Design of 3D Printed Aircraft Seat Structure using Latticing in combination with Topology Optimization and Generative Design

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Abstract: The aviation industry is responsible for 2% of all human-induced CO₂ emissions. According to Iata (a trade body), the number of air passengers is predicted to touch 16 billion by 2050. Minimizing weight is central in achieving an ideal balance between payload and range of an aircraft and consequently, low fuel consumption. For instance, in a Boeing 787, a 20% weight savings will result in 10 to 12% superior fuel efficiency. Besides reducing carbon footprint, aircraft performance improvements like better acceleration, higher structural strength and stiffness, and increased safety could also be achieved by lightweight design. In this research paper, we propound the design of an aircraft seat structure which can be fabricated from Polyetherimide resin by 3D Printing. The structure is designed using topology optimization, generative design, and latticing. The lattice structures are made and tested on nTopologyTM. The seat’s ergonomics are evaluated on Catia V5. The seat design meets all functional requirements without compromising on passenger comfort. The design can be used for standard commercial jets, and the weight savings are predicted to reduce fuel consumption drastically, resulting in lower costs and lower emissions.

1. INTRODUCTION

Light-weighting is associated with the use of advanced materials on structures that are optimized to have minimal mass. Light weighting can be achieved through the computational and numerical development of structures. Conventional numerical methods are sizing, shaping, finite element analysis, and topology optimization [1]. At the same time, latticing and generative design are popular computational techniques. Six factors are considered while choosing materials for seating in the aircraft industry: mechanical strength, ductility, low density, corrosion resistance, machinability, and cost [2]. According to studies conducted by Francis Froes [3], aluminum and seat cushion foam contribute 43% and 8% to seat weight, respectively. This accounts for the seat's structure and the cushioning. Therefore, this paper aims to reduce these components' weight, specifically since they account for 51% of the total seat weight.

Latticing converts solid-designed components into structures consisting of a network of nodes that are interconnected by beams or struts. Latticing reduces the weight of components significantly without compromising on structural integrity. In fact, the structure's interconnected nature enables it to adjust to loads from different angles, making it more resilient. Lattice structures are widely used because they are associated with mechanical properties, which standard bulk materials cannot achieve. This can be achieved by changing the position of nodes or altering beam strut dimensions. Latticing gives designers control over how structures will interact with external loads in the form of shock, vibrations, or fatigue loading. Lattices can be incorporated in designs to provide higher strength to weight ratio and better energy absorbance. For this paper, the main concerning load was the compressive load on the seat. Studies by An Hou and Kurt Gramol [4] showed that, under compression, triangle lattices are weaker due to bridging, which causes delamination. Hexagon structures are hence preferred.
Before proceeding with design optimization and analysis, several factors such as safety, comfort, and ergonomics must be analyzed to finalize design contours. Accordingly, several research studies have been previously published discussing the optimum seat designing parameters for maximum comfort. Ishant Gupta et al. [5] worked on simulating comfort and analyzing several design parameters of aircraft seats in the civil aviation industry by deploying the Delmia Human v6 software. It was inferred from this research study that the 95th percentile of the human population portrayed the most favorable results of a backrest angle of 105° and a seat height of 440mm. On the contrary, the 5th percentile population depicts the optimum design parameters of a seat height of 330mm and a backrest angle of 90°. Other techniques such as pressure mapping and the practical implementation of Ideal Pressure Distribution were carried out by Gabriel H. Campos et al. [6]. A morphed seat design was presented with an optimized seat curvature. Decentralization of the pressure distribution on the backrest was successful, and a similar contour was adopted in this current research study. Further research on biomechanical analysis on aircraft seats was done by R.H.M. Goossens et al. [7], where various factors, including seat height, depth, backrest height, width, armrest length, width, and the backrest inclination was analyzed for best comfort. These values and calculations were further employed in this research study. Light-weight techniques were done by S. Dangal et al. [8] by incorporating spring-foam technology to model a comfortable aircraft seat cushion. An overall weight reduction of 20% was achieved accordingly. Throwing light on this area, numerous other light-weighting techniques can be employed in industrial products.

Topology Optimisation is a commonly known technique by which a particular component can be optimized based on the numerous loads. Topology Optimization works iteratively, removing mass in low-stress concentration areas and reserving high-stress concentration regions, thereby generating an optimized structure. Each iteration removes a certain amount of mass from the total component according to the forces acting on it and the mesh. Generative Design, on the other hand, is also a flourishing technique for design optimization. Generative Design, as its name suggests, adds material based on the stress concentration in specific areas. The method requires creating preserve regions and obstacles as boundary conditions. Preserve regions are areas where mass cannot be compromised, and obstacle regions are specific locations on which mass cannot be added due to real-life constraints. This paper compares topology optimization and generative design of the supporting members on an aircraft seat and creates a low-weight design. Bearing this in mind, the following research study works on an alternative solution to creating light-weight aircraft seats for maximizing fuel efficiency, thereby minimizing fuel consumption.

