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Impact Analysis of Auxetic Structures for Military Applications

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Abstract: Auxetic structures are special structures which tend to become wider when subjected to longitudinal tension instead of getting compressed, which implies structures having a negative poisson's ratio. These structures are used in impact pads due to this unique property. In this comparative study were done on different types of materials and structures which are recognized for 3D printing the auxetic structures. The three stages of explicit dynamic analysis involves firstly selecting the most appropriate structures from chiral truss, re-entrant hexagon, arrow head and one non- auxetic structure which is hexagon structure. From this the structure having the least deformation at the impact point is selected which is re-entrant hexagon. Following this, keeping re-entrant hexagon as the structure, the next set of analysis is performed by varying the structure materials. Polycarbonate, polystyrene, polyvinyl chloride and high density polyethylene were studied and the analysis results showed, polyvinyl chloride as the suitable material. Lastly the limiting velocity for the impact is calculated by varying the impact velocity from 800m/s, 1000m/s and 1200m/s beyond which the structure experienced fracture. This study proposes the selection of suitable auxetic structure and material for manufacturing impact pads.
Keywords: Auxetic structures, impact pads, indentation resistance, explicit dynamics, 3D printing, FDM, Poisson's ratio

I. INTRODUCTION

Auxetic structures are kind of special type of structure which possess a negative poison ratio[1]. This property makes it unique from other structures since most of structures used in daily life have positive poison ratio. In case of positive poison ratio if compressive force is applied longitudinally then the structure will expand laterally and in case of negative poison ratio instead of expanding laterally it gets compressed. This is the main advantage in case of negative poison ratio by which it will have more indentation resistance compared to other structures. Due to this property of high indentation resistance, this structures also known as auxetic structures are used in mainly shock absorbing applications. Here mainly the analysis is done on re-entrant type auxetic structures which includes arrowhead, hexagon, chiral truss and non auxetic structure like simple honeycomb.

II. MECHANICAL PROPERTIES OF AUXETIC STRUCTURES

A. Deformation Mechanism of Re-entrant Structures

The auxetic behaviour in these structures are mainly because of flexure hinge mechanism of diagonal ribs within the structure when load is applied. Due to the tensile force in longitudinal direction, the ribs rotates in horizontal direction by which it elongates in the transverse direction[2]. Due to this it shows negative poison ratio in the structure.

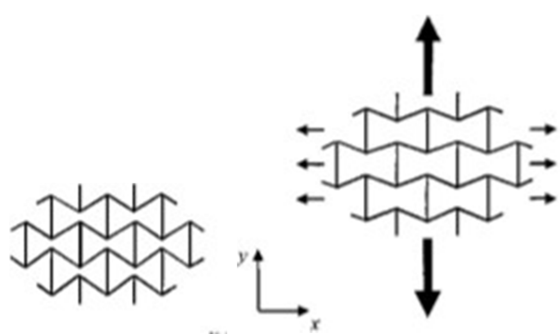


Figure 1. Deformation in re-entrant structures[3]

B. Indentation Behaviour

When the structures is impacted with an object, material flows into the impacted area increasing its density which is called indentation resistance, which is particularly high for auxetic structures. If any crack develops due to a load then the material near the crack will expand due to negative Poisson's ratio and will fill the crack [3,4].

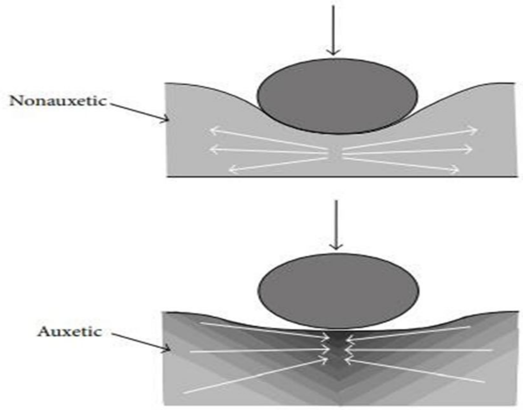


Figure 2. Indentation resistance in non-auxetic and auxetic structures.[3]

In order to increase more indentation resistance, the poison ratio of the auxetic structure should be very close to -1. In this case hardness will be almost infinite[5]. This can described with the help of following equation:

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

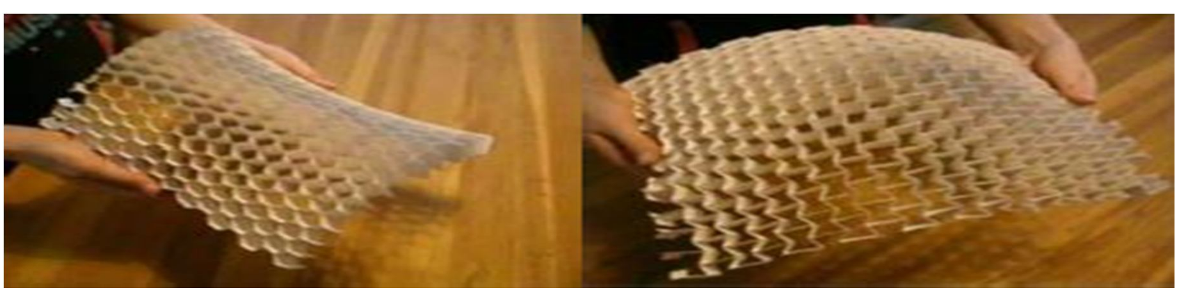
In this E is young's modulus, v is poison ratio and γ is constant which can be either 1 or 2/3 depending on uniform pressure distribution or Hertzian indentation respectively[6].

C. Fracture Toughness

It is a property of structure and tells about how much it could resist the crack propagation. In case of auxetic structure due its negative poison ratio, its fracture toughness is significantly higher than the other structures. As when there is compressive load takes place in the crack, instead of expansion the crack will contract and feel the enclosure and thereby resisting the crack propagation in the auxetic structures. Due to this more energy will be needed in order to make crack propagation [7].

