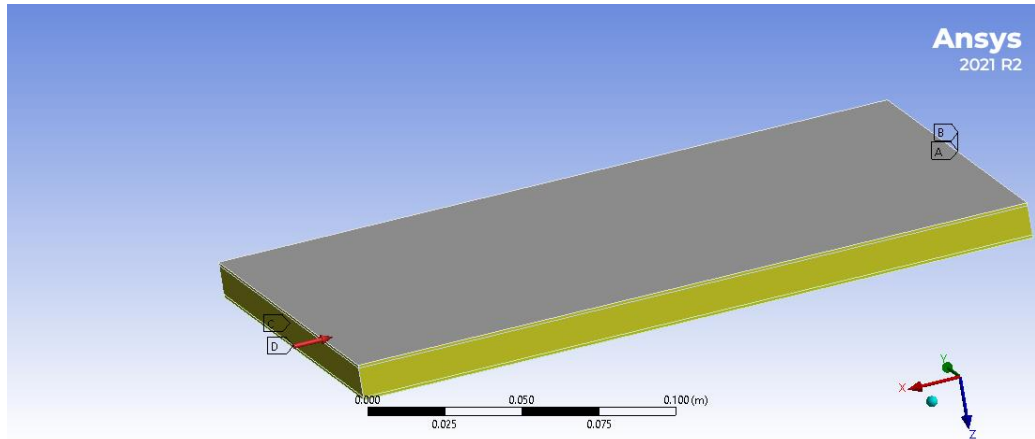


Figure 25: Force exerted for buckling analysis

In Eigenvalue buckling, to get the critical buckling load the exerted load is multiplied by the Eigenvalue gotten. The value gotten is the critical buckling load that causes the structure to buckle. Hence  $1N \times \text{Eigenvalue } (\lambda) = \text{Critical buckling load } (\sigma)$ . The lateral deflections rise as the load is increased beyond the critical load ( $\sigma$ ) and eventually, it may fail in other modes such as material yielding. The stress-strain analysis would also be carried out to determine the deformation of the auxetic sandwich structure. The applied force is 100N. The force was applied in the transverse direction (Z direction) as seen in figure 26 below.

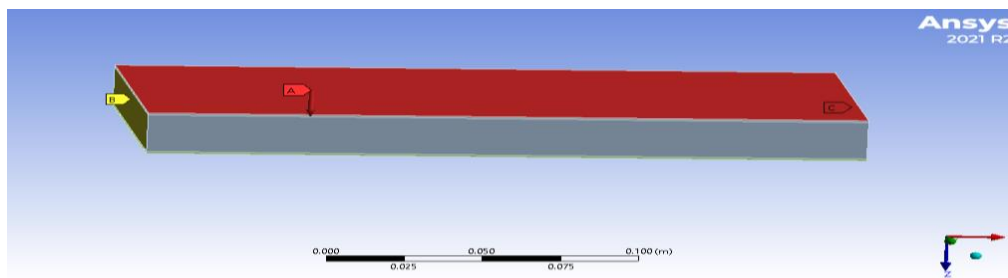


Figure 26: Applied force for stress-strain analysis

Table 2: Mechanical properties of aluminium alloy 2024

|                 |          |
|-----------------|----------|
| Poisson's ratio | 0.3      |
| Young's Modulus | 72.4 GPa |

|                     |                                                 |
|---------------------|-------------------------------------------------|
| Yield strength      | 290 MPa                                         |
| Density             | $2.8 \times 10^3 \text{ Kg/m}^3$                |
| Thermal expansivity | $23 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$ |
| Specific heat       | $795 \text{ J/Kg } ^\circ\text{C}$              |

### 3.3 Meshing of Finite Element

Mesh creation is one of the most important steps in performing an accurate simulation with FEA. A mesh is made up of elements with nodes, or coordinate locations in space that can vary depending on the element type and represent the shape of the geometry. Undefinable shapes are converted into "elements," which are more recognisable volumes, by the process of meshing. SOLID186 was the element type employed. The higher order 3-D 20-node solid element SOLID186 exhibits quadratic displacement behaviour. SOLID 185 element type is suitable for this simulation because it supports plasticity, hyperelasticity, creep, stress stiffening, large deflection, and large strain capabilities.

Twenty nodes, each with three degrees of freedom—translations in the nodal x, y, and z directions—define the element. Plasticity, hyper elasticity, creep, stress stiffening, large deflection, and big strain capabilities are supported by the element.

The total number of element nodes defined is 4356 and the number of elements is 2090. And the meshing used was a fine mesh as seen in figure 27 below. When it comes to the engineering simulation process, meshing is important. One of the most important aspects that should be taken into account to ensure simulation accuracy is creating a high-quality mesh [89]. Mesh elements enable the solution of governing

equations on mathematically defined volumes with predictable shapes. Partial differential equations are frequently the equations solved on these meshes.

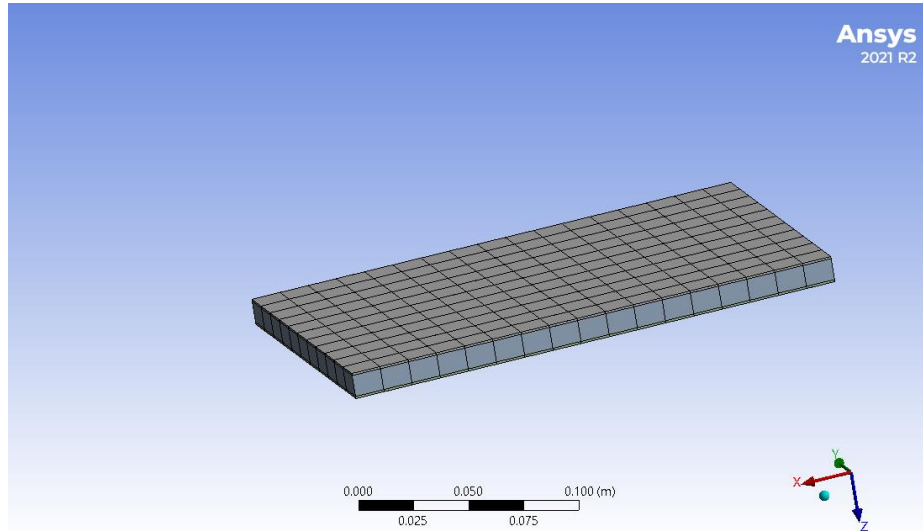


Figure 27: Finite element analysis mesh

## Chapter 4

### RESULTS AND DISCUSSION

#### 4.1 Overview of the Study Results

The study at hand simulated the behaviour of the auxetic structure under buckling. The structure was subjected to a load of 1 N. The main goal of the study was to show the response of auxetic structures under buckling load. A comparison was made with an auxetic structure with a different material composition (comparison between Carbon Fibre Reinforced Plastics and aluminium auxetic structures). The buckling loads would be calculated from the Eigenvalues gotten from the simulation. The ANSYS eigenvalue buckling analysis is commonly used to calculate the critical buckling (bifurcation) load of structures. The eigenvalue buckling analysis can also anticipate the buckling mode forms (eigenvectors). The scaled linear load plus the preload equals the critical buckling loads. The minimum Buckling Load (N) and buckling mode are typical of relevance. These buckling mode shapes are frequently the most valuable result of an eigenvalue buckling analysis, as they anticipate the structure's likely failure modes. In terms of buckling behaviour of structures, several factors can alter it for example thickness of the structure, mass of the structure, applied force etc. For this simulation, the thickness of the re-entrant auxetic structure cell would be put into consideration for both CFRP and aluminium to see its effect on the buckling behaviour of the structures. Also, the re-entrant cell's angle would be altered to see its effect on the buckling behaviour.

## 4.2 Generation of Material Properties from Auxetic Unit Cell Structure

The material mechanical properties were generated from the ANSYS R1 2021 workbench software after a simulation was done on a single unit cell. Mechanical properties are altered with the change of material, change in thickness, and change in the angle of the re-entrant cell. Other conditions can cause the mechanical properties to be altered, but our focus here is the conditions mentioned (thickness change, angle change and material change).

### 4.2.1 Comparison of Mechanical Properties of a Proposed Model with 15mm, 20mm and 25mm Thickness

Table 3: Mechanical properties of proposed model with 15mm, 20mm and 25mm thickness

| Mechanical Property         | 15 mm                    | 20 mm                    | 25 mm                    |
|-----------------------------|--------------------------|--------------------------|--------------------------|
| Density                     | 212.01 kg/m <sup>3</sup> | 257.02 kg/m <sup>3</sup> | 257.02 kg/m <sup>3</sup> |
| Young's Modulus X direction | 63.65 MPa                | 25.507 MPa               | 26.934 MPa               |
| Young's Modulus Y direction | 11.702 MPa               | 7.9373 MPa               | 8.377 MPa                |
| Young's Modulus Z direction | 5434.2 MPa               | 6587.9 MPa               | 6587.9 MPa               |
| Poisson's Ratio XY          | -2.2962                  | -1.7779                  | -1.7776                  |
| Poisson's Ratio YZ          | 0.00071062               | 0.00039759               | 0.00041962               |
| Poisson's Ratio XZ          | 0.0038653                | 0.0012777                | 0.0013492                |
| Shear Modulus XY            | 1.4545 MPa               | 1.1743 MPa               | 1.2244 MPa               |
| Shear Modulus YZ            | 404.12 MPa               | 321.22 MPa               | 321.87 MPa               |
| Shear Modulus XZ            | 1065.5 MPa               | 1114.6 MPa               | 1117.2 MPa               |

From the data shown in table 3 above what can be seen is density increased as the thickness increased. But there was no difference in density between an aluminium alloy of 20mm and 25mm with a value of 257.02 kg/m<sup>3</sup>. The same cannot be said of the Young's Modulus in the X direction, as thickness increases, Young's Modulus decreases. The change from 20mm to 25mm (25.507 MPa - 26.934 MPa) is not as drastic as the change from 15mm to 20mm (63.65 MPa - 25.507 MPa MPa). Likewise, is the increase in the Young's Modulus in the Y direction. As thickness increases, Young's Modulus increases. This is also the case with Young's Modulus in the Z direction. As thickness increases, Young's Modulus increases. This is the case because as thickness is increased, the strain is increased. As Young's Modulus is a factor of both stress and strain.

$$\text{Young's Modulus} = \frac{\text{Stress}}{\text{Strain}} \quad (8)$$

From the equation (8) above when strain is reduced keeping stress the same, Young's modulus is increased. The Poisson's ratio in XY reduces with increasing thickness. Also with increasing thickness, the shear modulus reduces.

#### **4.2.2 Comparison of Mechanical Properties of a Proposed Model with 65°, 70° and 75° Angle**

From Table 4, it can be seen that changing the angle of the re-entrant auxetic structure alters its mechanical properties but there was no change in mechanical properties when the angle was changed from 70° - 75°. The changes from 65° - 70° would be put into consideration. The density reduced with decreasing re-entrant angle. The Young's modulus in the X direction increased with increasing re-entrant angle but Young's modulus in the Y and Z directions reduced with increasing re-entrant angle. There is an increase in the Poisson's ratio with an increase in re-entrant angle.

Table 4: Mechanical properties of proposed model with angles of 65°, 70° and 75°

| Mechanical Property                | 65 °                   | 70 °                     | 75 °                     |
|------------------------------------|------------------------|--------------------------|--------------------------|
| <b>Density</b>                     | 261.1kg/m <sup>3</sup> | 196.56 kg/m <sup>3</sup> | 196.56 kg/m <sup>3</sup> |
| <b>Young's Modulus X direction</b> | 71.454 MPa             | 117.23 MPa               | 117.23 MPa               |
| <b>Young's Modulus Y direction</b> | 18.757 MPa             | 13.829 MPa               | 13.829 MPa               |
| <b>Young's Modulus Z direction</b> | 6692.4 MPa             | 5038.1 MPa               | 5038.1 MPa               |
| <b>Poisson's Ratio XY</b>          | -1.9174                | -2.8378                  | -2.8378                  |
| <b>Poisson's Ratio YZ</b>          | 0.0009249              | 0.00090582               | 0.00090582               |
| <b>Poisson's Ratio XZ</b>          | 0.0035234              | 0.0076789                | 0.0076789                |
| <b>Shear Modulus XY</b>            | 1.4998 MPa             | 1.6026 MPa               | 1.6026 MPa               |
| <b>Shear Modulus YZ</b>            | 392.34 MPa             | 441.26 MPa               | 441.26 MPa               |
| <b>Shear Modulus XZ</b>            | 1341.5 MPa             | 1038.7 MPa               | 1038.7 MPa               |

#### 4.2.3 Comparison of Mechanical Properties of a Proposed CFRP Model with 15mm, 20mm and 25mm Thickness

From Table 5, it can be seen the change of thickness of the re-entrant cell did not affect its density. The density remained 139.18 kg/m<sup>3</sup> consistently for all thicknesses. While the Young's Modulus in the X direction increased as the thickness of the re-entrant cell increased. This is also the case for the Young's Modulus in the Y direction, as the thickness of the re-entrant cell increased the Young's Modulus increased in the Y direction. But the Young's Modulus maintained a value of 3433.1 MPa as the thickness of the re-entrant cell increased. The Poisson's ratio increased slightly with an increased thickness in all directions (XY, YZ and XZ). The shear modulus also increased as the thickness of the re-entrant cell increased in all directions (XY, YZ and XZ).

Table 5: Mechanical properties of proposed CFRP model with 15mm, 20mm and 25 mm thickness

| Mechanical Property                | 15mm                     | 20mm                     | 25mm                     |
|------------------------------------|--------------------------|--------------------------|--------------------------|
| <b>Density</b>                     | 139.18 kg/m <sup>3</sup> | 139.18 kg/m <sup>3</sup> | 139.18 kg/m <sup>3</sup> |
| <b>Young's Modulus X direction</b> | 13.183 MPa               | 13.555 MPa               | 14.329 MPa               |
| <b>Young's Modulus Y direction</b> | 4.1006 MPa               | 4.2185 MPa               | 4.4569 MPa               |
| <b>Young's Modulus Z direction</b> | 3433.1 MPa               | 3433.1 MPa               | 3433.1 MPa               |
| <b>Poisson's Ratio XY</b>          | -1.7785                  | -1.7777                  | -1.7774                  |
| <b>Poisson's Ratio YZ</b>          | 0.00041805               | 0.00043007               | 0.00045438               |
| <b>Poisson's Ratio XZ</b>          | 0.0013439                | 0.0013819                | 0.0014608                |
| <b>Shear Modulus XY</b>            | 0.61029 MPa              | 0.62437 MPa              | 1.65157 MPa              |
| <b>Shear Modulus YZ</b>            | 164.55 MPa               | 164.92 MPa               | 165.26 MPa               |
| <b>Shear Modulus XZ</b>            | 570.84 MPa               | 572.26 MPa               | 573.61 MPa               |

#### 4.2.4 Comparison of Mechanical Properties of a Proposed CFRP Model with 65°, 70° and 75° Angle

From Table 6, the density of the re-entrant cell reduced as the angle of the cell increased. The Young's Modulus in the X direction did not give a linear change as the change from 65° - 70° (37.856 MPa - 33.721 MPa) was a reduction in Young's Modulus as the angle increased and the change from 70° - 75° (33.721 MPa - 62.104 MPa) was an increase in Young's Modulus as the angle increased. The case is the same for the Young's Modulus in the Y direction. The Young's Modulus in the Z direction reduced as the angle of the re-entrant cell increased. The Poisson's ratio increases as the angle of the re-entrant cell increases in all directions (XY, YZ and

XZ). The case is the same for the Shear Modulus as it increases in all directions (XY, YZ and XZ) as the angle of the re-entrant cell is increased.

Table 6: Mechanical properties of proposed CFRP model with angles of 65°, 70° and 75 °

| <b>Mechanical Property</b>         | <b>65°</b>               | <b>70°</b>               | <b>75 °</b>              |
|------------------------------------|--------------------------|--------------------------|--------------------------|
| <b>Density</b>                     | 141.39 kg/m <sup>3</sup> | 114.81 kg/m <sup>3</sup> | 106.44 kg/m <sup>3</sup> |
| <b>Young's Modulus X direction</b> | 37.856 MPa               | 33.721 MPa               | 62.104 MPa               |
| <b>Young's Modulus Y direction</b> | 9.9388 MPa               | 6.2005 MPa               | 7.3282 MPa               |
| <b>Young's Modulus Z direction</b> | 3487.6 MPa               | 2831.9 MPa               | 2625.5 MPa               |
| <b>Poisson's Ratio XY</b>          | -1.9171                  | -2.2959                  | -2.8369                  |
| <b>Poisson's Ratio YZ</b>          | 0.00099742               | 0.00076633               | 0.00097692               |
| <b>Poisson's Ratio XZ</b>          | 0.0037991                | 0.0041676                | 0.0082791                |
| <b>Shear Modulus XY</b>            | 0.79475 MPa              | 0.77112 MPa              | 0.84972 MPa              |
| <b>Shear Modulus YZ</b>            | 201.44 MPa               | 207.48 MPa               | 226.55 MPa               |
| <b>Shear Modulus XZ</b>            | 688.74 MPa               | 547.05 MPa               | 533.3 MPa                |

#### 4.2.5 Comparison of Mechanical Properties of Proposed Model and CFRP Model with 15mm Thickness

From Table 7, it is seen that the mechanical properties of aluminum alloy are vastly improved than that of Carbon Fibre Reinforced Plastics (CFRP). In comparison, the aluminum alloy material provides better mechanical properties than that of CFRP.

Table 7: Mechanical properties of proposed model and CFRP model with 15mm thickness

| Mechanical Property                | 15mm Aluminum Alloy      | 15mm CFRP                |
|------------------------------------|--------------------------|--------------------------|
| <b>Density</b>                     | 212.01 kg/m <sup>3</sup> | 139.18 kg/m <sup>3</sup> |
| <b>Young's Modulus X direction</b> | 63.65 MPa                | 13.183 MPa               |
| <b>Young's Modulus Y direction</b> | 11.702 MPa               | 4.1006 MPa               |
| <b>Young's Modulus Z direction</b> | 5434.2 MPa               | 3433.1 MPa               |
| <b>Poisson's Ratio XY</b>          | -2.2962                  | -1.7785                  |
| <b>Poisson's Ratio YZ</b>          | 0.00071062               | 0.00041805               |
| <b>Poisson's Ratio XZ</b>          | 0.0038653                | 0.0013439                |
| <b>Shear Modulus XY</b>            | 1.4545 MPa               | 0.61029 MPa              |
| <b>Shear Modulus YZ</b>            | 404.12 MPa               | 164.55 MPa               |
| <b>Shear Modulus XZ</b>            | 1065.5 MPa               | 570.84 MPa               |

### 4.3 Eigen Value Buckling Analysis

The buckling Eigen modes of the stiffened composite panel are determined using Eigen-value buckling analysis on the ANSYS R1 2021 workbench workspace. To achieve a physically correct deformed shape, the buckling Eigen modes will be exploited to inject defects into the geometry of the stiffened panel. The total axial force (applied axially on the structure) will be employed in this analysis since determining the buckling load will be easier. The buckling load is equal to the Eigenvalue multiplied by the axial load. Firstly the comparison of re-entrant auxetic structures with different material properties would be simulated and compared (aluminium and CFRP). The sections coming will show the buckling modes of both

material properties and the buckling modes when the angle of the re-entrant cell is changed and the corresponding table of Eigen value comparison.

#### 4.3.1 Buckling Modes of Proposed Model with 15mm Thickness

The Figures 28- 31 show the buckling modes of a sandwich structure with an aluminium alloy of 15mm auxetic re-entrant structure as the core. These modes (1-10) were gotten with an axially applied force of 1N. The red areas show the places of maximum buckling effect and the blue areas show the places of minimum buckling effect. The figures below show modes 1, 3, 6 and 9.