D. Synclastic Curvature

It is the ability of structure to become dome shape when it is bended is known as synclastic curvature. The auxetic structure when it's bended form a dome shape showing synclastic behaviour. Other structures when its bended form a saddle shape[8]. It is because when auxetic structures are bended it contracts in inner surfaces and expands in outer surfaces by which it forms a dome shape[9]. Due to its dome shape this structures can be easily manufactured without need of excessive machining which could damage the structure.



(a) **(b)**

Figure. 3. a) shape shown by non-auxetic materials, b) shape shown by auxetic materials[9]

E. Energy Absorption

Compared to other structures, auxetic structure have high energy absorption capacity and can absorb energies like ultrasonic, damping. At low frequencies it has better sound absorption capacity[10].

III. MATERIAL PROPERTIES OF MATERIALS USED IN AUXETIC STRUCTURES

Polyvinyl Chloride (PVC) is a thermoplastic polymer whose hardness is very high. The behaviour of properties depends on or varying according to temperature and molecular weight. They ameliorate with decrease in the temperature and increase in molecular weight. The indentation resistance is very high and the friction on it is ordinary[11]. Some other material properties include a tensile strength ranging from 10 to 30 N/mm^2, a coefficient of thermal expansion of 0.00005 mm/^{o}C, & density of 1.2 g/cm^3. High Density Polyethylene (HDPE) is another polymer that is thermoplastic. The resistance to any impact or tear can be adjusted by changing the formation of these. HDPE have flexibility, less temperature toughness, high resistance to chemicals. Some other material properties include a tensile strength ranging from 0.3 N/mm^2, a coefficient of thermal expansion of 0.0001 to 0.00022 mm/^{o}C, & density of 0.95 g/cm^3[12]. Polycarbonate (PC) is an amorphous thermoplastic material which are mostly transparent. These can sustain the toughness at very low temperature and rigidity to very high temperatures. It is strong and stiff material with good impact resistance but they have very low chemical resistance unlike the above two. Some other material properties include a tensile strength ranging from 75 N/mm^2, a coefficient of thermal expansion of 0.000065 mm/^{o}C, & density of 1.2 g/cm^3[13]. Polystyrene (PS) is quite similar to Polycarbonate in structure as both are non-polar and clear material. Due to dearth of crystallinity the chemical resistance is very high. Above the certain temperature it behaves a viscous liquid and therefore be moulded in various other structures. There are certain limitations with them such as the impact resistance is very low. The tensile and impact strength below the transition temperature is quite low for polystyrene. Some other material properties include a tensile strength ranging from 45 N/mm^2, a coefficient of thermal expansion of 0.00007 mm/^{o}C, & density of 1.07 g/cm^3[14].

IV. MANUFACTURING OF THE IMPACT PADS

The 3D printing technique used will be fused deposition modelling [15]. Fused deposition modelling (FDM) [16], a technique of additive manufacturing, is capable to fabricate lightweight auxetic structures of various polymer materials , the method being cost effective as well . Layer thickness, raster angle (direction of raster deposition), and number of contours are some of the major process parameters of FDM [17]. This technique needs less time to manufacture and is durable as well, complex lattice structure can be printed for its application in impact pads [18]. The main material would be PVC polymer, while the support material would be wax which is deposited from a separate nozzle. This is the technique which would be used to manufacture the auxetic structure.

V. APPLICATIONS

Auxetic structures due to their unique properties such as increased plane strain fracture resistance, increased shear modulus, indentation resistance and fracture toughness can find their way into interesting applications. One of the areas with high potential could be the biomedical field. A dilator used for opening the cavity of an artery in coronary angioplasty can be made by auxetic structure. For example, a blood vessel made of non-auxetic material will decrease its thickness when blood rushes through it, due to the pressure exerted by the blood resulting in fatigue fracture of the vessel due after large number of stress cycles. Whereas an auxetic material will increase its width at the position where the blood exerts the maximum pressure, due to its negative poisons ratio the material surrounding the area of impact moves in and thus its rupturing probability is reduced [21].

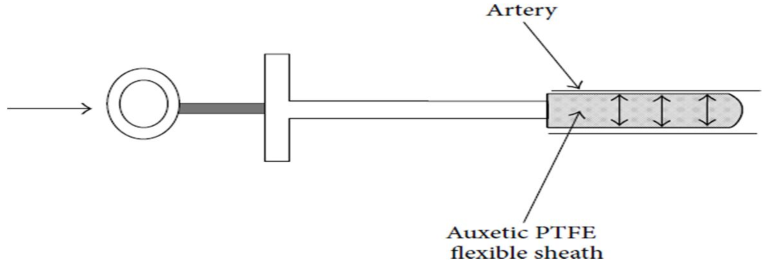


Figure. 4. A dilator with an auxetic sheath.[19]

Other biomedical applications consists surgical implants, and muscle anchors, where additional benefits of auxetic structure promotes bone-in growth. [21]

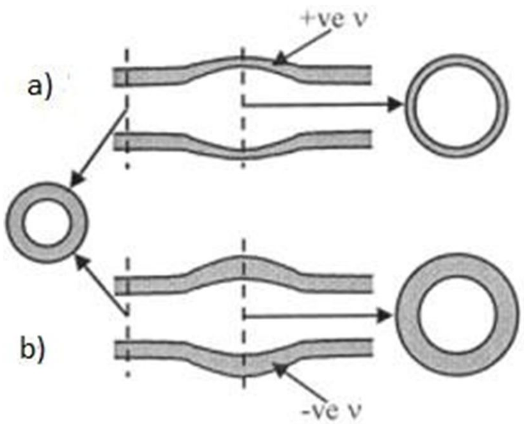


Figure. 5. (a) Non-auxetic vessel (b) Auxetic vessel[24]

A unique application of auxetic structure can be in the production of smart bandages and smart filters. When stress will be applied, when you pull them, their pores increases, thus adjustable filters can be made which can have holes both small and large. Auxetic structures can also be used in bandages inserted with medication, when the wound will press against the dressing, medication will be released which will be controlled by how much it is pulled. [22]

Other area is to develop a piezocomposite device geometry which has an auxetic polymer matrix which can be used in sensor and actuator applications. Also designs by Smith of the US Office of Naval Research, to optimize the performance of these devices have shown that an auxetic matrix is better than a non-auxetic matrix in several ways. [23]