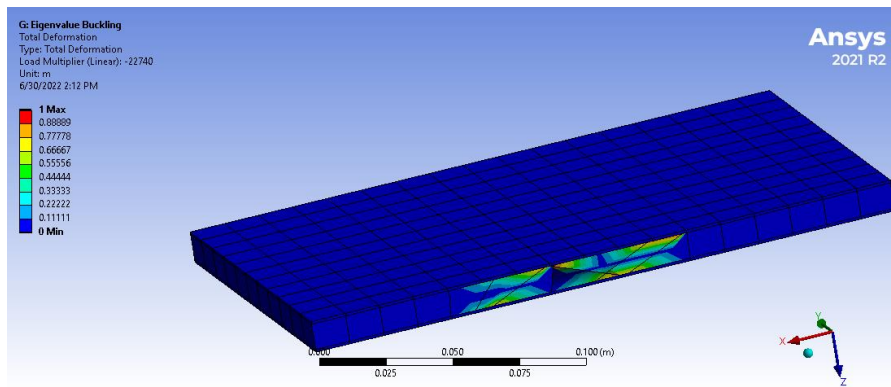


Figure 28: Buckling mode 1 of proposed model with 15mm thickness

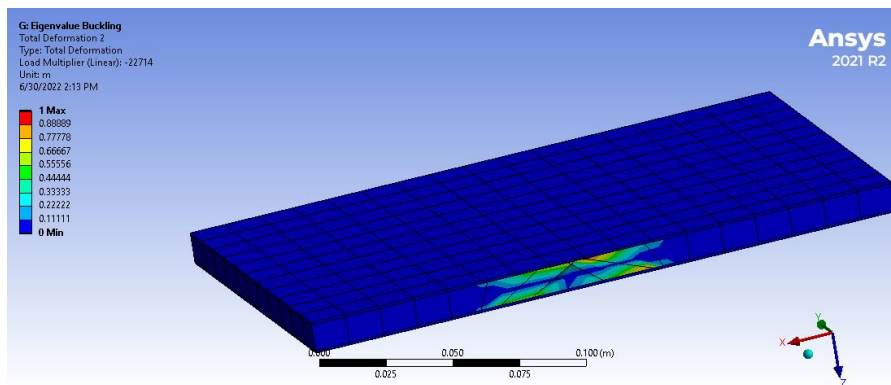


Figure 29: Buckling mode 3 of proposed model with 15mm thickness

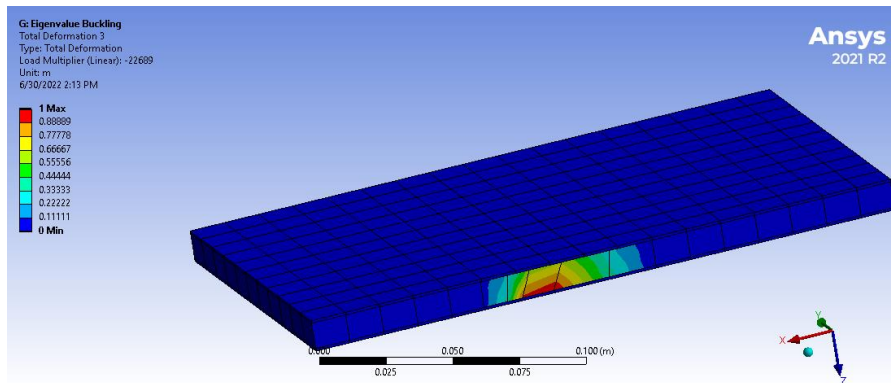


Figure 30: Buckling mode 6 of proposed model with 15mm thickness

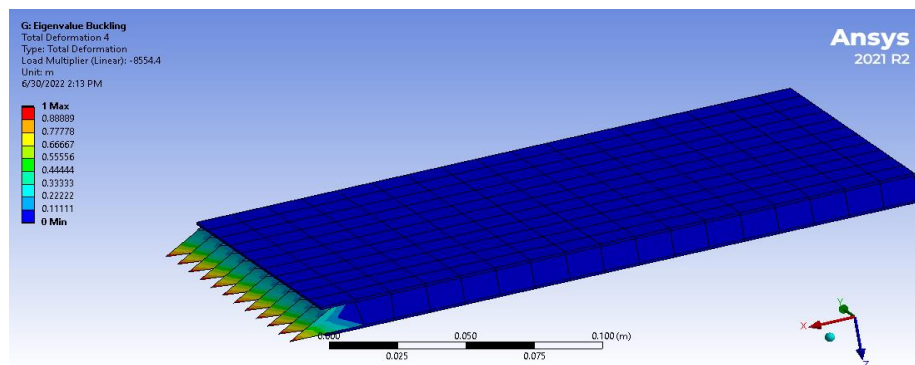


Figure 31: Buckling mode 9 of proposed model of 15mm thickness

The Table 8 extracted from these results shows that the maximum Eigen value gotten was 22740 giving the maximum load to make cause the structure to buckle to be  $1N \times 22740 = 22740N$ . The table below shows the Eigen values from modes 1-10.

Table 8: Eigenvalues corresponding to their modes

| Mode | Buckling Load (N) |
|------|-------------------|
| 1    | -22740            |
| 2    | -22739            |
| 3    | -22714            |
| 4    | -22713            |
| 5    | -22690            |
| 6    | -22689            |
| 7    | -17006            |
| 8    | -17005            |

|    |         |
|----|---------|
| 9  | -8554.4 |
| 10 | -8553.6 |

#### 4.3.2 Buckling Modes of Proposed Model with 20mm Thickness

The Figures 32-35 show the buckling modes of a sandwich structure with an aluminium alloy of 20mm auxetic re-entrant structure as the core. These modes (1-10) were gotten with an axially applied force of 1N. The red areas show the places of maximum buckling effect and the blue areas show the places of minimum buckling effect. The figures below show modes 1, 3, 6 and 9.

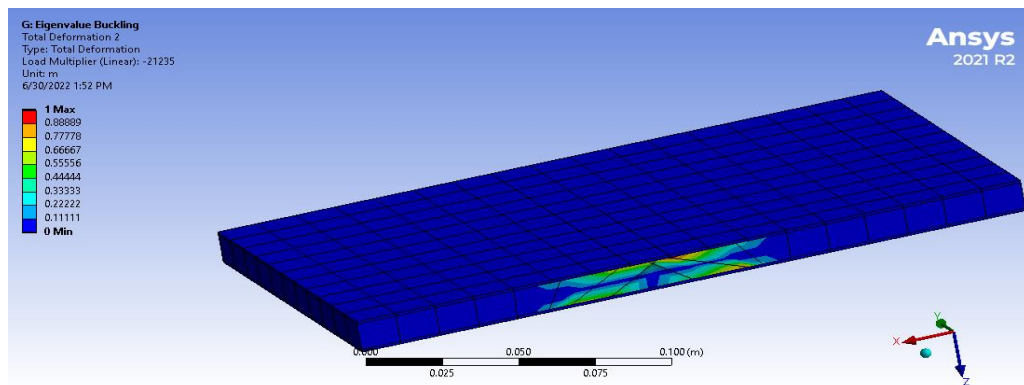


Figure 32: Buckling mode 1 of proposed model with 20 mm thickness

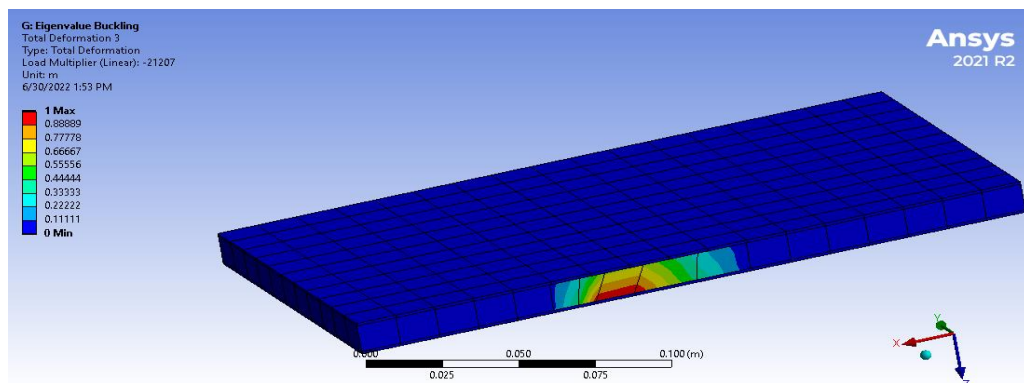


Figure 33: Buckling mode 3 of proposed model with 20mm thickness

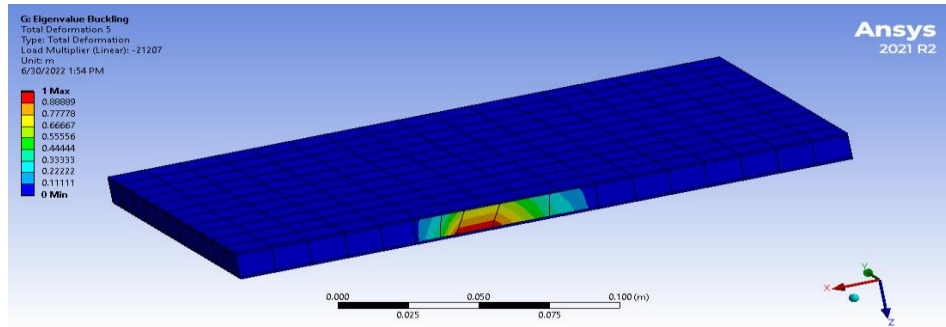


Figure 34: Buckling mode 6 of proposed model with 20mm thickness

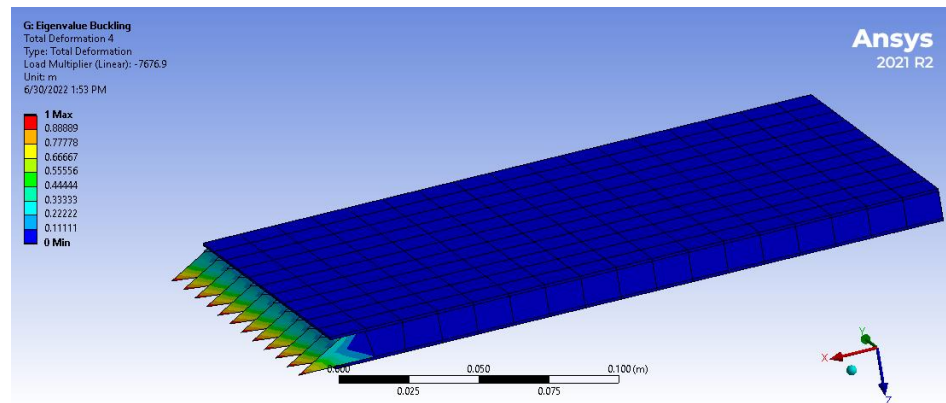


Figure 35: Buckling mode 9 of proposed model with 20mm thickness

The Table 9 extracted from these results shows that the maximum Eigen value gotten was 21267 giving the maximum load to make cause the structure to buckle to be  $1\text{N} \times 21267 = 21267\text{N}$ . The table below shows the Eigen values from modes 1-10 of proposed aluminium model with a thickness of 20mm.

Table 9: Eigenvalues corresponding to their modes

| Mode | Buckling Load (N) |
|------|-------------------|
| 1    | -21267            |
| 2    | -21266            |
| 3    | -21235            |
| 4    | -21235            |
| 5    | -21207            |
| 6    | -21207            |
| 7    | -15894            |

|    |         |
|----|---------|
| 8  | -15894  |
| 9  | -7676.9 |
| 10 | -7676.2 |

#### 4.3.3 Buckling Modes of Proposed Model with 25mm Thickness

The Figures 36-39 show the buckling modes of a sandwich structure with an aluminium alloy of 25mm auxetic re-entrant structure as the core. These modes (1-10) were gotten with an axially applied force of 1N. The red areas show the places of maximum buckling effect and the blue areas show the places of minimum buckling effect. The figures below show modes 1, 3, 6 and 9.

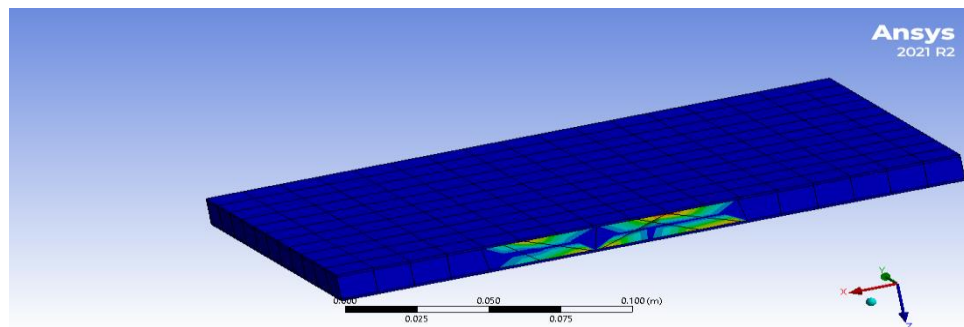


Figure 36: Buckling mode 1 of proposed model with 25mm thickness

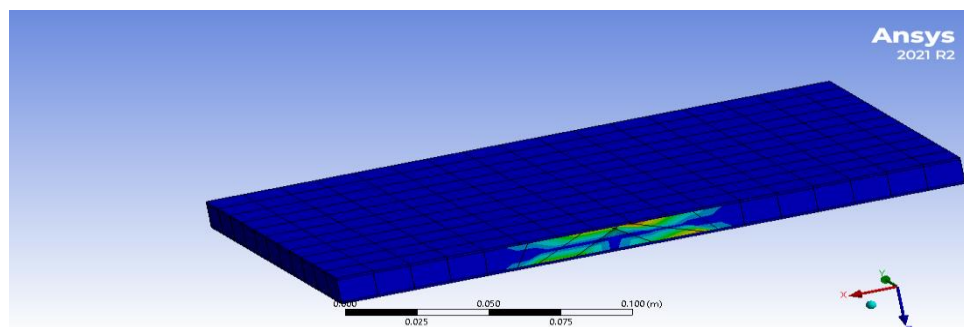


Figure 37: Buckling mode 3 of proposed model with 25mm thickness

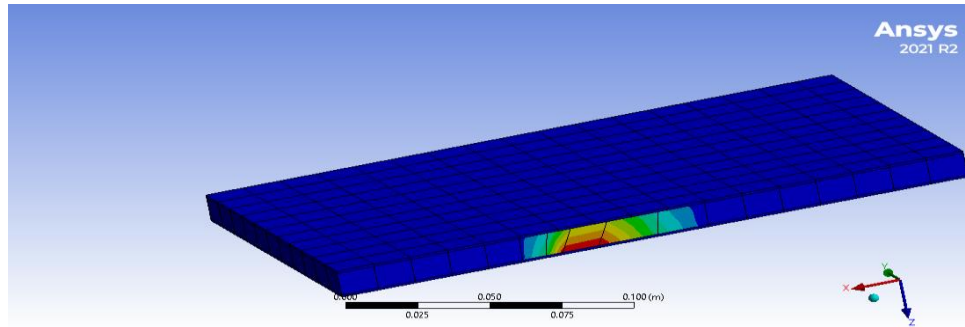


Figure 38: Buckling mode 6 of proposed model with 25mm thickness

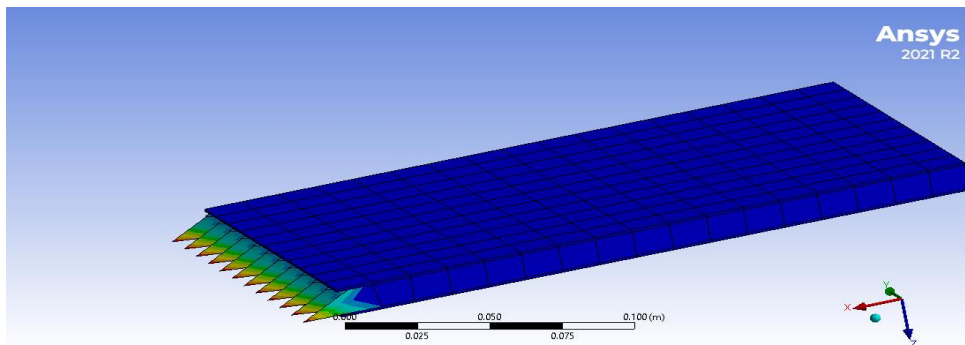


Figure 39: Buckling mode 9 of proposed model with 25mm thickness

The Table 10 extracted from these results show that the maximum Eigen value gotten was 22139 giving the maximum load to make cause the structure to buckle to be  $1N \times 22139 = 22139N$ . The table below shows the Eigenvalues from modes 1-10 of proposed aluminium model with a thickness of 25mm.

Table 10: Eigenvalues corresponding to their modes

| Mode | Buckling Load (N) |
|------|-------------------|
| 1    | -22139            |
| 2    | -22138            |
| 3    | -22106            |
| 4    | -22106            |
| 5    | -22077            |
| 6    | -22076            |
| 7    | -16559            |
| 8    | -16559            |

|    |         |
|----|---------|
| 9  | -8001.5 |
| 10 | -8000.7 |

#### 4.3.4 Buckling Modes of Proposed Model with a 65° Angle

The Figures 40-43 show the buckling modes of a sandwich structure with an aluminium alloy of a 65° angled auxetic re-entrant structure as the core. These modes (1-10) were gotten with an axially applied force of 1N. The red areas show the places of maximum buckling effect and the blue areas show the places of minimum buckling effect. The figures below show modes 1, 3, 6 and 9.

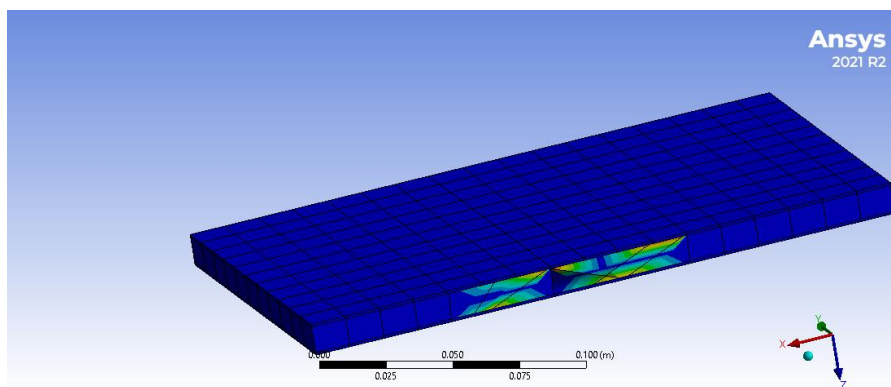


Figure 40: Buckling mode 1 of proposed model with an angle of 65°

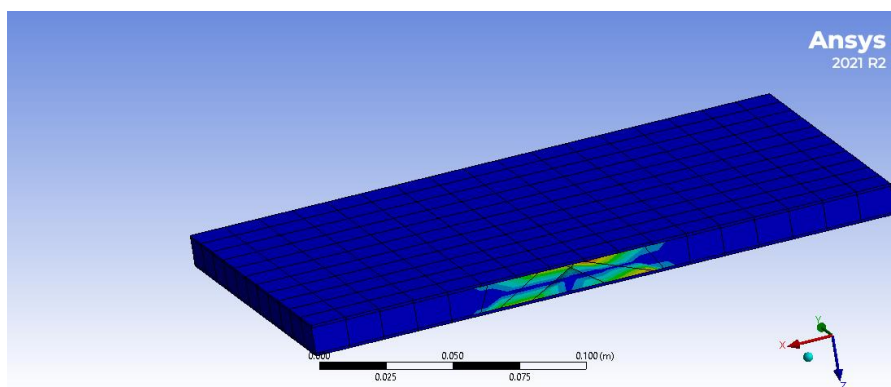


Figure 41: Buckling mode 3 of proposed model with an angle of 65°

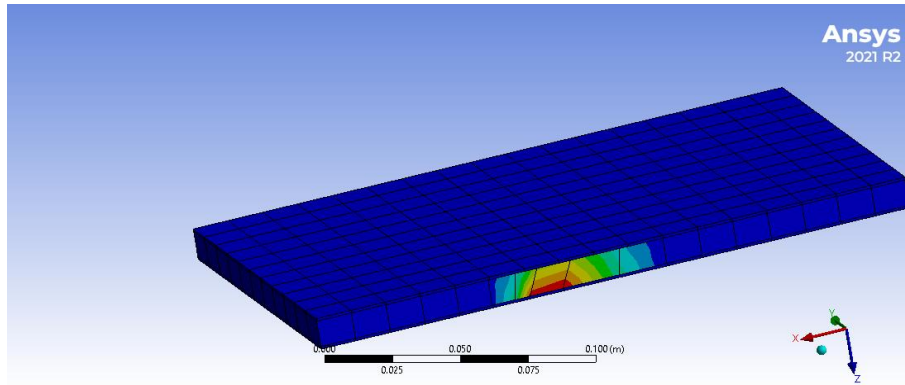


Figure 42: Buckling mode 6 of proposed model with an angle of 65°

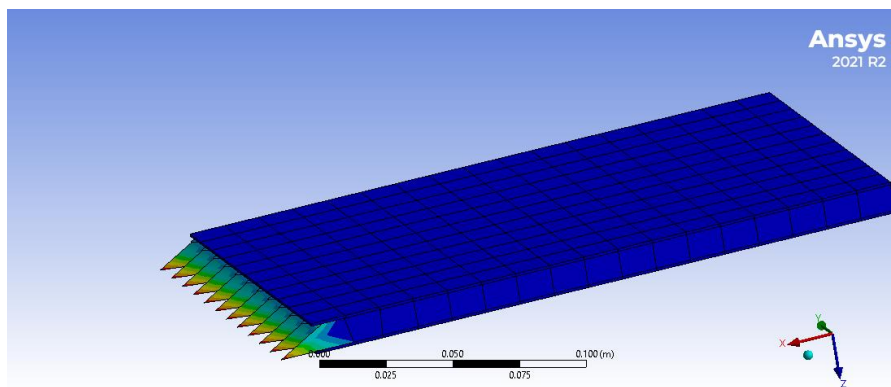


Figure 43: Buckling mode 9 of proposed model with an angle of 65°

The Table 11 extracted from these results show that the maximum Eigen value gotten was 22390 giving the maximum load to make cause the structure to buckle to be  $1N \times 22390 = 22390N$ . The table below shows the Eigenvalues from modes 1-10 of proposed aluminium model with an angle of 65°.

Table 11: Eigenvalues corresponding to their modes

| Mode | Buckling Load (N) |
|------|-------------------|
| 1    | -22390            |
| 2    | -22390            |
| 3    | -22364            |
| 4    | -22364            |
| 5    | -22340            |
| 6    | -22339            |

|    |         |
|----|---------|
| 7  | -17784  |
| 8  | -17784  |
| 9  | -9097.8 |
| 10 | -9097   |

#### 4.3.5 Buckling Modes of Proposed Model with a 70° Angle

The Figures 44-47 show the buckling modes of a sandwich structure with an aluminium alloy of a 70° angled auxetic re-entrant structure as the core. These modes (1-10) were gotten with an axially applied force of 1N. The red areas show the places of maximum buckling effect and the blue areas show the places of minimum buckling effect. The following Figures show modes 1, 3, 6 and 9.

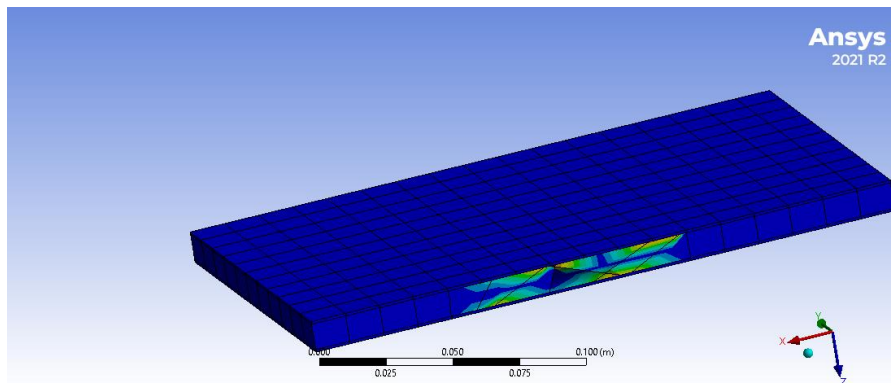


Figure 44: Buckling mode 1 of proposed model with an angle of 70°

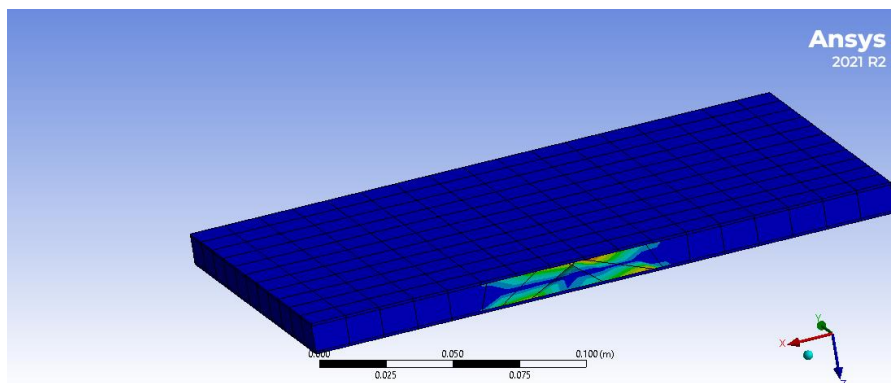


Figure 45: Buckling mode 3 of proposed model with an angle of 70°

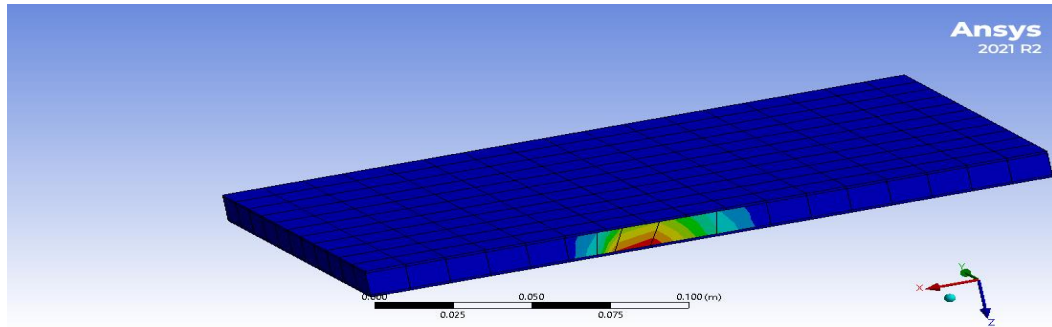


Figure 46: Buckling mode 6 of proposed model with an angle of 70°

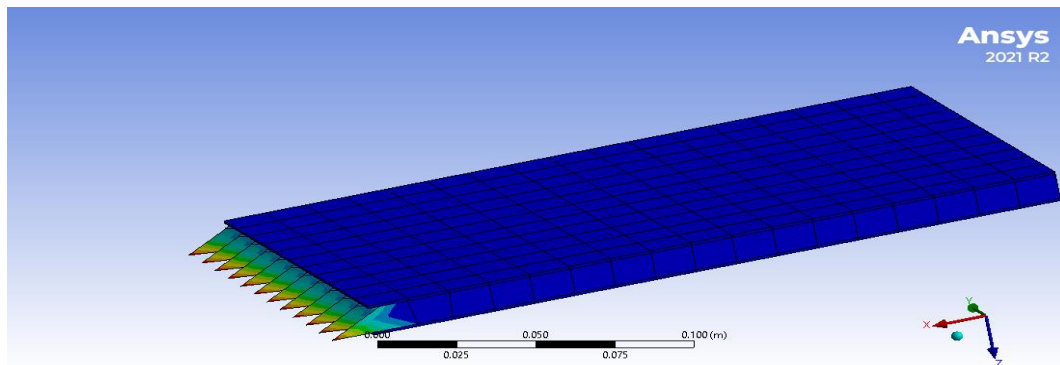


Figure 47: Buckling mode 9 of proposed model with an angle of 70°

The Table 12 extracted from these results show that the maximum Eigen value gotten was 24280 giving the maximum load to make cause the structure to buckle to be  $1N \times 24280 = 24280N$ . The table below shows the Eigenvalues from modes 1-10 of proposed aluminium model with an angle of 70°.

Table 12: Eigenvalues corresponding to their modes

| Mode | Buckling Load (N) |
|------|-------------------|
| 1    | -24280            |
| 2    | -24280            |
| 3    | -24256            |
| 4    | -24255            |
| 5    | -24233            |
| 6    | -24233            |
| 7    | -18123            |

|    |         |
|----|---------|
| 8  | -18123  |
| 9  | -9297   |
| 10 | -9296.2 |

#### 4.3.6 Buckling Modes of Proposed Model with a 75° Angle

The Figures 48-51 show the buckling modes of a sandwich structure with an aluminium alloy of a 75° angled auxetic re-entrant structure as the core. These modes (1-10) were gotten with an axially applied force of 1N. The red areas show the places of maximum buckling effect and the blue areas show the places of minimum buckling effect. The Following Figures show modes 1, 3, 6 and 9.

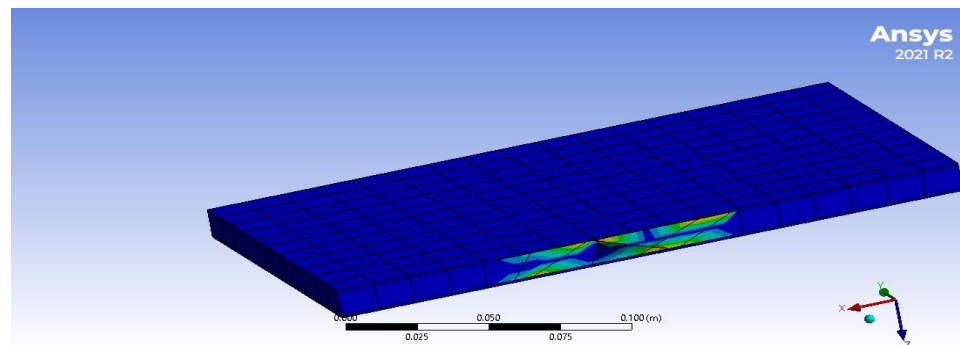


Figure 48: Buckling mode 1 of proposed model with an angle of 75°

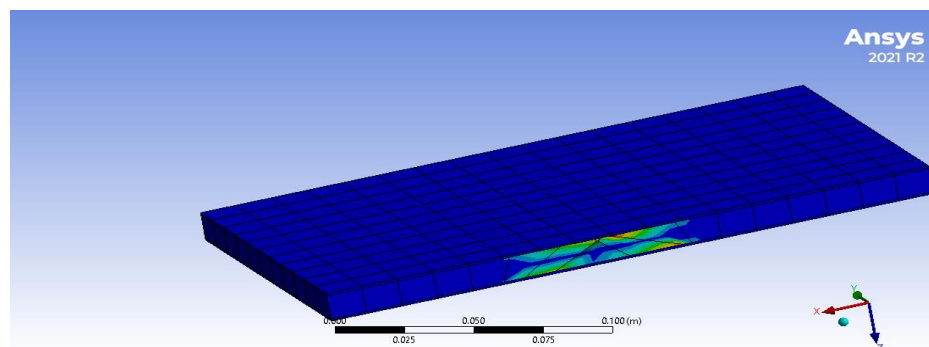


Figure 49: Buckling mode 3 of proposed model with an angle of 75°

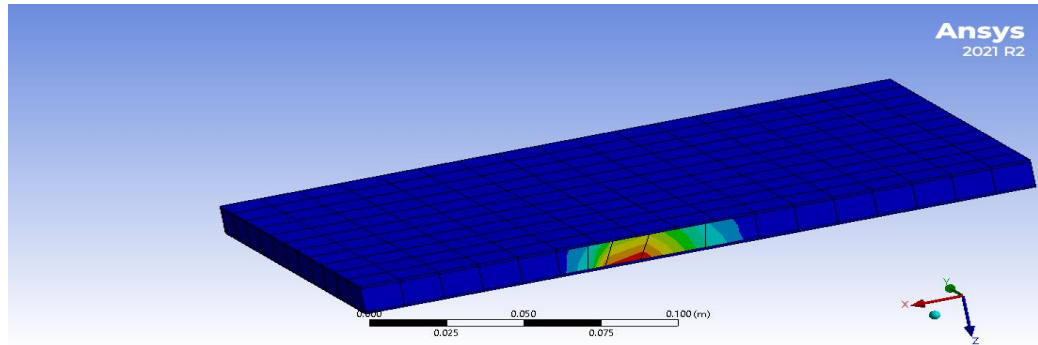


Figure 50: Buckling mode 6 of proposed model with an angle of  $75^\circ$

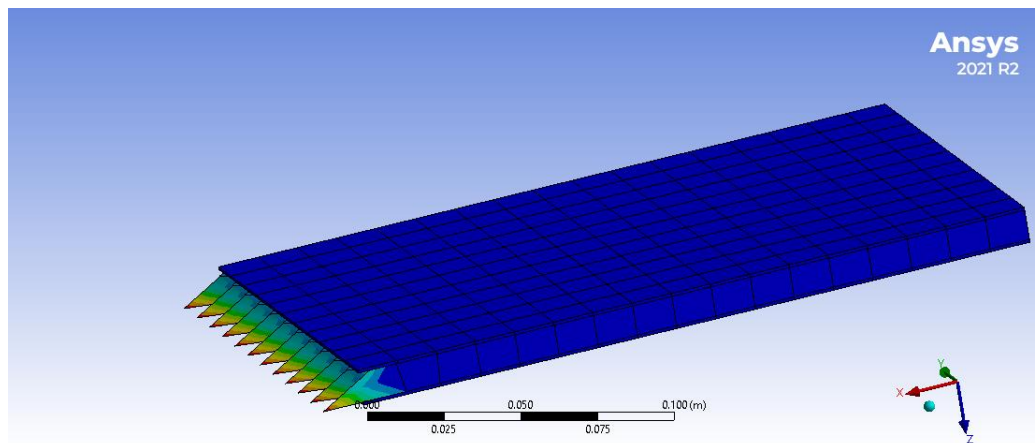


Figure 51: Buckling mode 9 of proposed model with an angle of  $75^\circ$

The Table 13 extracted from these results show that the maximum Eigen value gotten was 24280 giving the maximum load to make cause the structure to buckle to be  $1\text{N} \times 24280 = 24280\text{N}$ . The table below shows the Eigenvalues from modes 1-10 of proposed aluminium model with an angle of  $75^\circ$ .

Table 13: Eigenvalues corresponding to their modes

| Mode | Buckling Load (N) |
|------|-------------------|
| 1    | -24280            |
| 2    | -24280            |
| 3    | -24256            |
| 4    | -24255            |
| 5    | -24233            |
| 6    | -24233            |

|    |         |
|----|---------|
| 7  | -18123  |
| 8  | -18123  |
| 9  | -9297   |
| 10 | -9296.2 |

From the data Gotten from 4.3.1 – 4.3.5 can be seen that change in re-entrant angle does not cause a linear change in buckling load but a linear change can be found in the change of core thickness. As the thickness increases, the load it takes to buckle (buckling load) increases as well.

#### 4.3.7 Buckling Modes of Proposed CFRP Model with 15mm Thickness

The Figures 52-55 show the buckling modes of a sandwich structure with a Carbon Fibre Reinforced Plastic of 15mm auxetic re-entrant structure as the core. These modes (1-10) were gotten with an axially applied force of 1N. The red areas show the places of maximum buckling effect and the blue areas show the places of minimum buckling effect. The following Figures show modes 1, 3, 6 and 9.

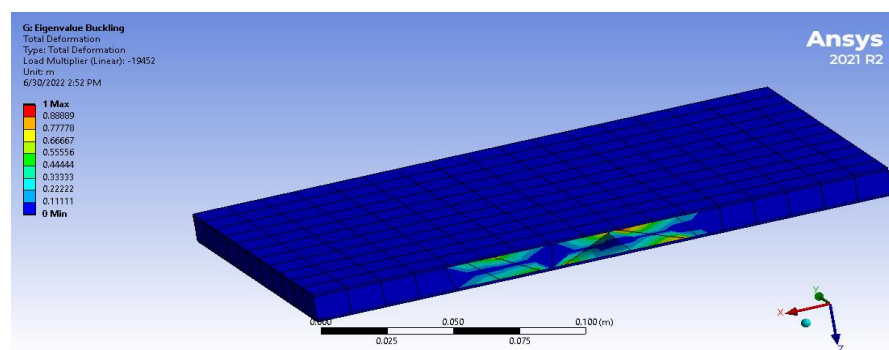


Figure 52: Buckling mode 1 of proposed model with 15mm thickness

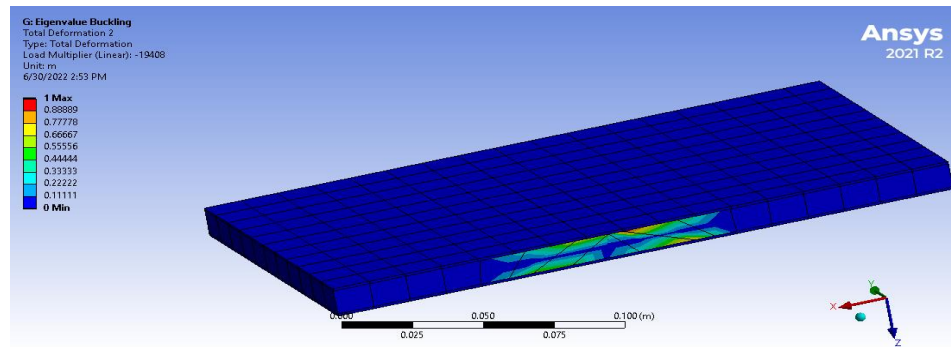


Figure 53: Buckling mode 3 of proposed model with 15mm thickness

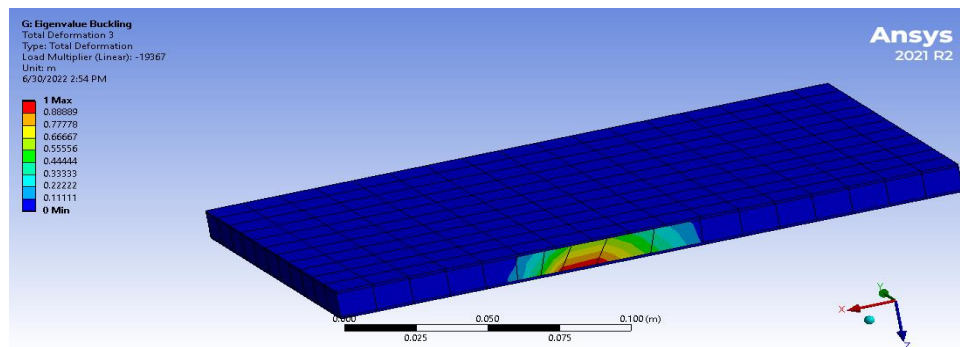


Figure 54: Buckling mode 6 of proposed model with 15mm thickness

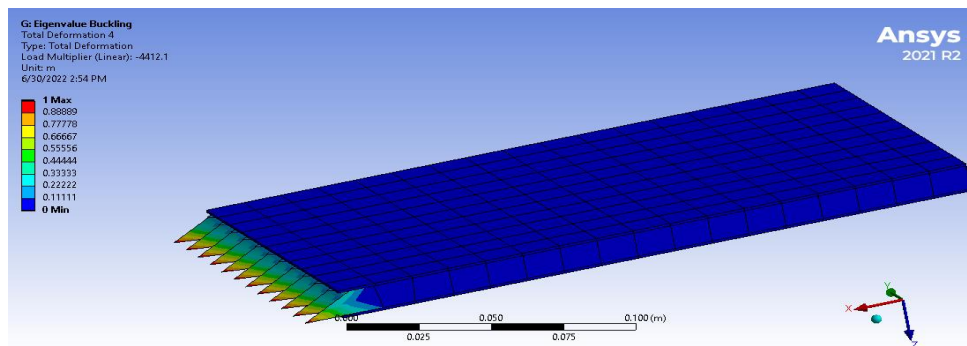


Figure 55: Buckling mode 9 of proposed model with 15mm thickness

The Table 14 extracted from these results show that the maximum Eigen value gotten was 19452 giving the maximum load to make cause the structure to buckle to be  $1\text{N} \times 19452 = 19452\text{N}$ . The table below shows the Eigenvalues from modes 1-10.