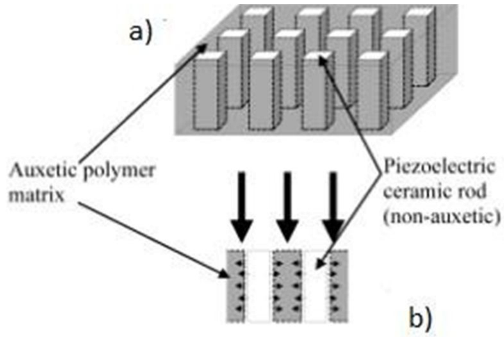


Figure. 6. Piezocomposite devices, consisting of non-auxetic b) piezoelectric ceramic rods within a) an auxetic polymer.[23]

Other application can be in narrow bodies moving in a projectile motion like a bullet, wherein some portion of the bullet can be made by non-auxetic material, such that the overall Poisson's ratio is zero which facilitates in a highly efficient movement. [24]

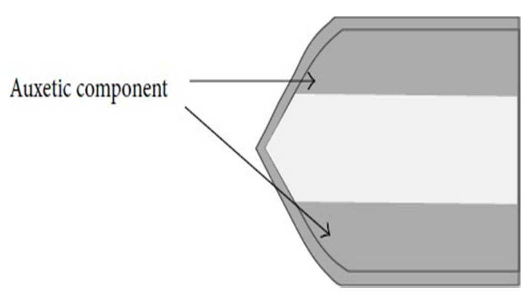


Figure. 7. A bullet with some auxetic components.[24]

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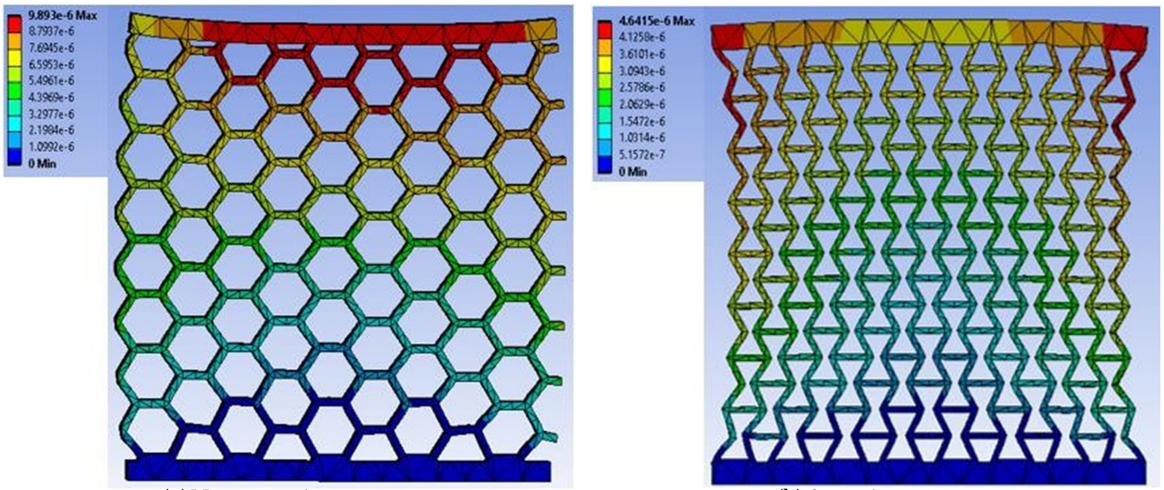
VI. STATIC STRUCTURAL ANALYSIS OF AUXETIC V/S NON-AUXETIC STRUCTURE

Impact pads comes under protective armours and are mainly used in military applications like knee pads to resist the impact force. Due to negative Poisson’s ratio when any impact strikes on the pad instead of expansion, the structure contracts by surrounding the point of impact by which the impact doesn’t go into much depth of the material as the material surrounding it will resist it by compressive force (Figure. 7). Hence it gets high indentation resistance which is one of the most important property to be considered in impact pads.



(a)Non-auxetic structure (b)Auxetic structure

Figure. 8. Static structural analysis of non-auxetic and auxetic structures

Applying compression load on a normal structure it is seen that the structure widens from the middle corresponding to positive Poisson’s ratio. Comparatively, it can be seen in Figure.
7(b) that the structure narrows in the middle showing negative Poisson’s ratio.
Auxetic materials are used where there is need of negative Poisson’s ratio, large shear resistance, improved hardness (large indentation resistance), lower fatigue crack propagation, higher toughness and vibration absorption. Auxetic materials can be used in many fields such as in biomedical field to make a dilator for opening the cavity of an artery or in smart bandages or smart filters in which the pores become larger when you apply stress to them. Another application is in sensor and actuator industry for which composites are used with piezoelectric ceramic rods as core with an auxetic polymer matrix. They are also used in shoe soles to absorb the impact strength, when the sole hits the ground it expands and volume increases by which pressure gets distributed.
Due to their unique mechanical properties and excellent shock absorption capability auxetic materials can be used to make impact pads for body armour. Impact pads in case of an impact load such as a bullet, uniformly distributes the force to the surrounding area and also creates a gap between the load and the person hence protecting him. The use of auxetic material can increase the hardness of these pads and can prove to be very beneficial for military.

VII. METHODOLOGY

In this study, the auxetic nature of impact pads with three different geometries consisting re- entrant hexagon, arrowhead and chiral truss were analysed along with a non-auxetic structure honeycomb. The dimensions of impact pad studied are of 100x100x10 mm for impact loading. These impact pads were modelled using SolidWorks and Fusion 360. To perform impact analysis on all structures, a bullet with a constant speed of 800m/s was impacted at the top surface to determine the feasibility of the structures. The various properties of these structures were found by finite element analysis of impact loading conditions using ANSYS EXPLICIT DYNAMICS package, version 20.0. From the above results it was seen that concluded that re-entrant hexagon structure is the most suitable structure comparing from the figures 12, 13, 14 and 15. Further impact analysis was done on re-entrant hexagon considering four different materials including polycarbonate (PC), high density polyethylene (HDPE), polystyrene (PS) and polyvinyl chloride (PVC). To find promising results, impact loading on these four materials by bullet velocity of 800m/s was considered. By comparing stress and strain developed in the four different materials polyvinyl chloride was selected to be the suitable material among the four for this case of application.