Table 14: Eigenvalues corresponding to their modes

| Mode | Buckling Load (N) |
|------|-------------------|
| 1    | -19452            |
| 2    | -19452            |
| 3    | -19408            |
| 4    | -19408            |
| 5    | -19368            |
| 6    | -19367            |
| 7    | -11017            |
| 8    | -11017            |
| 9    | -4412.1           |
| 10   | -4411.5           |

#### 4.3.8 Buckling Modes of Proposed CFRP Model with 20mm Thickness.

The Figures 56-59 show the buckling modes of a sandwich structure with a Carbon Fibre Reinforced Plastic of 20mm auxetic re-entrant structure as the core. These modes (1-10) were gotten with an axially applied force of 1N. The red areas show the places of maximum buckling effect and the blue areas show the places of minimum buckling effect. The figures below show modes 1, 3, 6 and 9.

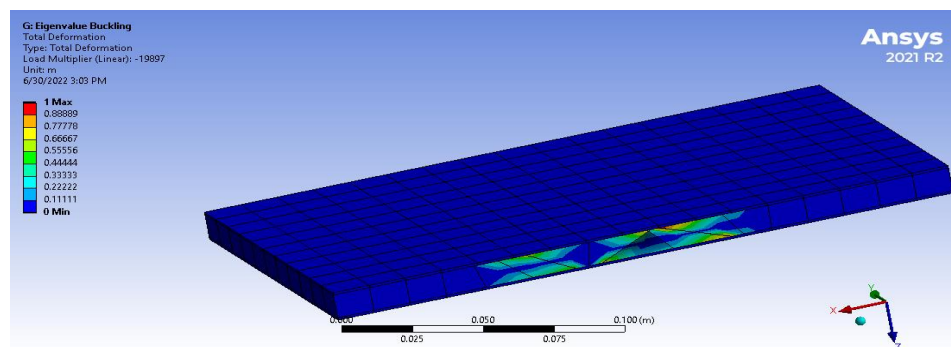


Figure 56: Buckling mode 1 of proposed model with 20mm thickness

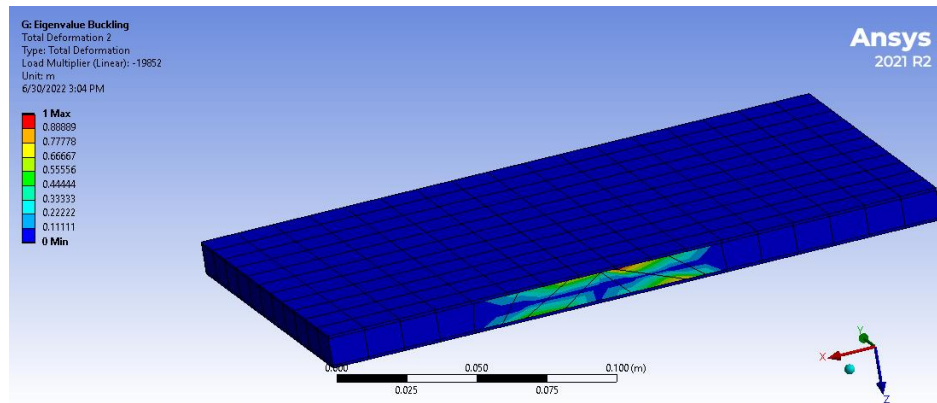


Figure 57: Buckling mode 3 of proposed model with 20mm thickness

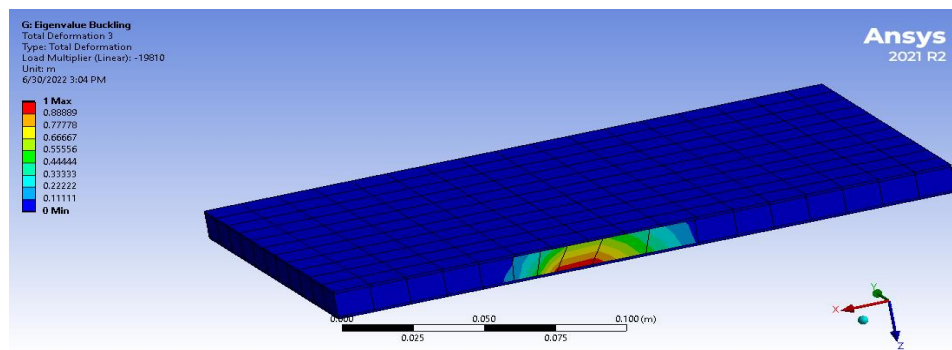


Figure 58: Buckling mode 6 of proposed model with 20mm thickness

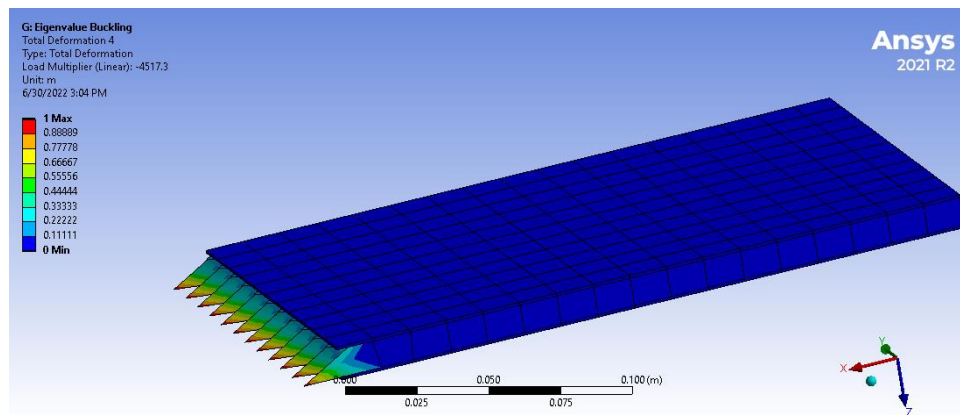


Figure 59: Buckling mode 9 of proposed model with 20mm thickness

The Table 15 extracted from these results show that the maximum Eigen value gotten was 19897 giving the maximum load to make cause the structure to buckle to be  $1\text{N} \times 19897 = 19897\text{N}$ . The table below shows the Eigenvalues from modes 1-10.

Table 15: Eigenvalues corresponding to their modes

| Mode | Buckling Load (N) |
|------|-------------------|
| 1    | -19897            |
| 2    | -19896            |
| 3    | -19852            |
| 4    | -19852            |
| 5    | -19810            |
| 6    | -19810            |
| 7    | -11281            |
| 8    | -11281            |
| 9    | -4517.3           |
| 10   | -4516.8           |

#### 4.3.9 Buckling Modes of Proposed CFRP Model with 25mm Thickness

The Figures 60- 63 show the buckling modes of a sandwich structure with a Carbon Fibre Reinforced Plastic of 25mm auxetic re-entrant structure as the core. These modes (1-10) were gotten with an axially applied force of 1N. The red areas show the places of maximum buckling effect and the blue areas show the places of minimum buckling effect. The following Figures below show modes 1, 3, 6 and 9.

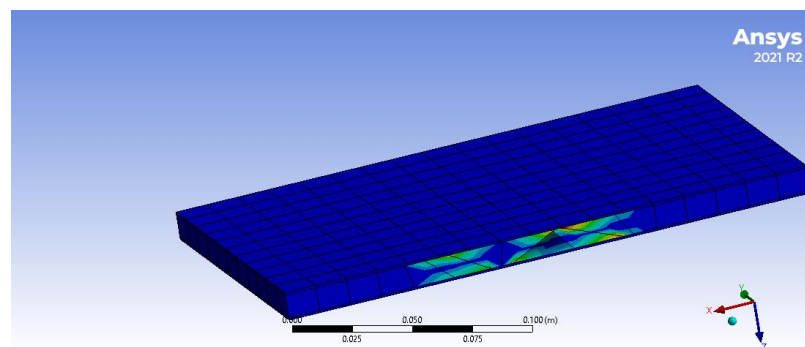


Figure 60: Buckling mode 1 of proposed model with 25mm thickness

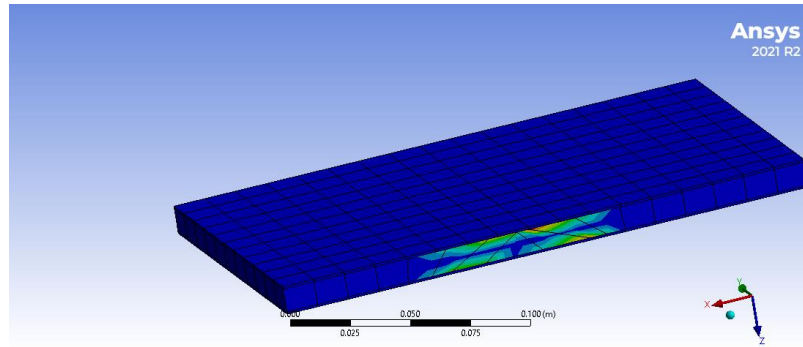


Figure 61: Buckling mode 3 of proposed model with 25mm thickness

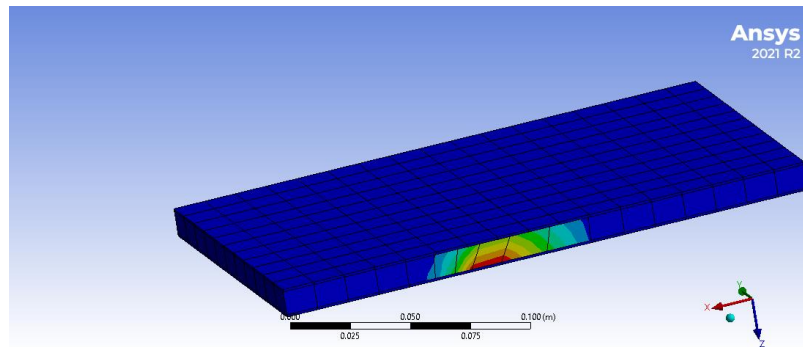


Figure 62: Buckling mode 6 of proposed model with 25mm thickness

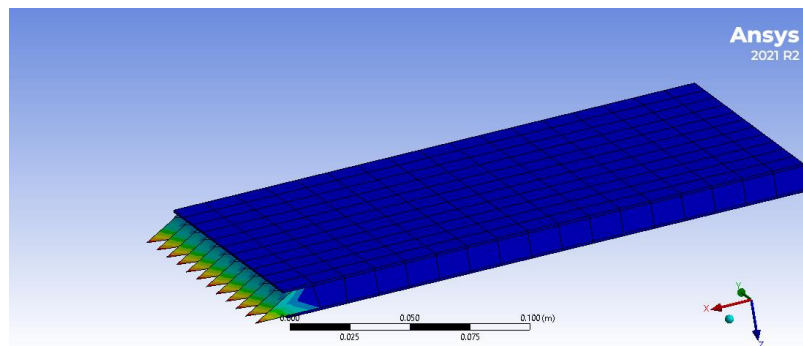


Figure 63: Buckling mode 9 of proposed model with 25mm thickness

The Table 16 extracted from these results show that the maximum Eigen value gotten was 20729 giving the maximum load to make cause the structure to buckle to be  $1\text{N} \times 20729 = 20729\text{N}$ . The table below (Table 16) shows the Eigenvalues from modes 1-10.

Table 16: Eigenvalues corresponding to their modes

| Mode | Buckling Load (N) |
|------|-------------------|
| 1    | -20729            |
| 2    | -20729            |
| 3    | -20682            |
| 4    | -20682            |
| 5    | -20639            |
| 6    | -20639            |
| 7    | -11767            |
| 8    | -11767            |
| 9    | -4713.2           |
| 10   | -4712.6           |

#### 4.3.10 Buckling Modes of Proposed CFRP Model with a 65° Angle

The figures below (figure 64-figure 67) show the buckling modes of a sandwich structure with a Carbon Fibre Reinforced Plastic of a 65° angled auxetic re-entrant structure as the core. These modes (1-10) were gotten with an axially applied force of 1N. The red areas show the places of maximum buckling effect and the blue areas show the places of minimum buckling effect. The following Figures show modes 1, 3, 6 and 9.

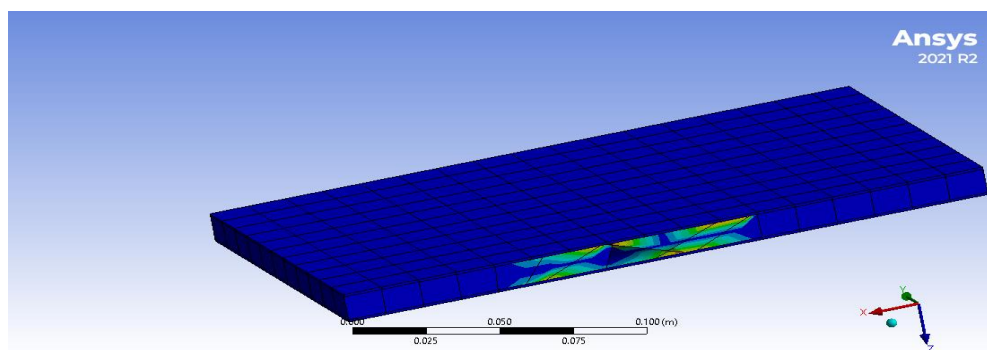


Figure 64: Buckling mode 1 of proposed model with an angle of 65°

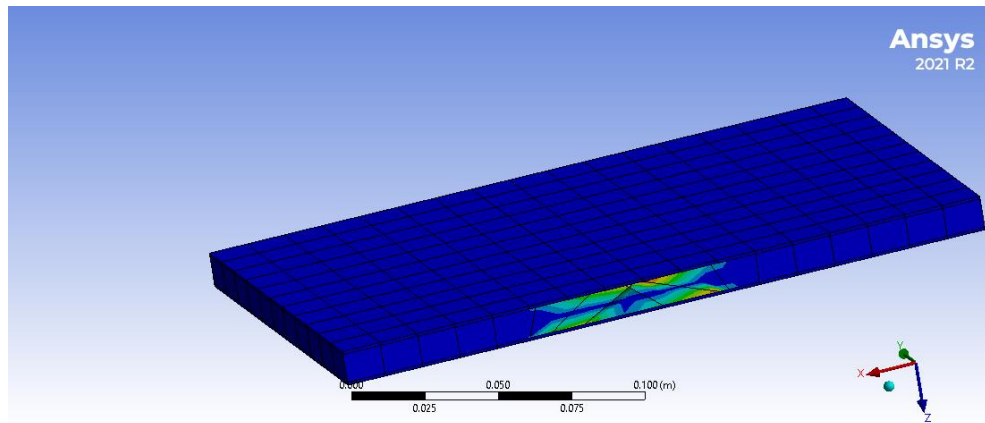


Figure 65: Buckling mode 3 of proposed model with an angle of  $65^{\circ}$

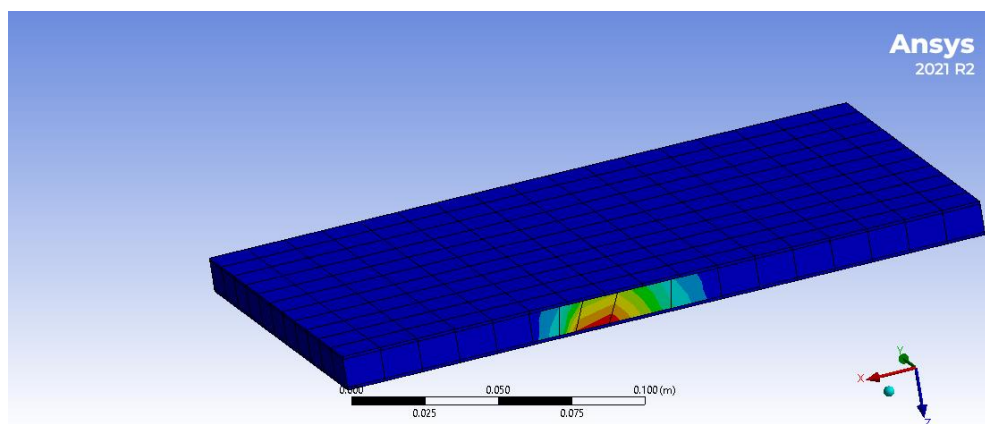


Figure 66: Buckling mode 6 of proposed model with an angle of  $65^{\circ}$

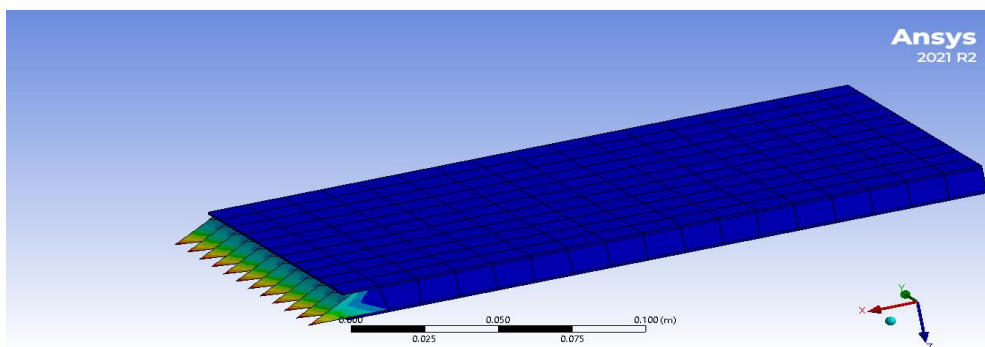


Figure 67: Buckling mode 9 of proposed model with an angle of  $65^{\circ}$

The Table 17 extracted from these results show that the maximum Eigen value gotten was 24280 giving the maximum load to make cause the structure to buckle to be  $1\text{N} \times 24280 = 24280\text{N}$ . The table below shows the Eigenvalues from modes 1-10.