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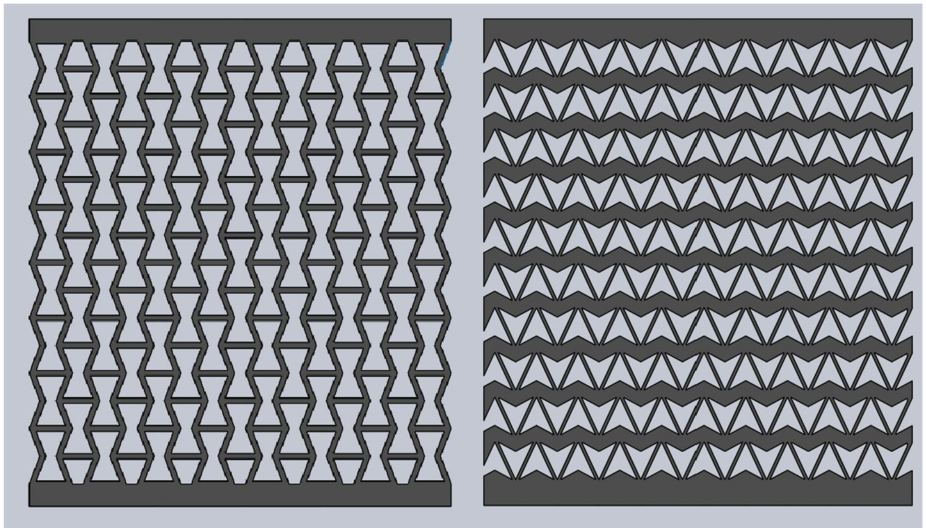
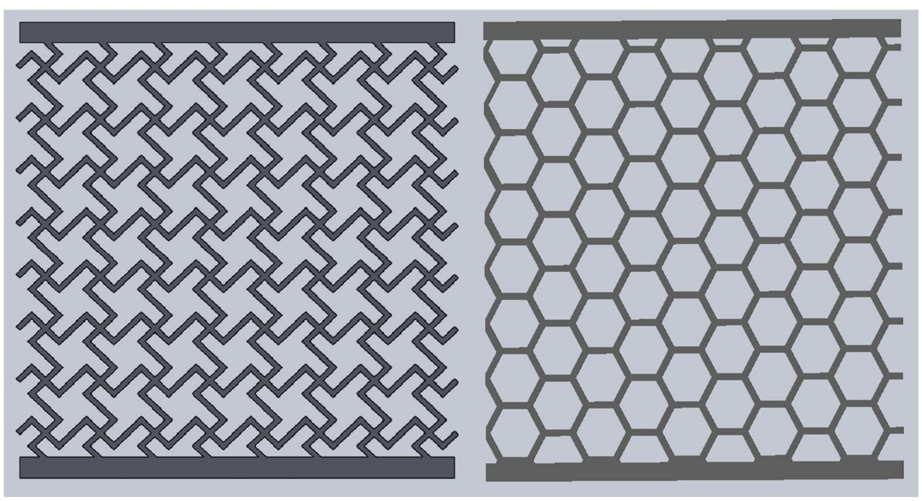
Further in the study, a re-entrant hexagon structure made of polyvinyl chloride was studied for higher impacting speeds of bullet 1000 and 1200 m/s. The structure is seen to fail at 1200m/s bullet speed or higher.

A. Impact Pad Design



a) b)



c) d)

Figure 9. a) Re-entrant Hexagon, b) Arrowhead, c) Chiral Truss, d) Hexagon (Non-auxetic)

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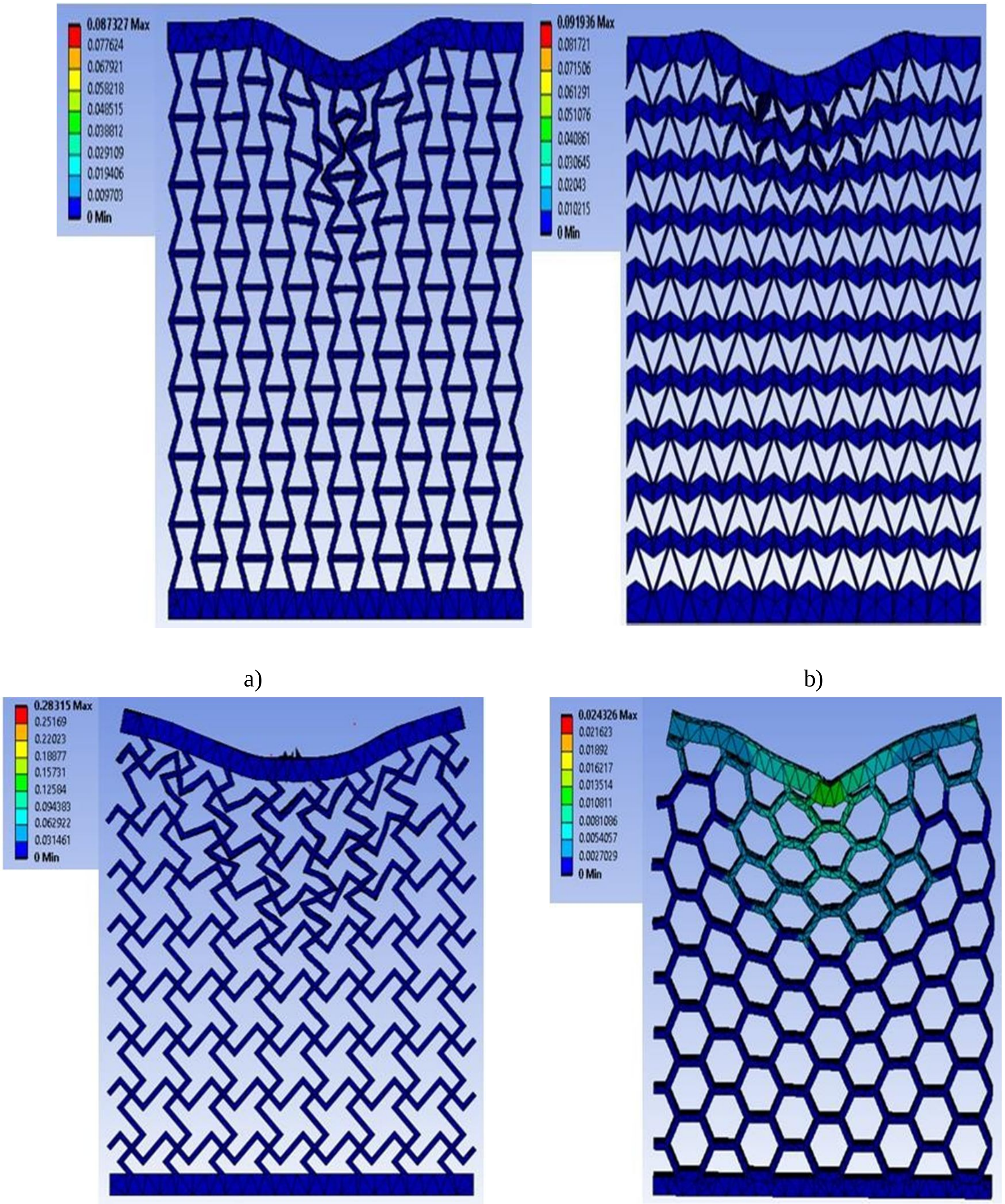
B. Analysis

1) *Analysis of different structures based on constant impact velocity of 800m/s:* The structures are impacted with a constant bullet speed of 800m/s to compare their deformation and their ability to withstand high impact forces.



a) b)

c) d)

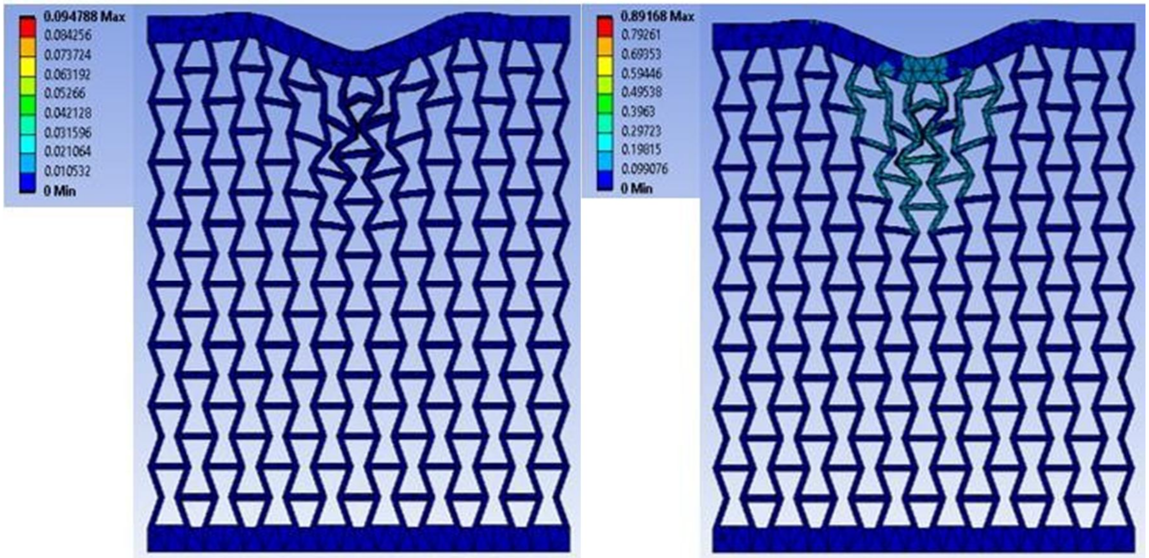
Figure 10. a) Re-entrant Hexagon, b) Arrowhead, c) Chiral Truss, d) Hexagon (Non-auxetic)

In the case of hexagon structure the area of contact turned light green which shows high deformation compared to all the other structures. Based on these deformations re-entrant hexagon is selected to be the most suitable for this particular application.

2) Analysis of different materials, keeping the structure and impact speed the same at 800m/s.

The deformations and strain of all the materials was analysed.

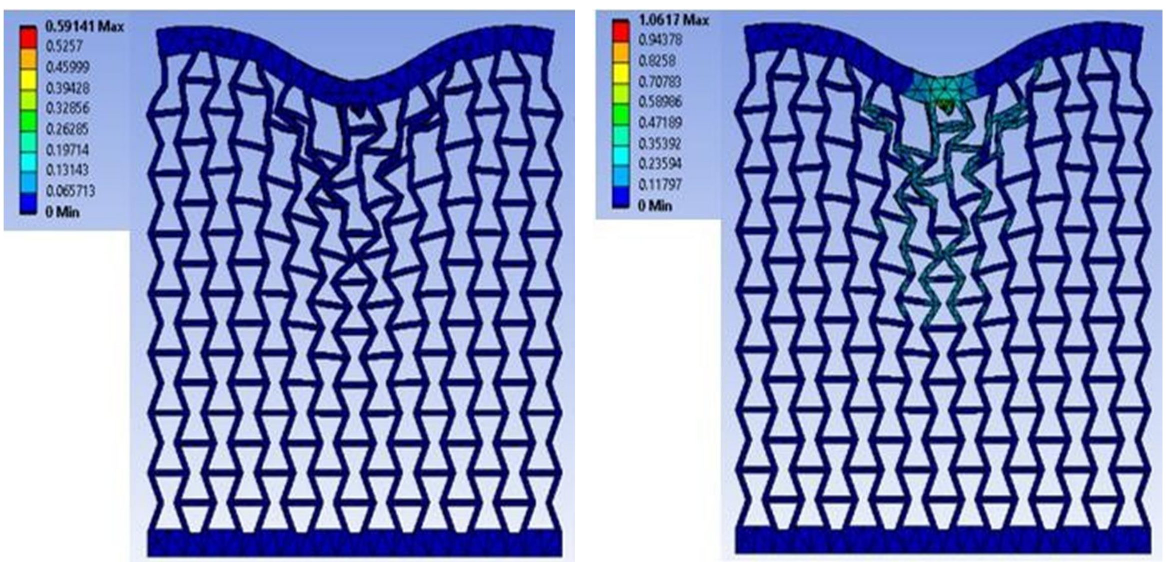
a) Polycarbonate



a) b)