Table 17: Eigenvalues corresponding to their modes

| Mode | Buckling Load (N) |
|------|-------------------|
| 1    | -24280            |
| 2    | -24280            |
| 3    | -24256            |
| 4    | -24255            |
| 5    | -24233            |
| 6    | -24233            |
| 7    | -18123            |
| 8    | -18123            |
| 9    | -9297             |
| 10   | -9296.2           |

#### 4.3.11 Buckling Modes of Proposed CFRP Model with a 70° Angle

The figures below (figure 68-figure 71) show the buckling modes of a sandwich structure with a Carbon Fibre Reinforced Plastic of a 70° angled auxetic re-entrant structure as the core. These modes (1-10) were gotten with an axially applied force of 1N. The red areas show the places of maximum buckling effect and the blue areas show the places of minimum buckling effect. The following Figures show modes 1, 3, 6 and 9.

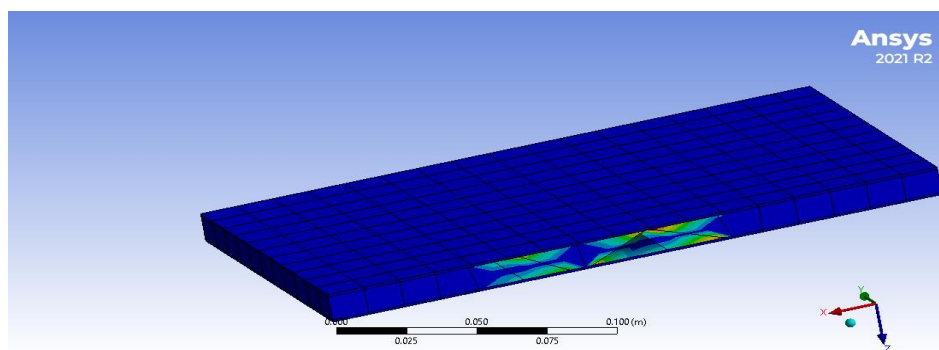


Figure 68: Buckling mode 1 of proposed model with an angle of 70°

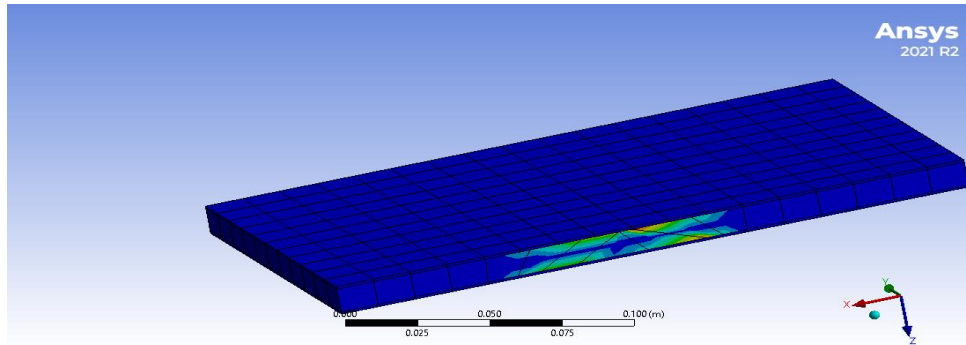


Figure 69: Buckling mode 3 of proposed model with an angle of  $70^\circ$

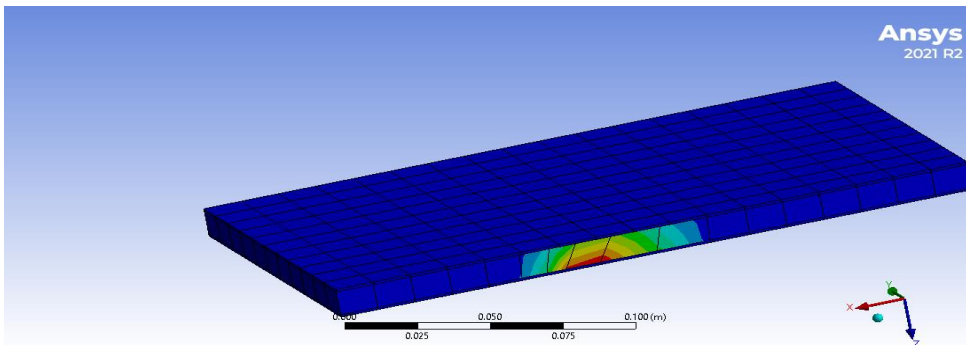


Figure 70: Buckling mode 6 of proposed model with an angle of  $70^\circ$

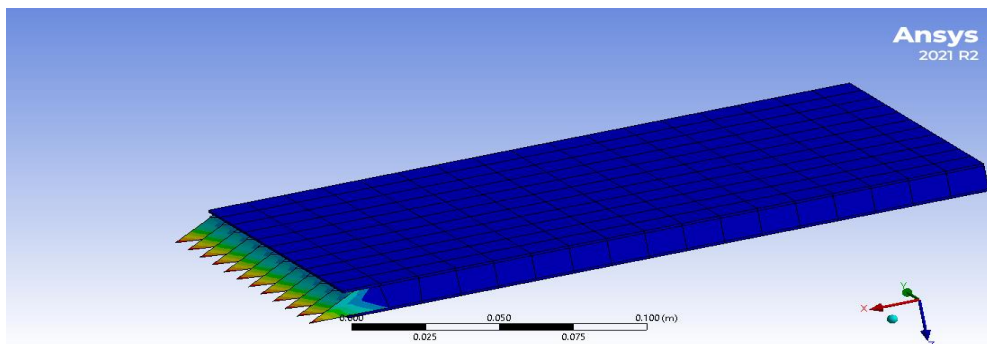


Figure 71: Buckling mode 9 of proposed model with an angle of  $70^\circ$

The Table 18 extracted from these results show that the maximum Eigenvalue gotten was 20992 giving the maximum load to make cause the structure to buckle to be  $1\text{N} \times 20992 = 20992\text{N}$ . The table below shows the Eigenvalues from modes 1-10.

Table 18: Eigenvalues corresponding to their modes

| Mode | Buckling Load (N) |
|------|-------------------|
| 1    | -20992            |
| 2    | -20992            |
| 3    | -20955            |
| 4    | -20955            |
| 5    | -20921            |
| 6    | -20921            |
| 7    | -11946            |
| 8    | -11945            |
| 9    | -4976.7           |
| 10   | -4976.2           |

#### 4.3.12 Buckling Modes of Proposed CFRP Model with a 75° Angle.

The Figures 72- 75 show the buckling modes of a sandwich structure with a Carbon Fibre Reinforced Plastic of a 75° angled auxetic re-entrant structure as the core. These modes (1-10) were gotten with an axially applied force of 1N. The red areas show the places of maximum buckling effect and the blue areas show the places of minimum buckling effect. The following Figures show modes 1, 3, 6 and 9.

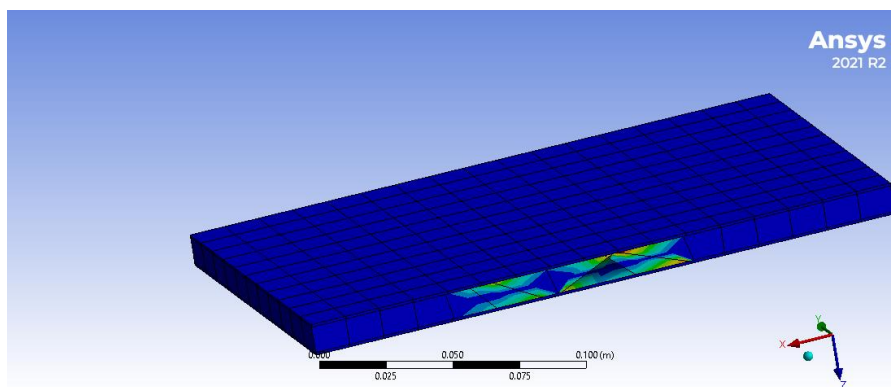


Figure 72: Buckling mode 1 of proposed model with an angle of 75°

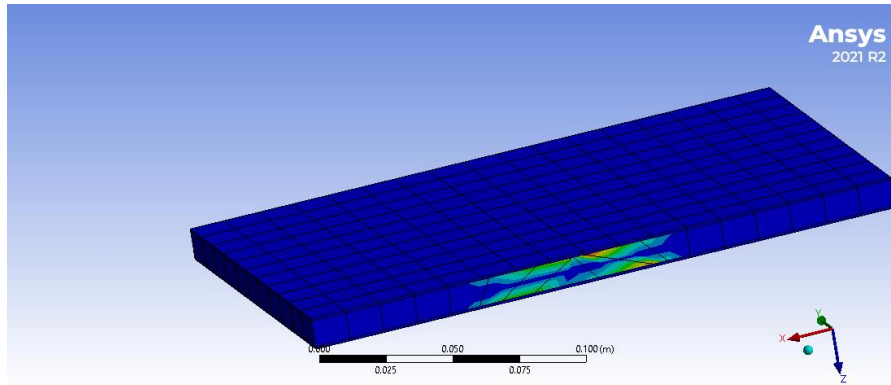


Figure 73: Buckling mode 3 of proposed model with an angle of 75°

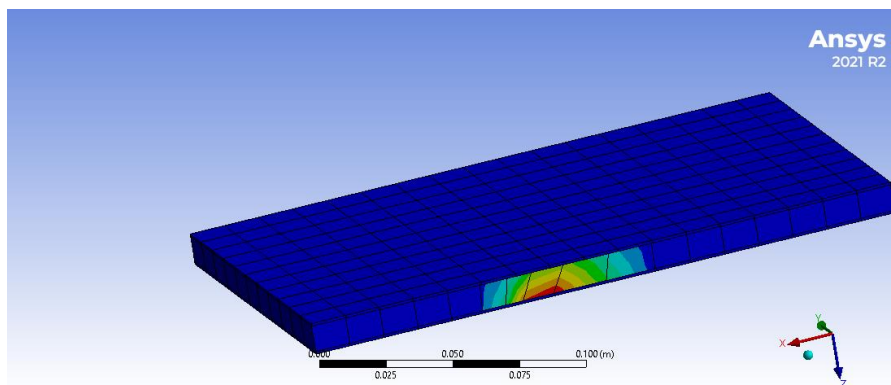


Figure 74: Buckling mode 6 of proposed model with an angle of 75°

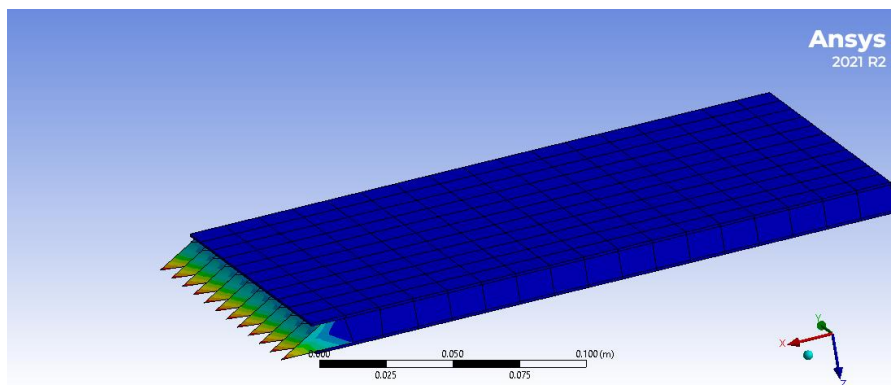


Figure 75: Buckling mode 9 of proposed model with an angle of 75°

The Table 19 extracted from these results show that the maximum Eigenvalue gotten was 22373 giving the maximum load to make cause the structure to buckle to be  $1\text{N} \times 22373 = 22373\text{N}$ . The table below shows the Eigenvalues from modes 1-10.

Table 19: Eigenvalues corresponding to their modes

| <b>Mode</b> | <b>Buckling Load (N)</b> |
|-------------|--------------------------|
| 1           | -22373                   |
| 2           | -22373                   |
| 3           | -22338                   |
| 4           | -22338                   |
| 5           | -22306                   |
| 6           | -22306                   |
| 7           | -12697                   |
| 8           | -12697                   |
| 9           | -5389.9                  |
| 10          | -5389.4                  |

From the data Gotten from 4.3.6 – 4.3.11 can be seen that change in re-entrant angle does not cause a linear change in buckling load but a linear change can be found in the change of core thickness. As the thickness increases, the load it takes to buckle (buckling load) increases as well.

Other model configurations were made to simulate their buckling loads. Table 20 below shows the modes (1, 3 6 and 9) and their respective buckling loads of proposed model.

Table 20: Configurations of proposed models and their buckling loads

| <b>Configurations</b> | <b>Mode 1</b> | <b>Mode 3</b> | <b>Mode 6</b> | <b>Mode 9</b> |
|-----------------------|---------------|---------------|---------------|---------------|
| <b>20mm×70° angle</b> | -24310        | -24286        | -24272        | -9320.3       |
| <b>20mm×75° angle</b> | -24322        | -24316        | -24293        | -9360         |

|                       |        |        |        |         |
|-----------------------|--------|--------|--------|---------|
| <b>25mm×70° angle</b> | -24350 | -24342 | -24319 | -9371.4 |
| <b>25mm×75° angle</b> | -24363 | -24355 | -24332 | -9383.3 |

#### 4.3.13 Comparison of Buckling Loads of Proposed 15mm Model to Proposed 15mm CFRP Model

The comparison in this section is to show the similarities or differences in Eigenvectors between 15mm thick Aluminum alloy auxetic re-entrant core and 15mm thick CFRP auxetic re-entrant core and to know which material is best for structural design. The table below shows their modes (1-10) and their Eigenvalues (Buckling Load (N)).

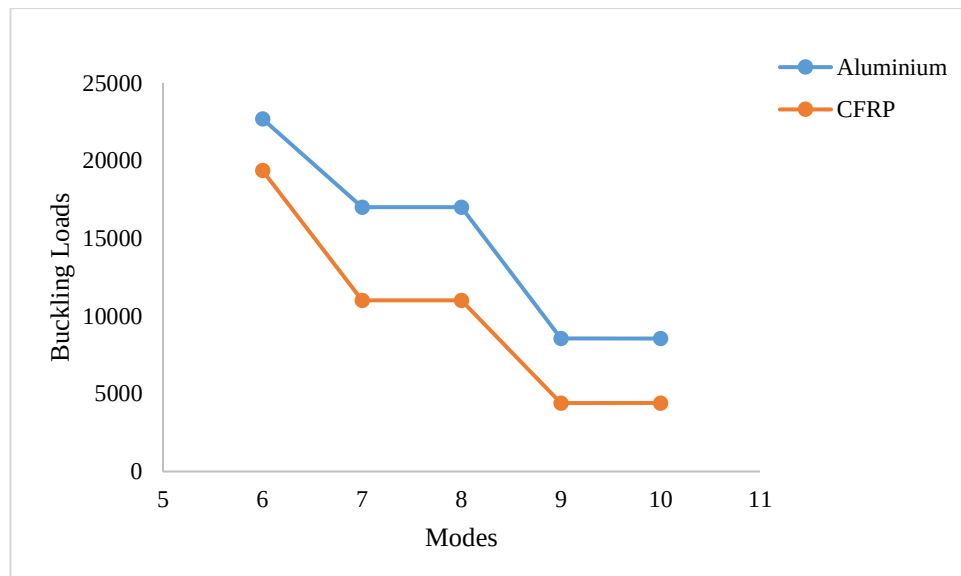


Figure 76: Eigenvalue comparison of 15mm aluminum alloy auxetic re-entrant core and 15mm CFRP auxetic re-entrant core.

As seen in Figure 76, there was variation in buckling loads in each modes showing the structure vibrates at different frequencies in different modes. Aluminium alloy provides a better buckling load of 22,740N compared to the buckling load of CFRP

which is 19,452N. These values are the critical buckling loads where the structure cannot withstand the axial compressive loading.

#### 4.3.14 Comparison of Buckling Loads of Proposed 70° Model to Proposed 70° CFRP Model

The comparison in this section is to show the similarities or differences in Eigenvectors between 70° angled aluminum alloy auxetic re-entrant core and 70° angled CFRP auxetic re-entrant core and to know which material is best for structural design. The figure 77 below shows their modes and their Buckling Load (N).

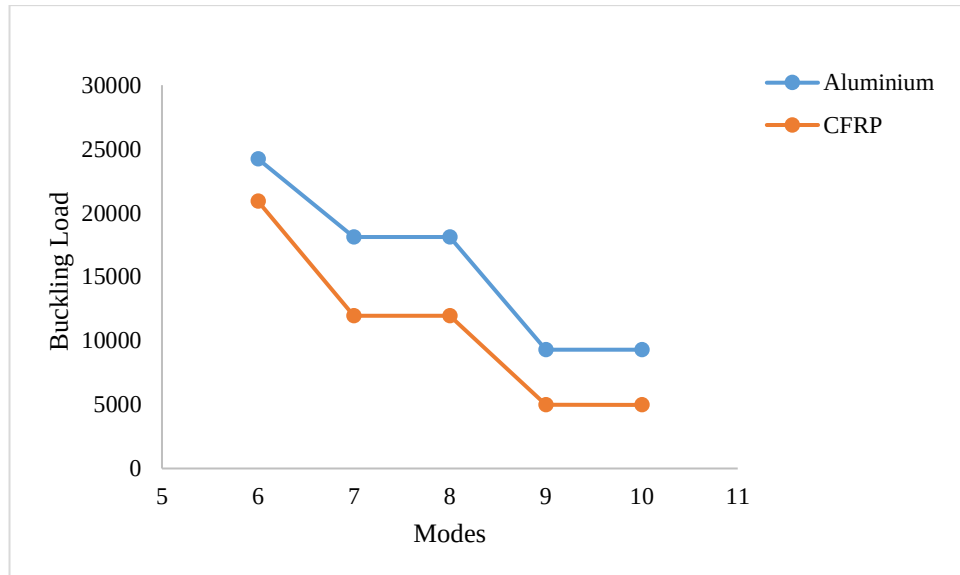


Figure 77: Eigenvalue comparison of 70° angled aluminum alloy auxetic re-entrant core and 70° angled CFRP auxetic re-entrant core.

As seen in figure 77, there was variation in buckling loads in each modes showing the structure vibrates at different frequencies in different modes. The comparison with the thicknesses aluminium alloy provided a better buckling load (24,280N) compared to that of CFRP (20,992N) when the re-entrant angle is 70°. This means that it is going to take aluminium alloy a critical load of 24,280N for the sandwich

structure to completely buckle and it is going to take CFRP a critical load of 20,992N for the sandwich structure to buckle.

#### 4.4 Stress and Strain Analysis and Comparison

The sandwich structures were positioned for a 3-point bend test to simulate the stress and strain of the structure. Stress analysis is needed for engineering science because failures occur in mechanical parts and these failures can be due to stresses and strain in those components. The stress and strain were observed in the figures shown. The simulation was done for different sandwich core thicknesses (15mm, 20mm and 25mm) and different re-entrant core angles ( $65^\circ$ ,  $70^\circ$  and  $75^\circ$ ) for different materials (aluminum alloy and CFRP). Areas with red depict areas with maximum stress and strain while blue areas depict areas with minimum stress and strain.