Figure 11. a) The deformation produced, b) The strain developed in the structure

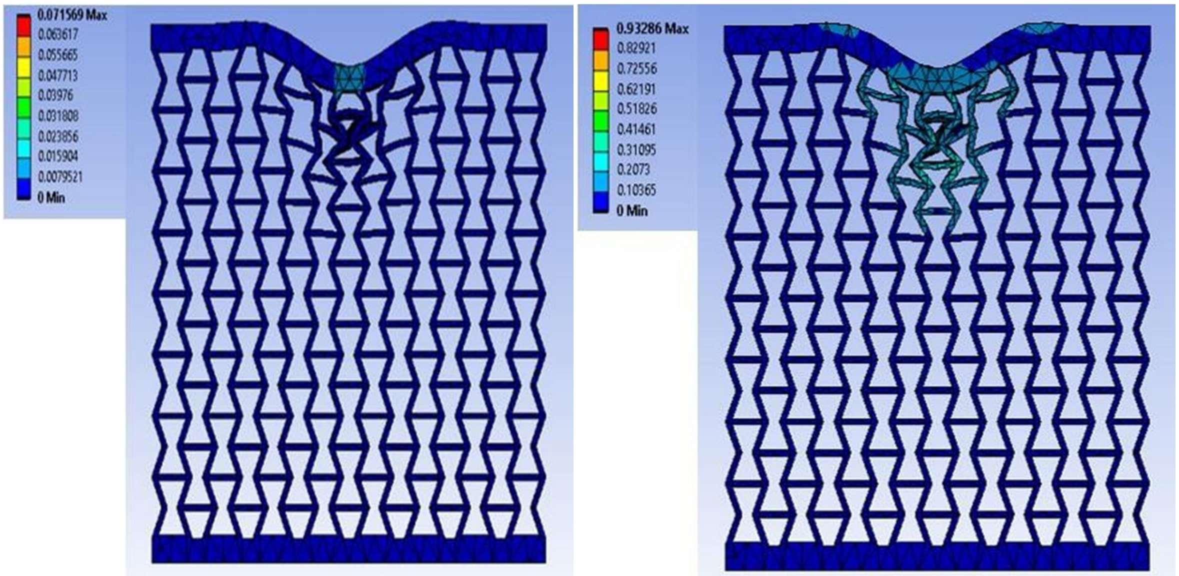
b) High Density Polyethylene



a) b)

Figure 12. a) The deformation produced, b) The strain developed in the structure

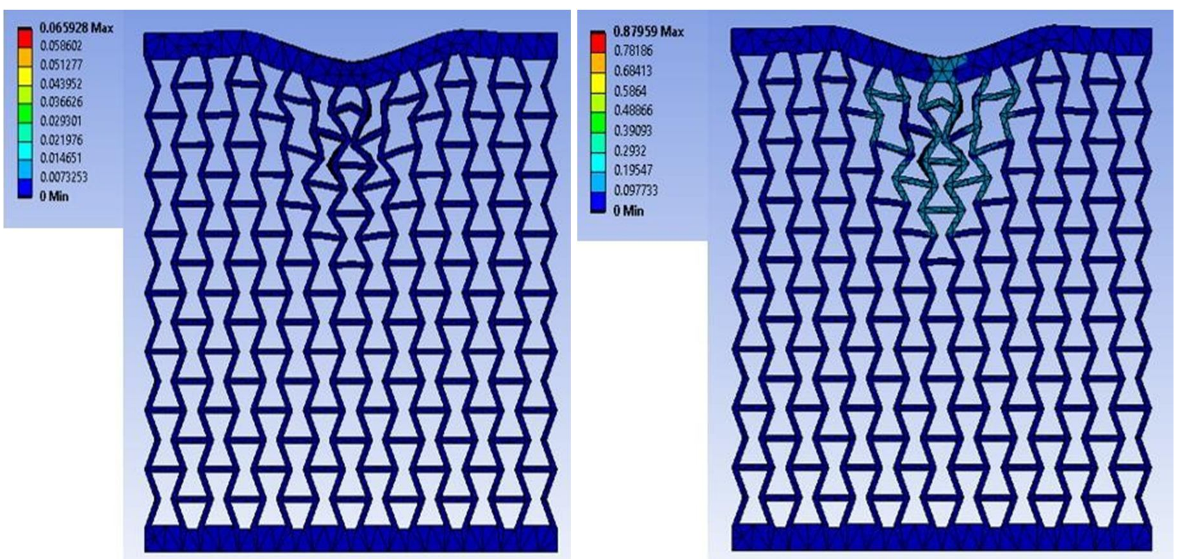
c) Polystyrene



a) b)

Figure 13. a) The deformation produced, b) The strain developed in the structure

d) Polyvinyl Chloride



a) b)

Figure 14. a) The deformation produced, b)The strain developed in the structure

After this simulation polyvinyl chloride is selected for further analysis because the deformation and strain developed in that structure was comparatively lesser than that produced in other material's structure. It is also observed that the impact progressed symmetrical through the surface thereby reducing the overall impact force.

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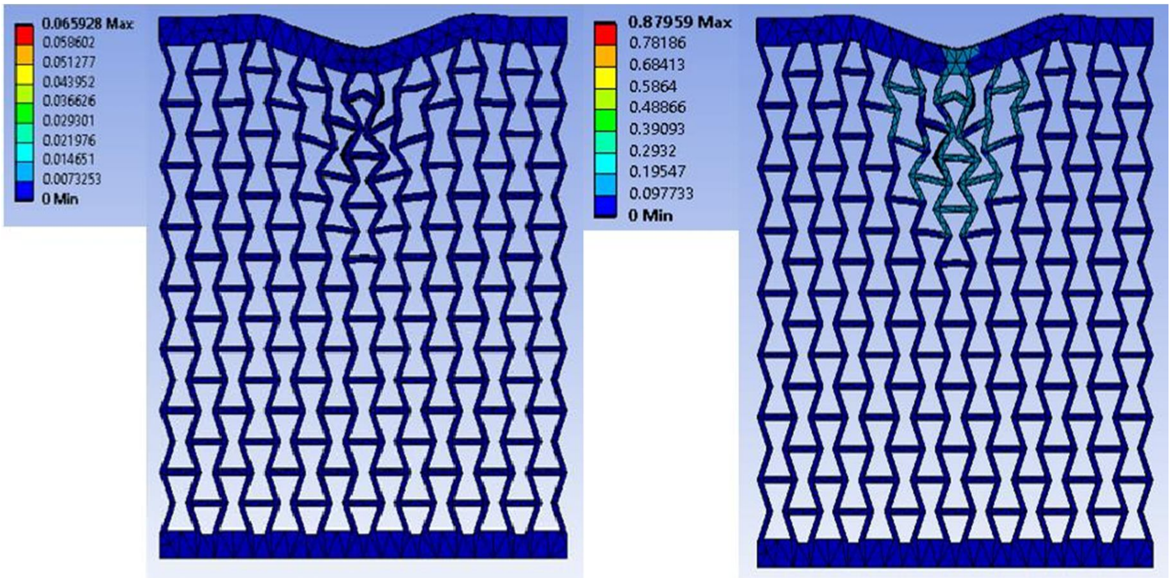
3) *Analysis of the selected material and structure for higher impact speeds:* The selected structure being re-entrant hexagon and the selected material being polyvinyl chloride is analysed for higher impact speeds of 800, 1000 and 1200 m/s.

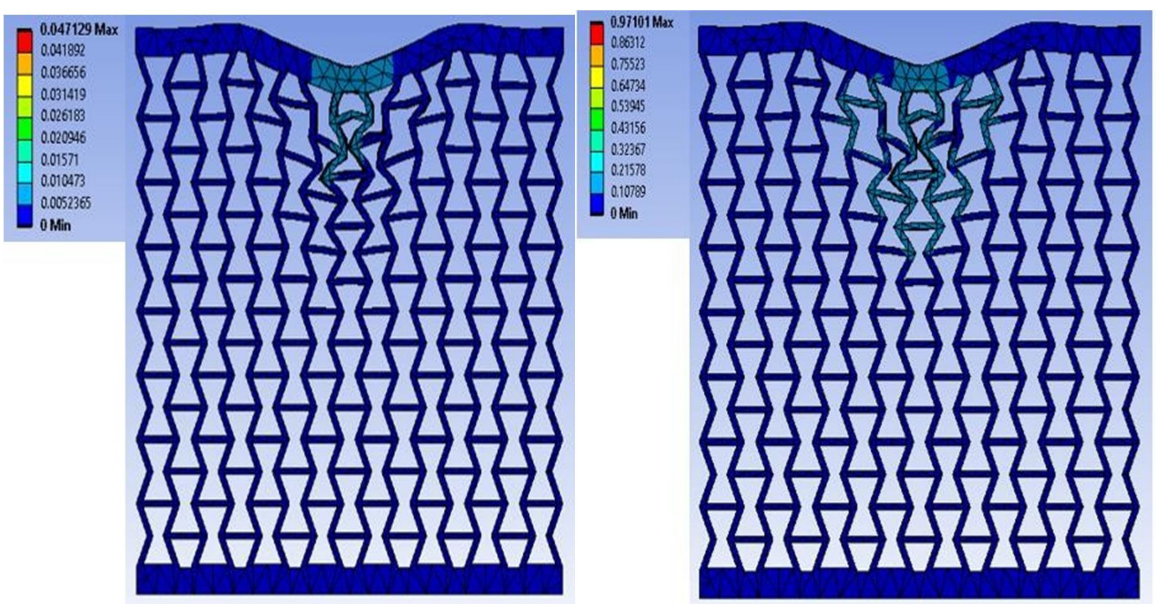
a) *At 800 m/s Impact Speed*



a) b)

Figure 15. a) The deformation produced, b) The strain developed

b) *At 1000 m/s Impact Speed*



a) b)

Figure. 16. a) The deformation produced, b) The strain developed

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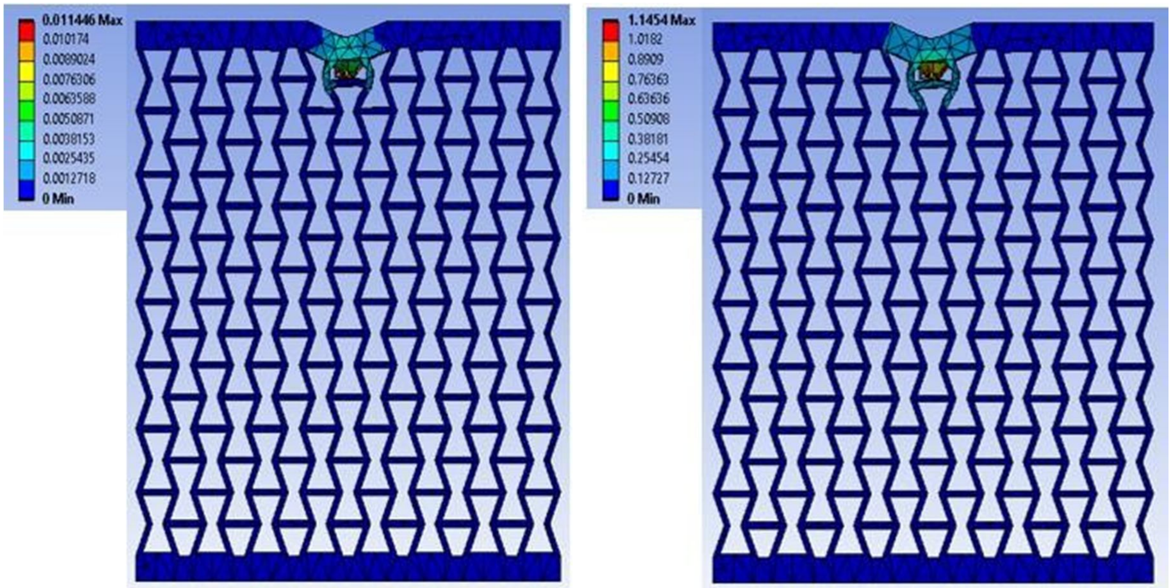
c) At 1200 m/s Impact Speed



a) b)