##### 4.4.1 Stress And Strain for 15mm, 20mm and 25mm Thickness Proposed Model

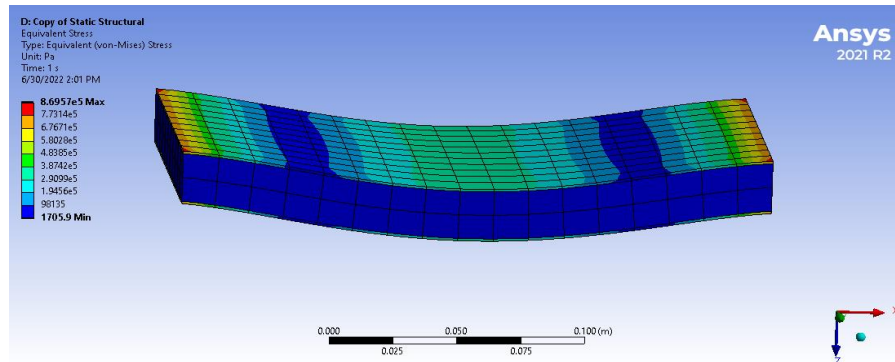


Figure 78: Stress component of proposed model with thickness of 15mm

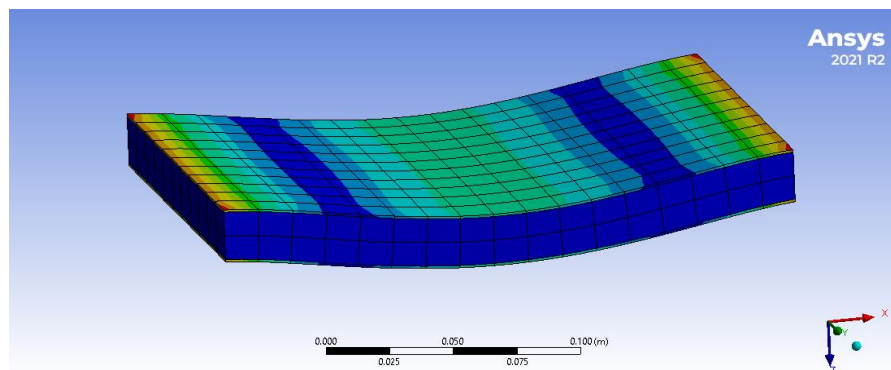


Figure 79: Stress component of proposed model with thickness of 20mm

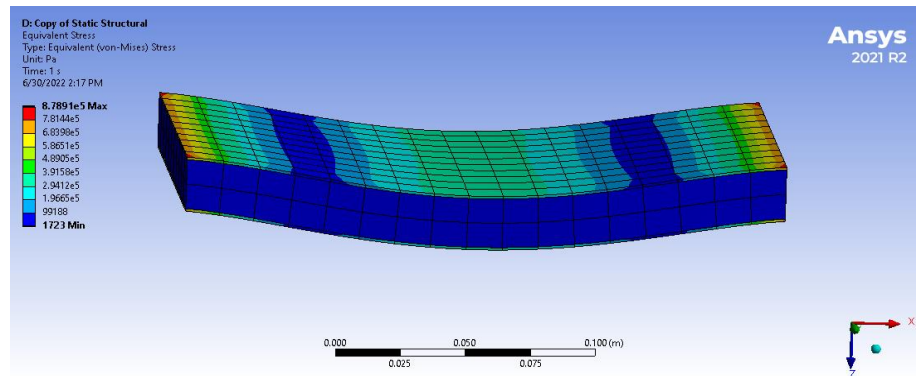


Figure 80: Stress component of proposed model with thickness of 25mm

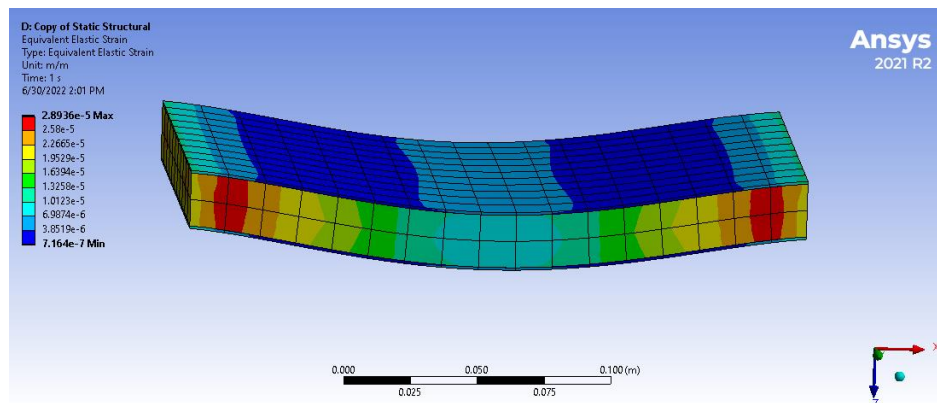


Figure 81: Strain component of proposed model with thickness of 15mm

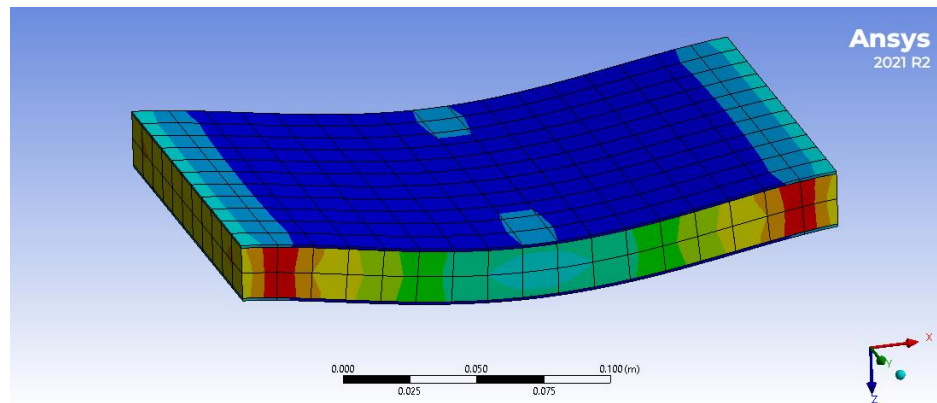


Figure 82: Strain component of proposed model with thickness of 20mm

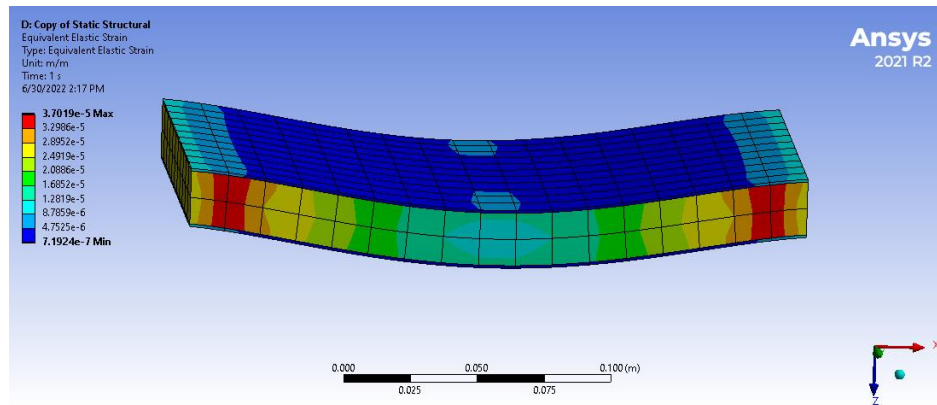


Figure 83: Strain component of proposed model with thickness of 25mm

Table 21: Stress-strain table of 15mm, 20mm and 25mm of aluminium alloy core

| Aluminum Alloy core             |          |          |          |
|---------------------------------|----------|----------|----------|
|                                 | 15mm     | 20mm     | 25mm     |
| <b>Stress (Pa)</b>              | 869570   | 879353.2 | 878909.6 |
| <b>strain (mm<sup>-1</sup>)</b> | 2.89E-05 | 3.71E-05 | 3.70E-05 |

From Table 20, as thickness increases, the stress and strain of the sandwich structure increase as well.

#### 4.4.2 Stress and Strain for 65°, 70°mm and 75° Thickness Proposed Model

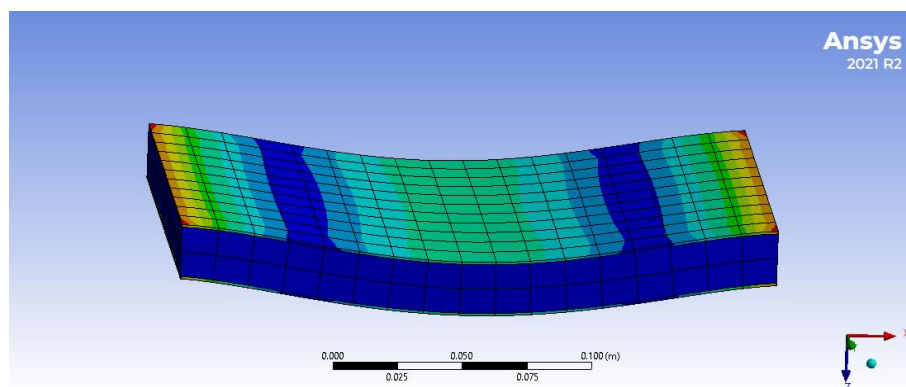


Figure 84: Stress component of proposed model with a re-entrant angle of 65°

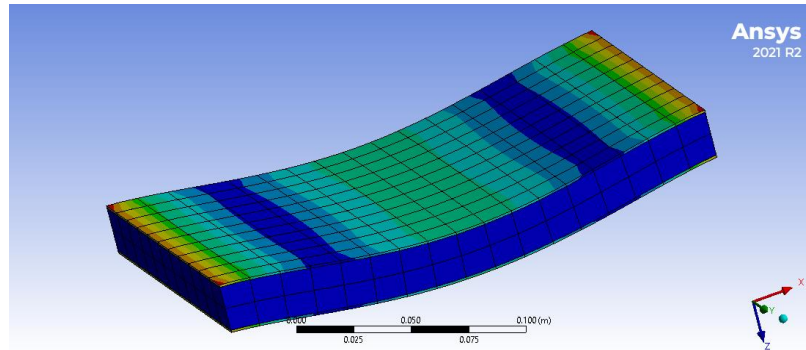


Figure 85: Stress component of proposed model with a re-entrant angle of 70°

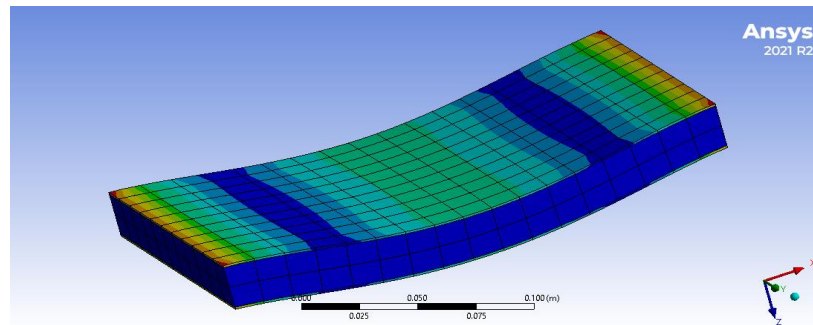


Figure 86: Stress component of proposed model with a re-entrant angle of 75°

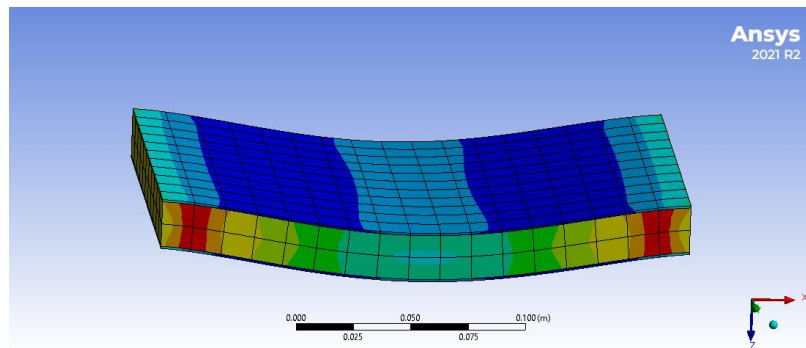


Figure 87: Strain component of proposed model with a re-entrant angle of 65°

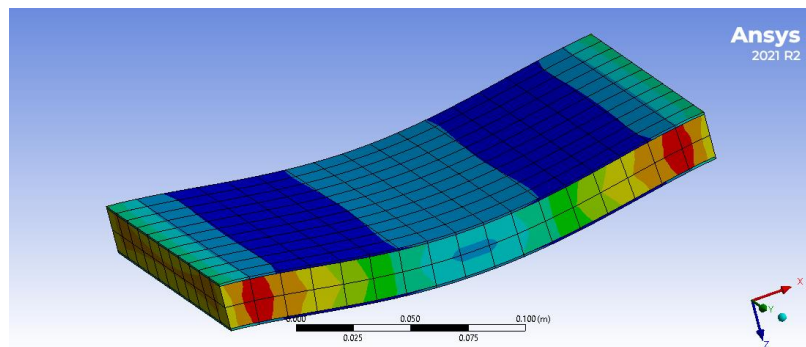


Figure 88: Strain component of proposed model with a re-entrant angle of 70°

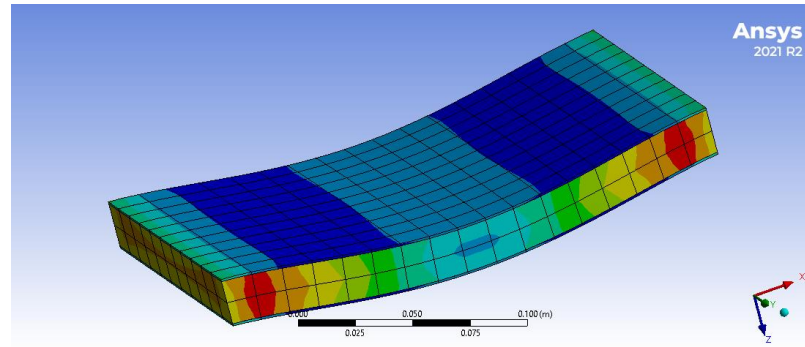


Figure 89: Strain component of proposed model with a re-entrant angle of 75°

Table 22: Stress-strain table of 65°, 70° and 75° of aluminium alloy re-entrant cell

| Aluminum Alloy core             |          |          |          |
|---------------------------------|----------|----------|----------|
|                                 | 65°      | 70°      | 75°      |
| <b>Stress (Pa)</b>              | 837834   | 868783.4 | 868783.4 |
| <b>strain (mm<sup>-1</sup>)</b> | 2.92E-05 | 2.52E-05 | 2.52E-05 |

From table 21 it is seen that as the angle of the re-entrant cell is increased, the stress and strain of the sandwich structure increases as well.

#### 4.4.3 Stress and Strain for 15mm, 20mm and 25mm Proposed CFRP Model

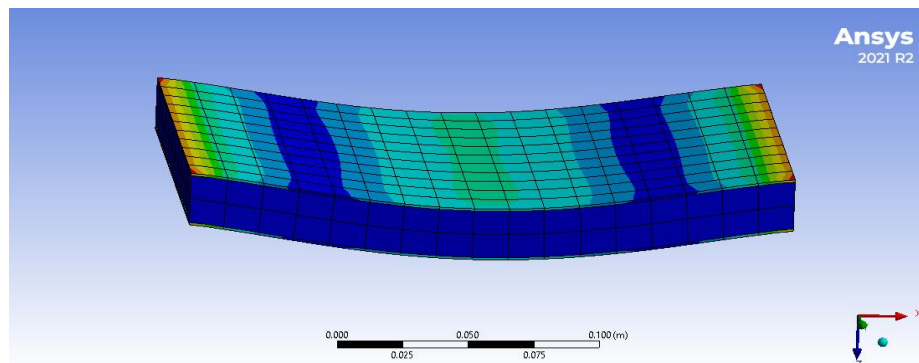


Figure 90: Stress component proposed model with thickness of 15mm

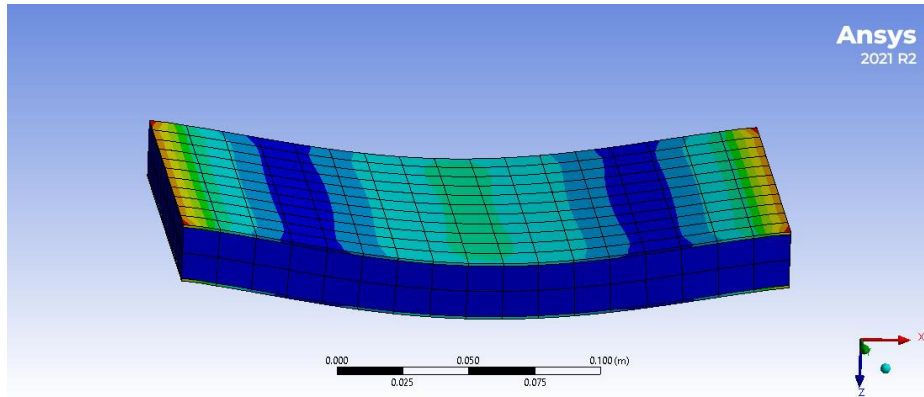


Figure 91: Stress component of proposed model with thickness of 20mm

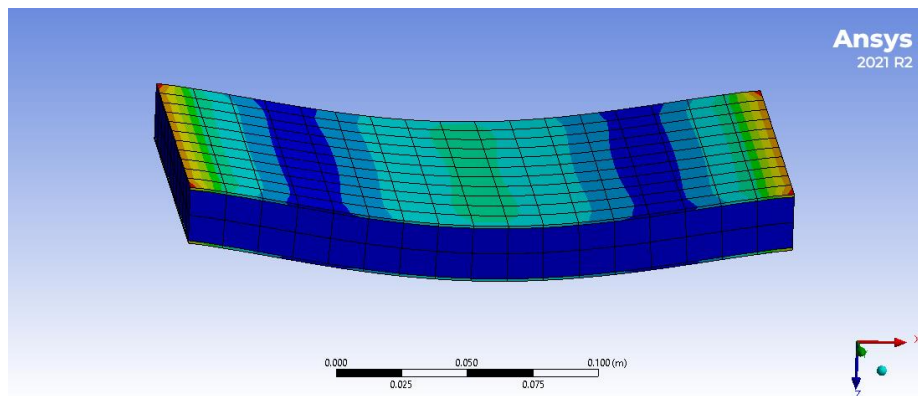


Figure 92: Stress component of proposed model with thickness of 20mm

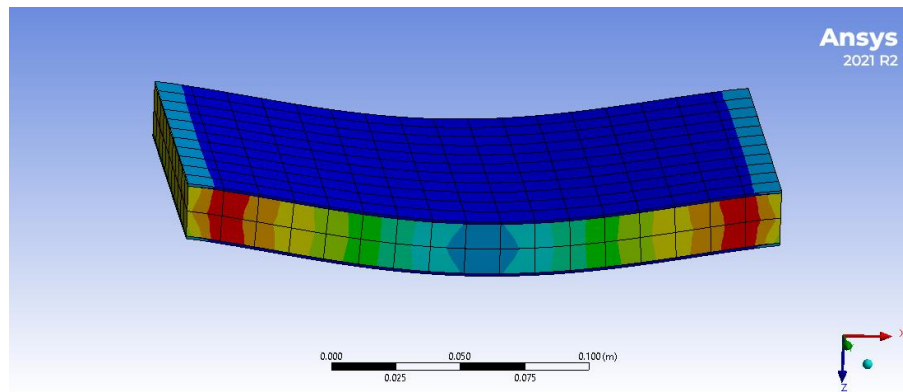


Figure 93: Strain component of proposed model with thickness of 15mm

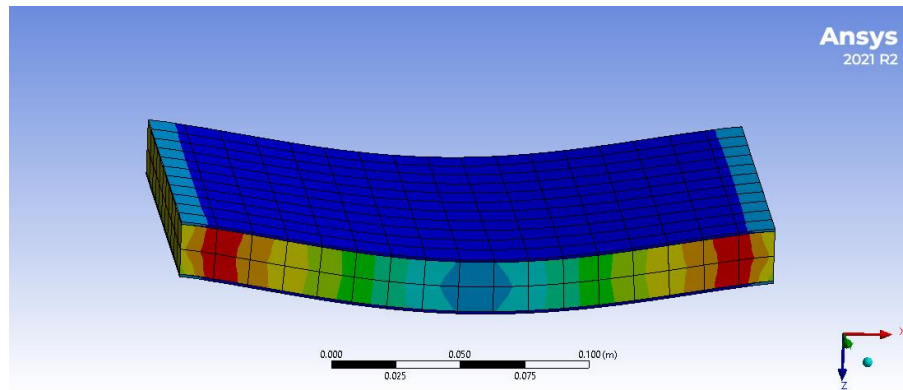


Figure 94: Strain component of proposed model with thickness of 20mm

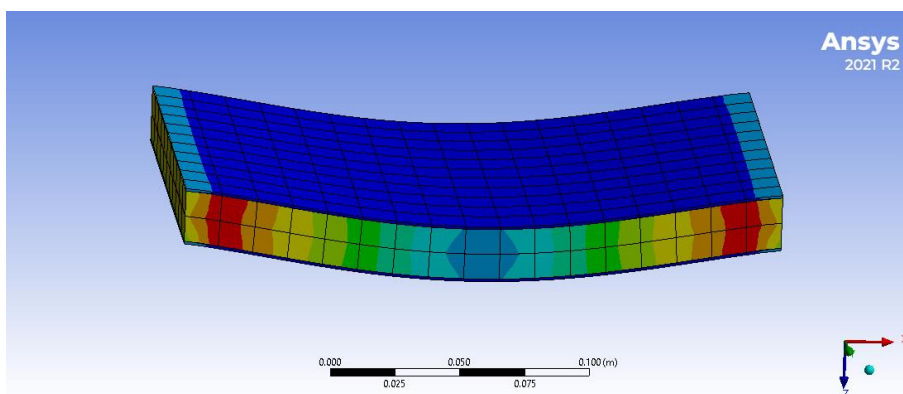


Figure 95: Strain component of proposed model with thickness of 25mm

Table 23: Stress-strain table of 15mm, 20mm and 25mm CFRP core

| CFRP core                       |          |          |          |
|---------------------------------|----------|----------|----------|
|                                 | 15mm     | 20mm     | 25mm     |
| <b>Stress (Pa)</b>              | 1033837  | 1033273  | 1032689  |
| <b>strain (mm<sup>-1</sup>)</b> | 6.52E-05 | 6.51E-05 | 6.49E-05 |

As seen from Table 22 above, as the thickness of the sandwich core increased the stress and strain of the sandwich structure decreased. This phenomenon is different from that of an aluminium alloy as the sandwich core.

#### 4.4.4 Stress and Strain for 65°, 70°mm and 75° Angle of Proposed CFRP Model

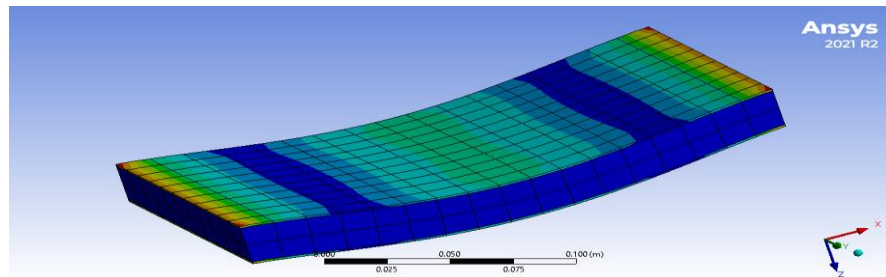


Figure 96: Stress component of proposed model with re-entrant angle of 65°

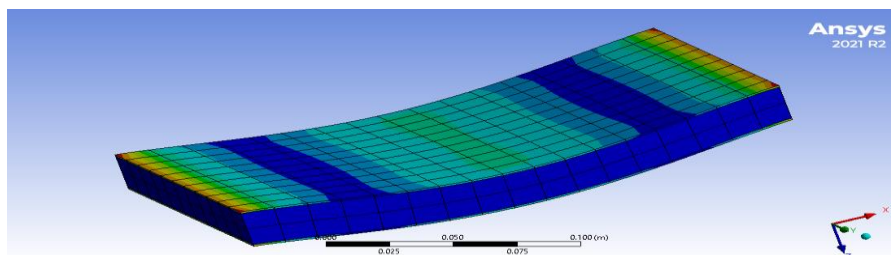


Figure 97: Stress component of proposed model with re-entrant angle of 70°

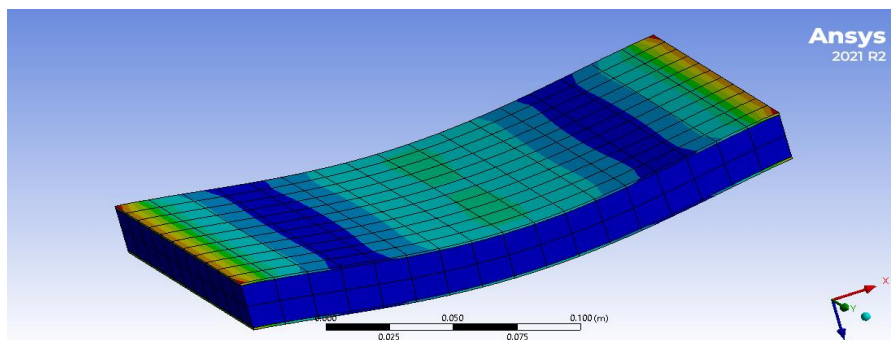


Figure 98: Stress component of proposed model with re-entrant angle of 75°

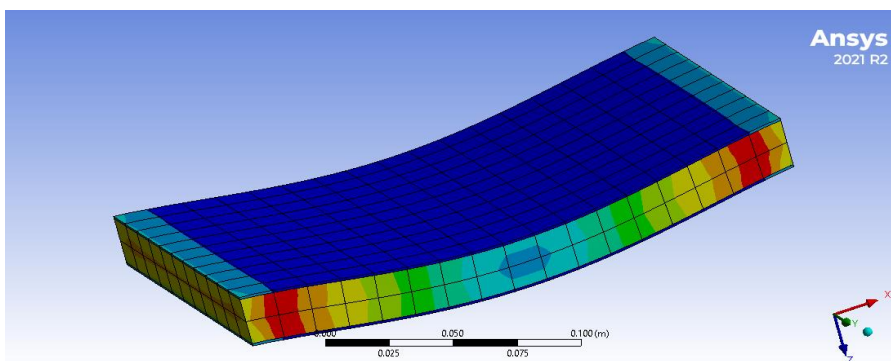


Figure 99: Strain component of proposed model with re-entrant angle of 65°

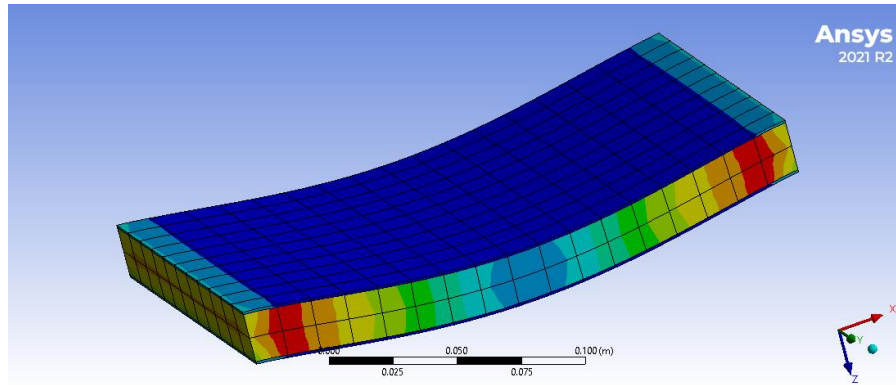


Figure 100: Strain component of proposed model with re-entrant angle of  $70^\circ$

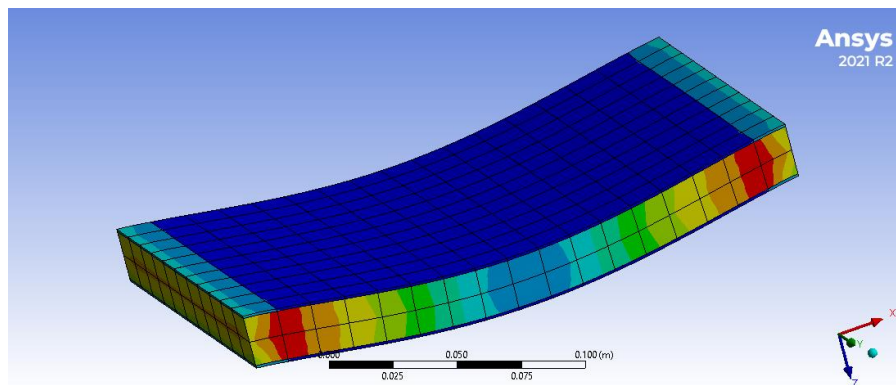


Figure 101: Strain component of proposed model with re-entrant angle of  $75^\circ$

Table 24: Stress-strain table of  $65^\circ$ ,  $70^\circ$  and  $75^\circ$  of CFRP re-entrant cell

| CFRP core                                   |            |            |            |
|---------------------------------------------|------------|------------|------------|
|                                             | $65^\circ$ | $70^\circ$ | $75^\circ$ |
| <b>Stress (Pa)</b>                          | 985072     | 1033733    | 1036971    |
| <b>strain (<math>\text{mm}^{-1}</math>)</b> | 4.96E-05   | 5.20E-05   | 4.60E-05   |

From table 23 above, it is seen that as the angle of the reentrant cell is increased the stress increases as well. The same cannot be said for the strain component because it has no linearity between the parameters.

#### 4.4.5 Comparison Between the Stress and Strain Components of Proposed Model and CFRP Model with 15mm Thickness

The table below compares the stress and strain components of a sandwich core made up of aluminium alloy and a sandwich core made up of CFRP, both with thicknesses of 15mm. The stress component of the CFRP sandwich auxetic re-entrant core is 15.8% higher than that of the aluminium alloy sandwich auxetic re-entrant core. The strain component has a massive 144.3% difference which shows that CFRP has a higher strain than aluminium alloy. The graphical representation is shown in Figures 102 and 103 below. It compares the stress-strain of both materials at different thicknesses (15mm, 20mm and 25mm). As seen in Figures 102 and 103 the stress and strain components of CFRP are higher than that of aluminium alloy.

Table 25: Comparison of stress-strain components of a sandwich structure with aluminium alloy and CFRP core with 15mm thickness

|                                 | Aluminum Alloy | CFRP     |
|---------------------------------|----------------|----------|
| <b>Stress (Pa)</b>              | 869570         | 1033837  |
| <b>Strain (mm<sup>-1</sup>)</b> | 2.89E-05       | 6.52E-05 |

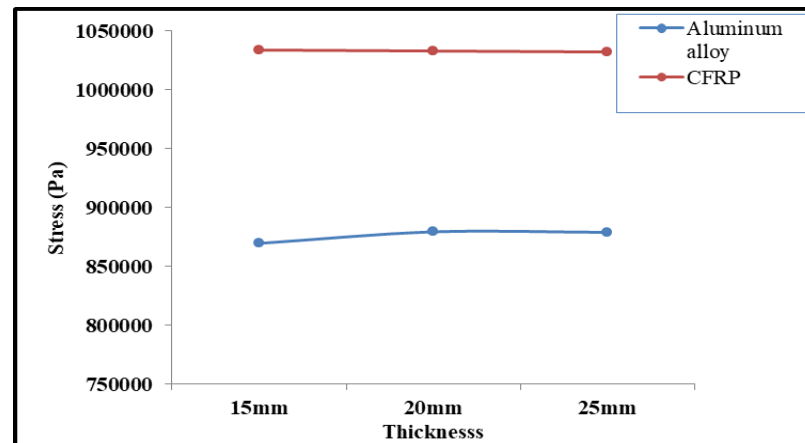


Figure 102: Stress component of proposed model with thicknesses 15mm, 20mm and 25mm.

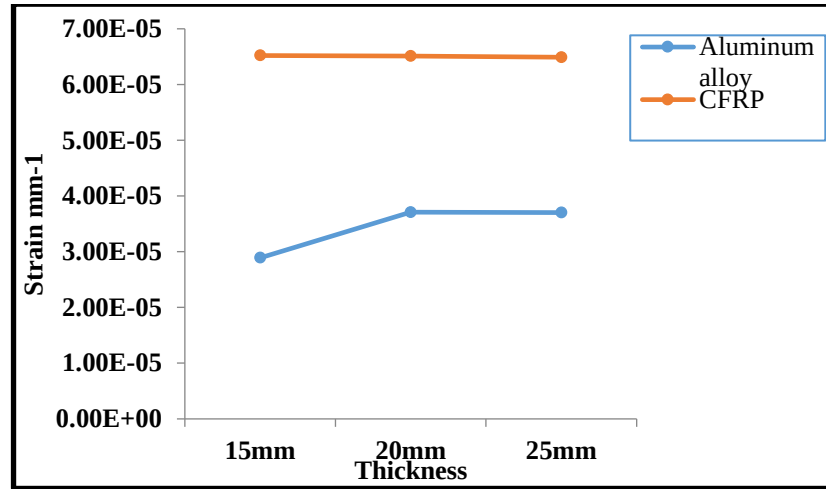


Figure 103: Strain component of proposed model with thicknesses 15mm, 20mm and 25mm.

#### 4.5 Validation of Result

As no experiments have been done on the buckling behaviour of sandwich auxetic structures in recent literatures, the result was validated with experiments done on stress and strain components of sandwich structures by K.S. Ashraff Ali et al [90]. The comparison made in table 26 below shows the maximum stress and strain analysis values of the proposed model and the maximum stress and strain analysis values of the experimental model. Although the structures in comparison are different, the proposed model being an aluminium auxetic sandwich structure of 15mm thickness and the experimental model being an aluminium hexagonal honeycomb sandwich structures with glass fibre face sheets of 1mm thickness, comparisons show the difference in stress strain values.

Table 26: Result comparison

|                            | Proposed model       | Experimental model    |
|----------------------------|----------------------|-----------------------|
| Stress (MPa)               | 1.034                | 0.023                 |
| Strain (mm <sup>-1</sup> ) | 6.52 e <sup>-5</sup> | 3.788 e <sup>-7</sup> |

## Chapter 5

### CONCLUSION

Because of its peculiar activity, it has sparked the interest of many scientists who are concerned about auxetic materials. Many efforts have been made to investigate not just auxetic materials but the mechanics that give rise to the property, and production processes, the mechanical indentation, deformation, viscoelastic properties, and other functional qualities that arise from auxeticity. The applications of auxetic materials show a very bright potential with these fundamental researches. Auxetic materials and structures require a lot of development for application-specific research. Apart from the functional aspects of auxetic structures, they are likely to be used as structural materials. Examples are microporous auxetic polymer materials that are prepared using a specially designed processing route by Evans et al.[39] shows good modulus and strength. Auxetics that are also designed on the molecular scale are possible to be used as structural materials. Different types of auxetic structures have been discovered i.e. auxetic cellular solids, microporous auxetic structures and molecular auxetic structures. Auxetic cellular solids are the more broad auxetics consisting of chiral structures, re-entrant structures, rotational structures, missing rib structures etc.

From the data gotten in the previous chapter, Aluminum alloy provides better material properties for structural implementation due to its higher buckling load than Carbon fibre reinforced plastics. CFRPs would buckle quicker than aluminium alloy

due to their lower buckling loads. But they have better stress-strain components than aluminium alloys. This does not make up for its lower buckling load compared to that of aluminium alloy. Several tests and parameters were used (thickness change, material change and re-entrant angle change) to give us a good basis for our material selection which is aluminium alloy.

During the research process the limitation faced was the difficulty in getting research works that pertained to buckling behaviour of auxetic structures. Another limitation encountered in this research was time limit gotten to complete the research. It is expected that substantial development in the theoretical and practical elements of auxetics will be made in future works, leading to material design for additional applications and bringing stiffer and stronger auxetic materials for use. It is feasible to construct unique and optimal auxetic structures with the desired range of Poisson's ratio using advanced optimization and modelling approaches. With time the limitation of limited research done on buckling behaviours of auxetic structures would be carried out. More parameters and data would be discovered, and more accurate results would be determined.

## REFERENCES

- [1] “(IUCr) Auxetics: don’t pull me, i’ll get fatter!”  
<https://www.iucr.org/news/newsletter/volume-27/number-2/auxetics> (accessed Nov. 18, 2021).
- [2] A. Alderson and K. L. Alderson, “Auxetic materials,” *Proc. inst. mech. eng. part g j. aerosp. eng.*, vol. 221, no. 4, pp. 565–575, apr. 2007, doi: 10.1243/09544100jaero185.
- [3] “Auxetics – materiability.” <http://materiability.com/auxetics/> (accessed Nov. 18, 2021).
- [4] J. Schwerdtfeger *et al.*, “design of auxetic structures via mathematical optimization,” *adv. mater.*, vol. 23, no. 22–23, pp. 2650–2654, jun. 2011, doi: 10.1002/adma.201004090.
- [5] N. Novak, M. Vesenjask, and Z. Ren, “Computational simulation and optimization of functionally graded auxetic structures made from inverted tetrapods,” *phys. status solidi*, vol. 254, no. 12, p. 1600753, dec. 2017, doi: 10.1002/pssb.201600753.
- [6] N. T. Kaminakis, G. A. Drosopoulos, and G. E. Stavroulakis, “Design and verification of auxetic microstructures using topology optimization and homogenization,” *Arch. Appl. Mech.*, vol. 85, no. 9–10, pp. 1289–1306, Sep. 2015, doi: 10.1007/s00419-014-0970-7.

- [7] X. Ren, R. Das, P. Tran, T. D. Ngo, and Y. M. Xie, “Auxetic metamaterials and structures: a review,” *Smart Mater. Struct.*, vol. 27, no. 2, p. 023001, Feb. 2018, doi: 10.1088/1361-665X/aaa61c.
- [8] G. Imbalzano, P. Tran, T. D. Ngo, and P. V. S. Lee, “A numerical study of auxetic composite panels under blast loadings,” *Compos. Struct.*, vol. 135, pp. 339–352, Jan. 2016, doi: 10.1016/j.compstruct.2015.09.038.
- [9] K. Bertoldi, P. M. Reis, S. Willshaw, and T. Mullin, “Negative poisson’s ratio behavior induced by an elastic instability,” *adv. mater.*, vol. 22, no. 3, pp. 361–366, jan. 2010, doi: 10.1002/adma.200901956.
- [10] T. Lim, “Auxetic Materials and Structures”, Engineering Materials, 2015. Available: 10.1007/978-981-287-275-3
- [11] “Auxetic materials materials with negative poisson rsquo s ratio | Ashjari | material science & engineering international journal.” <https://medcraveonline.com/medcrave.org/index.php/mseij/article/view/17816/33654> (accessed nov. 18, 2021).
- [12] R. S. Lakes, “Negative-poisson’s-ratio materials: auxetic solids,” *annu. rev. mater. res.*, vol. 47, no. 1, pp. 63–81, jul. 2017, doi: 10.1146/annurev-matsci-070616-124118.
- [13] A. A. Javadi, A. Faramarzi, and R. Farmani, “Design and optimization of microstructure of auxetic materials,” doi: 10.1108/02644401211212398.