Figure. 17. a) The deformation produced, b) The strain developed

VIII. RESULTS AND DISCUSSIONS

Through our series of analysis, we narrowed down to a single auxetic structure and its corresponding material for manufacturing of impact pads. The analysis were mainly divided into three sections. The first set involved determining the best structuring from re-entrant hexagon, arrowhead, chiral truss and hexagon(non auxetic) by assigning a dummy material and performing impact analysis with a bullet velocity of 800m/s , from this the best structure identified was re-entrant hexagon. Moving on, having recognised the suitable structure, the next phase involved finding out the material, from a set of four materials namely polycarbonate, polyvinyl chloride, polystyrene, high density polyethylene . The best material identified was polyvinyl chloride. Now the near limiting velocity for the impact pads is determined by varying the bullet velocity from 800m/s to 1200m/s with an increment of 200m/s. This completes our analysis and through our observed results we plan to manufacture the impact pads.

IX. CONCLUSION

Auxetic structures have unique mechanical properties and excellent indentation resistance. It was shown that even different auxetic structures could behave differently under similar testing conditions. The structures mainly re-entrant hexagon and arrowhead showed promising results for impact resistance, shock absorption. Impact analysis of impact pads with varying structures and materials were studied. It is shown that for a successful design of impact pads both structure and material are necessary. Impact pads can be designed to lower the impact force by transferring the forces in the lateral direction thus lowering the effect of force at the bottom layers. When an auxetic structure is hit by an impact force, for example in this study by a bullet, it dissipated the force in lateral directions. The computer simulation results showed that these structures can be used in many applications ranging from body armours, helmets, impact pads to structural components.

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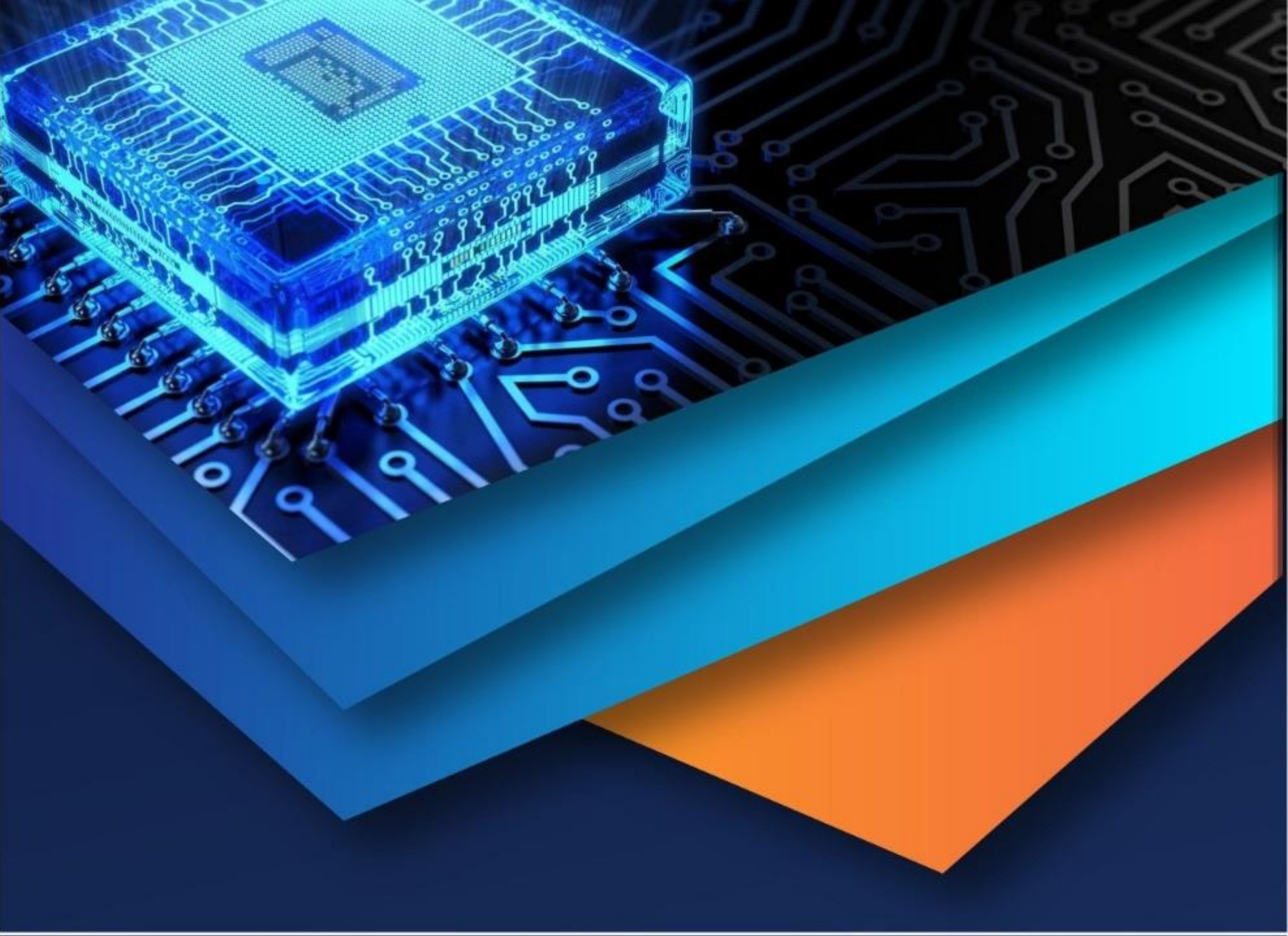

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