- [14] A. G. Kolpakov, "Determination of the average characteristics of elastic frameworks," *J. Appl. Math. Mech.*, vol. 49, no. 6, pp. 739–745, Jan. 1985, doi: 10.1016/0021-8928(85)90011-5.
- [15] K. E. Evans, "Auxetic polymers," *Membr. Technol.*, vol. 137, no. 2001, p. 9, 2001, Accessed: Jan. 13, 2022. [Online]. Available: <https://www.infona.pl//resource/bwmeta1.element.elsevier-deb925f9-6df4-3a53-a090-e854b0eae5f>.
- [16] L. N. G. F., "A treatise on the mathematical theory of elasticity," *nature*, vol. 105, no. 2643, pp. 511–512, jun. 1920, doi: 10.1038/105511a0.
- [17] H. Kimizuka, H. Kaburaki, and Y. Kogure, "Mechanism for negative poisson ratios over the  $\alpha$ - $\beta$  transition of cristobalite, SiO<sub>2</sub>: A molecular-dynamics study," *Phys. Rev. Lett.*, vol. 84, no. 24, pp. 5548–5551, Jun. 2000, doi: 10.1103/PhysRevLett.84.5548.
- [18] J. N. Grima and K. E. Evans, "Auxetic behavior from rotating triangles," *J. Mater. Sci.*, vol. 41, no. 10, pp. 3193–3196, May 2006, doi: 10.1007/s10853-006-6339-8.
- [19] J. N. Grima, R. Gatt, A. Alderson, and K. E. Evans, "On the origin of auxetic behaviour in the silicate  $\alpha$ -cristobalite," *J. Mater. Chem.*, vol. 15, no. 37, p. 4003, 2005, doi: 10.1039/b508098c.
- [20] E. Pasternak and A. V. Dyskin, "Materials and structures with macroscopic

- negative Poisson's ratio," *Int. J. Eng. Sci.*, vol. 52, pp. 103–114, Mar. 2012, doi: 10.1016/j.ijengsci.2011.11.006.
- [21] R. Lakes, "Foam structures with a negative poisson's ratio," *science* (80-. ), vol. 235, no. 4792, pp. 1038–1040, feb. 1987, doi: 10.1126/science.235.4792.1038.
- [22] J. N. Grima, "Physics of disordered systems '10 auxetic metamaterials," accessed: jan. 13, 2022. [online]. available: <http://www.auxetic.info>.
- [23] K. E. Evans, M. A. Nkansah, I. J. hutchinson, and S. C. Rogers, "Molecular network design," *Nature*, vol. 353, no. 6340, pp. 124–124, Sep. 1991, doi: 10.1038/353124a0.
- [24] S. K. Bhullar, "Characterization of auxetic polyurethanes foam for biomedical implants," *e-Polymers*, vol. 14, no. 6, pp. 441–447, Nov. 2014, doi: 10.1515/epoly-2014-0137.
- [25] "Auxetics – materiability." <https://materiability.com/portfolio/auxetics/> (accessed Jun. 22, 2022).
- [26] "Scopus preview - Scopus - Welcome to Scopus." <https://www.scopus.com/home.uri> (accessed Dec. 09, 2021).
- [27] Y. Zhang, L. Sun, X. Ren, X. Y. Zhang, Z. Tao, and Y. Min Xie, "Design and analysis of an auxetic metamaterial with tuneable stiffness," *Compos. Struct.*,

vol. 281, p. 114997, Feb. 2022, doi: 10.1016/j.compstruct.2021.114997.

- [28] X. Y. Zhang, X. Ren, X. Y. Wang, Y. Zhang, and Y. M. Xie, “A novel combined auxetic tubular structure with enhanced tunable stiffness,” *Compos. Part B Eng.*, vol. 226, p. 109303, Dec. 2021, doi: 10.1016/j.compositesb.2021.109303.
- [29] H. Tan *et al.*, “Crashworthiness design and multi-objective optimization of a novel auxetic hierarchical honeycomb crash box,” *Struct. Multidiscip. Optim.*, vol. 64, no. 4, pp. 2009–2024, Oct. 2021, doi: 10.1007/s00158-021-02961-9.
- [30] A. Jean-Claude and S. Venant, “Résumé des leçons sur l’application de la mécanique à l’établissement des constructions et des machines,” 1st ed. France, 1848.
- [31] G. N. Greaves, “Poisson’s ratio over two centuries: challenging hypotheses,” doi: 10.1098/rsnr.2012.0021.
- [32] W. S. Hemp, “Foundations of Solid Mechanics. Y. C. Fung. Prentice-Hall, New Jersey. 1965. 525 pp. Diagrams. £5.,” *The Journal of the Royal Aeronautical Society*, vol. 70, no. 663, pp. 453–454, 1966.
- [33] L. D. Landau, E. M. Lifshitz, J. B. Sykes, W. H. Reid, and E. H. Dill, “*Theory of elasticity: vol. 7 of course of theoretical physics*,” *phys. today*, vol. 13, no. 7, pp. 44–46, jul. 1960, doi: 10.1063/1.3057037.

- [34] E. Kittinger, J. Tichý, and E. Bertagnolli, “Example of a negative effective poisson’s ratio,” *phys. rev. lett.*, vol. 47, no. 10, pp. 712–714, sep. 1981, doi: 10.1103/physrevlett.47.712.
  
- [35] L. J. Gibson, Michael Farries Ashby, G. S. Schajer, and C. I. Robertson, “The mechanics of two-dimensional cellular materials,” *Proc. R. Soc. London. A. math. phys. sci.*, vol. 382, no. 1782, pp. 25–42, jul. 1982, doi: 10.1098/rspa.1982.0087.
  
- [36] “An isotropic three-dimensional structure with Poisson’s ratio  $\nu = -1$ ,” *J. Elast.*, vol. 15, no. 4, pp. 427–430, 1985, doi: 10.1007/BF00042531.
  
- [37] K. W. Wojciechowski, “Constant thermodynamic tension monte carlo studies of elastic properties of a two-dimensional system of hard cyclic hexamers,” *mol. phys.*, vol. 61, no. 5, pp. 1247–1258, aug. 1987, doi: 10.1080/00268978700101761.
  
- [38] K. W. Wojciechowski and A. C. Brańka, “Negative Poisson ratio in a two-dimensional “isotropic” solid,” *Phys. Rev. A*, vol. 40, no. 12, pp. 7222–7225, Dec. 1989, doi: 10.1103/PhysRevA.40.7222.
  
- [39] K. E. Evans and B. D. Caddock, “Microporous materials with negative Poisson’s ratios. II. Mechanisms and interpretation,” *J. Phys. D. Appl. Phys.*, vol. 22, no. 12, p. 013, Dec. 1989, doi: 10.1088/0022-3727/22/12/013.
  
- [40] M. H. Fu, Y. Chen, and L. L. Hu, “A novel auxetic honeycomb with enhanced

- in-plane stiffness and buckling strength,” *Compos. Struct.*, vol. 160, pp. 574–585, Jan. 2017, doi: 10.1016/J.COMPSTRUCT.2016.10.090.
- [41] T. C. Lim, “Buckling and vibration of circular auxetic plates,” *J. Eng. Mater. Technol. Trans. ASME*, vol. 136, no. 2, Apr. 2014, doi: 10.1115/1.4026617/366634.
- [42] W. Yang, Z.-M. Li, W. Shi, B.-H. Xie, and M.-B. Yang, “Review On auxetic materials.”
- [43] K. L. Alderson and K. E. Evans, “Auxetic materials: the positive side of being negative,” *Eng. Sci. Educ. J.*, vol. 9, no. 4, pp. 148–154, Aug. 2000, doi: 10.1049/esej:20000402.
- [44] K. E. Evans and A. Alderson, “Auxetic materials: functional materials and structures from lateral thinking!,” *adv. mater.*, vol. 12, no. 9, pp. 617–628, may 2000, doi: 10.1002/(sici)1521-4095(200005)12:9<617::aid-adma617>3.0.co;2-3.
- [45] V. H. Carneiro, J. Meireles, and H. Puga, “Auxetic materials-a review,” *mater. sci.*, vol. 31, no. 4, pp. 561–571, 2013, doi: 10.2478/s13536-013-0140-6.
- [46] Q. Liu, “Literature review: materials with negative poisson’s ratios and potential applications to aerospace and defence,” 2006.
- [47] R. S. Lakes and K. Elms, “Indentability of conventional and negative

- poisson's ratio foams," *j. compos. mater.*, vol. 27, no. 12, pp. 1193–1202, dec. 1993, doi: 10.1177/002199839302701203.
- [48] J. B. Choi and R. S. Lakes, "Fracture toughness of re-entrant foam materials with a negative poisson's ratio: experiment and analysis," *int. j. fract.*, vol. 80, no. 1, pp. 73–83, 1996, doi: 10.1007/bf00036481.
- [49] K. L. Alderson, R. S. Webber, and K. E. Evans, "Novel variations in the microstructure of auxetic ultra-high molecular weight polyethylene. Part 2: mechanical properties," *Polym. Eng. Sci.*, vol. 40, no. 8, pp. 1906–1914, Aug. 2000, doi: 10.1002/pen.11322.
- [50] Y. Prawoto, "Seeing auxetic materials from the mechanics point of view: A structural review on the negative poisson's ratio," *Comput. Mater. Sci.*, vol. 58, pp. 140–153, Jun. 2012, doi: 10.1016/j.commatsci.2012.02.012.
- [51] L. Dong, D. S. Stone, and R. S. Lakes, "Softening of bulk modulus and negative Poisson ratio in barium titanate ceramic near the Curie point," *Philos. Mag. Lett.*, vol. 90, no. 1, pp. 23–33, Jan. 2010, doi: 10.1080/09500830903344907.
- [52] H. Lekesiz, S. K. Bhullar, A. A. Karaca, and M. B. G. Jun, "Mechanical characterization of auxetic stainless steel thin sheets with reentrant structure," *Smart Mater. Struct.*, vol. 26, no. 8, p. 085022, Jul. 2017, doi: 10.1088/1361-665X/AA73A4.

- [53] A. Rawal, D. Singh, A. Rastogi, and S. Sharma, "On the origin of negative Poisson's ratio in buckypapers," *Extrem. Mech. Lett.*, vol. 42, p. 101059, Jan. 2021, doi: 10.1016/j.eml.2020.101059.
- [54] M. Mir, M. N. Ali, J. Sami, and U. Ansari, "Review of Mechanics and Applications of Auxetic Structures," *Adv. Mater. Sci. Eng.*, vol. 2014, pp. 1–17, 2014, doi: 10.1155/2014/753496.
- [55] A. Alderson, J. Rasburn, K. E. Evans, and J. N. Grima, "Auxetic polymeric filters display enhanced de-fouling and pressure compensation properties," *Membr. Technol.*, vol. 2001, no. 137, pp. 6–8, Sep. 2001, doi: 10.1016/S0958-2118(01)80299-8.
- [56] L. Santo *et al.*, "Deployable auxetic shape memory alloy cellular antenna demonstrator: design, manufacturing and modal testing You may also like Shape memory composite antennas for space applications Deployable auxetic shape memory alloy cellular antenna demonstrator: design, manufacturing and modal testing," 2012, doi: 10.1088/0964-1726/21/7/075013.
- [57] K. L. Alderson, A. Alderson, G. Smart, V. R. Simkins, and P. J. Davies, "Auxetic polypropylene fibres:Part 1 - Manufacture and characterisation," *plast. rubber compos.*, vol. 31, no. 8, pp. 344–349, Oct. 2002, doi: 10.1179/146580102225006495.
- [58] N. Ravirala, A. Alderson, K. L. Alderson, and P. J. Davies, "Expanding the range of auxetic polymeric products using a novel melt-spinning route," *Phys.*

*status solidi*, vol. 242, no. 3, pp. 653–664, Mar. 2005, doi: 10.1002/pssb.200460384.

- [59] N. Ravirala, K. L. Alderson, P. J. Davies, V. R. Simkins, and A. Alderson, “Negative poisson’s ratio polyester fibers,” *text. res. j.*, vol. 76, no. 7, pp. 540–546, jul. 2006, doi: 10.1177/0040517506065255.
- [60] Hook PB, Evans KE, and Hannington JP, “Moisture sensitive auxetic material,” 2006.
- [61] W. Miller, P. B. Hook, C. W. Smith, X. Wang, and K. E. Evans, “The manufacture and characterisation of a novel, low modulus, negative Poisson’s ratio composite,” *Compos. Sci. Technol.*, vol. 69, no. 5, pp. 651–655, Apr. 2009, doi: 10.1016/j.compscitech.2008.12.016.
- [62] P. U. Kelkar, H. S. Kim, K.-H. Cho, J. Y. Kwak, C.-Y. Kang, and H.-C. Song, “Cellular auxetic structures for mechanical metamaterials: a review,” *sensors*, vol. 20, no. 11, p. 3132, jun. 2020, doi: 10.3390/s20113132.
- [63] E. Andrews, L. Gibson and M. Ashby, "The creep of cellular solids", *Acta Materialia*, vol. 47, no. 10, pp. 2853-2863, 1999. Available: 10.1016/s1359-6454(99)00150-0 [Accessed 30 September 2022].
- [64] “Auxetic metamaterials and structures: a review,” 2018, doi: 10.1088/1361-665X/aaa61c.

- [65] C. . Smith, J. . Grima, and K. . Evans, “A novel mechanism for generating auxetic behaviour in reticulated foams: missing rib foam model,” *Acta Mater.*, vol. 48, no. 17, pp. 4349–4356, Nov. 2000, doi: 10.1016/S1359-6454(00)00269-X.
- [66] N. Gaspar, X. Ren, C. Smith, J. Grima, and K. Evans, “Novel honeycombs with auxetic behaviour,” *Acta mater.*, vol. 53, no. 8, pp. 2439–2445, May 2005, doi: 10.1016/j.actamat.2005.02.006.
- [67] J. N. Grima and K. E. Evans, “Auxetic behavior from rotating squares,” *J. Mater. Sci. Lett.*, vol. 19, no. 17, pp. 1563–1565, 2000, doi: 10.1023/A:1006781224002.
- [68] J. N. Grima, A. Alderson, and K. E. Evans, “Negative poisson’s ratios from rotating rectangles,” *Comput. methods Sci. Technol.*, vol. 10, no. 2, pp. 137–145, 2004, doi: 10.12921/cmst.2004.10.02.137-145.
- [69] J. N. Grima, A. Alderson, and K. E. Evans, “Auxetic behaviour from rotating rigid units,” *Phys. status solidi*, vol. 242, no. 3, pp. 561–575, Mar. 2005, doi: 10.1002/pssb.200460376.
- [70] K. L. Alderson, A. P. Kettle, P. J. Neale, A. P. Pickles, and K. E. Evans, “The effect of the processing parameters on the fabrication of auxetic polyethylene Part II The effect of sintering temperature and time,” 1995.
- [71] E. M. . W. D. R. . Sevic, “Matter. research,” *mater. res. soc. symp. proc.*, vol.

371, p. 495, 1994.

- [72] P.J. McMullan, S. Kumar, and A.C. Griffin, “Textile fibres engineered from molecular auxetic polymers,” *Natl. Text. Cent. Annu. Rep.* , 2007.
- [73] M. P. Bendsøe and O. Sigmund, “Topology optimization,” in *optimization of structural and mechanical systems*, world scientific, 2007, pp. 161–194.
- [74] A. Clausen, F. Wang, J. S. Jensen, O. Sigmund, and J. A. Lewis, “Topology optimized architectures with programmable poisson’s ratio over large deformations,” *adv. mater.*, vol. 27, no. 37, pp. 5523–5527, oct. 2015, doi: 10.1002/adma.201502485.
- [75] J. Dirrenberger, S. Forest, and D. Jeulin, “Effective elastic properties of auxetic microstructures: anisotropy and structural applications,” doi: 10.1007/s10999-012-9192-8.
- [76] J. Dirrenberger, S. Forest, and D. Jeulin, “Elastoplasticity of auxetic materials,” *Comput. Mater. Sci.*, vol. 64, pp. 57–61, Nov. 2012, doi: 10.1016/j.commatsci.2012.03.036.
- [77] P. S. Theocaris and G. E. Stavroulakis, “Multilevel optimal design of composite structures including materials with negative Poisson’s ratio,” *Struct. Optim.*, vol. 15, no. 1, pp. 8–15, Feb. 1998, doi: 10.1007/BF01197432.
- [78] P. S. Theocaris, G. E. Stavroulakis, and P. D. Panagiotopoulos, “Negative

- poisson's ratios in composites with star-shaped inclusions: a numerical homogenization approach," *Arch. Appl. Mech. (Ingenieur Arch.)*, vol. 67, no. 4, pp. 274–286, Apr. 1997, doi: 10.1007/s004190050117.
- [79] N. Auffray, J. Dirrenberger, and G. Rosi, "A complete description of bi-dimensional anisotropic strain-gradient elasticity," *Int. J. Solids Struct.*, vol. 69–70, pp. 195–206, Sep. 2015, doi: 10.1016/j.ijsolstr.2015.04.036.
- [80] J. Dirrenberger, S. Forest, D. Jeulin, and C. Colin, "Homogenization of periodic auxetic materials," *Procedia Eng.*, vol. 10, pp. 1847–1852, 2011, doi: 10.1016/j.proeng.2011.04.307.
- [81] K. K. Saxena, R. Das, and E. P. Calius, "Three decades of auxetics research – materials with negative poisson's ratio: a review," *adv. eng. mater.*, vol. 18, no. 11, pp. 1847–1870, nov. 2016, doi: 10.1002/adem.201600053.
- [82] F. Warmuth, M. Wormser, and C. Körner, "Single phase 3D phononic band gap material," *Sci. Rep.*, vol. 7, no. 1, p. 3843, Dec. 2017, doi: 10.1038/s41598-017-04235-1.
- [83] R. Lakes, "Experimental micro mechanics methods for conventional and negative poisson's ratio cellular solids as cosserat continua," *j. eng. mater. technol.*, vol. 113, no. 1, pp. 148–155, jan. 1991, doi: 10.1115/1.2903371.
- [84] A. Spadoni and M. Ruzzene, "Elasto-static micropolar behavior of a chiral auxetic lattice," *J. Mech. Phys. Solids*, vol. 60, no. 1, pp. 156–171, Jan. 2012,

doi: 10.1016/j.jmps.2011.09.012.

- [85] M. Shokri Rad, Y. Prawoto, and Z. Ahmad, “Analytical solution and finite element approach to the 3D re-entrant structures of auxetic materials,” *Mech. Mater.*, vol. 74, pp. 76–87, Jul. 2014, doi: 10.1016/j.mechmat.2014.03.012.
- [86] J. Qiao and C. Q. Chen, “Analyses on the in-plane impact resistance of auxetic double arrowhead honeycombs,” *j. appl. mech.*, vol. 82, no. 5, may 2015, doi: 10.1115/1.4030007.
- [87] K. E. Evans, M. A. Nkansah, and I. J. Hutchinson, “Auxetic foams: modelling negative poisson’s ratios,” *acta metall. mater.*, vol. 42, no. 4, pp. 1289–1294, apr. 1994, doi: 10.1016/0956-7151(94)90145-7.
- [88] F. Scarpa, P. Panayiotou, and G. Tomlinson, “Numerical and experimental uniaxial loading on in-plane auxetic honeycombs,” *J. Strain Anal. Eng. Des.*, vol. 35, no. 5, pp. 383–388, Jul. 2000, doi: 10.1243/0309324001514152.
- [89] “Why ansys meshing is important for structural fea & fluid cfd simulation.” <https://simutechgroup.com/why-is-meshing-important-for-fea-fluid-simulations/> (accessed jul. 04, 2022).
- [90] K. Ashraff Ali, S. Suresh Kumar, J. Allen Jeffrey, M. Ravikumar and S. Rajkumar, "An insight into stress and strain analysis over on hexagonal aluminium sandwich honeycomb with various thickness glass fiber face sheets", *Materials Today: Proceedings*, vol. 47, pp. 493-499, 2021. Available:

10.1016/j.matpr.2021.05.038 [Accessed 30 September 2022].