2. METHODOLOGY

2.1 THEORETICAL CALCULATIONS

The leg of an aircraft seat is one of the most load-bearing components among the entire seat assembly. Hence, a rigorous analysis must be done to ensure reliability and optimization. This paper has focussed mainly on two computational techniques, i.e., topology optimization and generative design, to optimize the part with minimum weight and maximum performance. Before performing computational structural analysis on the leg, the forces acting on it were analyzed. A free-body diagram of the leg was created, and we subsequently concluded that the two forces acting on it were as follows:

1. Force exerted by the weight of the passenger as well as the remaining components of the seat (Vertically downward force) – The maximum weight of a passenger was considered to be 125kg, and the remaining weight of the seat as 10kg for a total of 135kg (worst-case scenario). Since the acceleration due to gravity is 9.81m/s², the total force exerted on 2 legs will be 1324.35N. As a result, the force exerted on a single leg will be around 660N.

2. The pseudo force exerted on the leg due to acceleration and deceleration of the aircraft (Horizontal forward/backward force) – An aircraft in motion does not travel at a constant velocity, and hence it is essential to consider the force on the leg, which acts in a horizontally backward direction. The average maximum velocity attained by an aircraft was taken to be
285kmph by analyzing several aircraft speeds. Based on a research study, the ground roll distance before take-off was taken as 2314ft, which nearly equals 705.3072m. Using the 3rd kinematic equation of motion i.e., \((v^2 - u^2) = 2 \times a \times s\), the maximum acceleration was calculated to be 4.426m/s\(^2\). Hence, the pseudo force acting on one leg will be approximately 300N.

**VERTICALLY DOWNWARD FORCE**

\[ w_{person} = \text{weight of person} = 125kg \]
\[ w_{seat} = \text{weight of seat} = 10kg \]
\[ g = \text{gravitational constant} = 9.81ms^{-2} \]
\[ W_{Total} = w_{person} + w_{seat} = 125 + 10 = 135kg \]
\[ F_{Vertical} = W_{Total} \times g = 135 \times 9.81 = 1324N \]
\[ F_{Vertical\ on\ 1\ leg} = \frac{F_{Vertical}}{2} = \frac{1324.35}{2} = 662.175 \sim 660N \]

**HORIZONTALLY BACKWARD FORCE**

\[ v^2 - u^2 = 2 \times a \times s \]
\[ v = \text{Final Velocity} = 285 \text{ kmph} = 79ms^{-1} \]
\[ u = \text{Initial Velocity} = 0 \text{ ms}^{-1} \]
\[ s = \text{ground roll distance} = 2314ft = 705.3072m \]
\[ a = \text{acceleration} = 4.426ms^{-2} \]
\[ F_{Total} = \text{Total Horizontal Force} = m \times a \]
\[ = 135 \times 4.426 \sim 597.51N \]
\[ = 600N \]
\[ F_{1\ leg} = \text{Horizontal Force on 1 leg} = \frac{F_{Total}}{2} = \frac{600}{2} = 300N \]

2.2 **TOPOLOGY OPTIMISATION**

After the forces acting on the leg were calculated, a solid model was created using Solidworks and was further imported to Ansys Workbench Design Modeller. A highly refined mesh sized 1mm was generated, and a mesh refinement of 3x was applied on the three holes where beams will be attached. This was done to further refine the mesh in areas subjected to a more significant amount of stress and deformation. Subsequently, the three holes and an offset material of 10mm were kept around it as a preserve region. The remaining volume was kept solid to allow the software to optimize that region based on stress experienced and total deformation. The design optimization of the leg was done using numerous Aluminium grades using topological methods. For this, Aluminium 2, 6 and 7 series materials were chosen. Al 7075-T6511, Al- 7050-T7651, Al 6061-T89 and Al 2024-T861 showed the best results, as shown in Table 1.

2.3 **GENERATIVE DESIGN FOR ADDITIVE MANUFACTURING**

Generative design is an iterative design process that uses a program to generate multiple-segmented outputs that meet certain constraints. Further, an engineer can refine the optimal results by selecting specific output or changing input values, ranges and distribution. The novel generative design feature in Autodesk Fusion 360 was deployed for an alternative optimization of the aircraft seat leg. Instead of importing a solid model into the design software, a smaller model consisting of preserve and obstacle geometry was used. Generative design is thus a method by which the software adds material, not interfering with the obstacle geometry and maintaining the preserved geometries. The generative design studies were mainly conducted using the Aluminum grades 7075 T6 and 6061 T6. Four outcome studies were run for each of the two grades based on the manufacturing method required for the leg.
2.4 LATTICING

Lattice structures are generally created using one of two popular techniques, i.e., a uniform voxel-based approach or the conformal latticing approach. The uniform voxel technique divides the component into unit volumes and maps lattice topology into those volumes. [9] In conformal latticing, the unit cells are structured along the surfaces that are to be reinforced. Their deformation occurs such that it conforms to the component surface. Since the lattices are mapped into the unit volumes in the uniform voxel technique, many lattice unit cells are broken or disconnected at the surfaces, making them weak. These discontinuities result in fracture of the structure when loaded in compression or tension. In contrast, the conformal latticing technique creates hexahedral meshes on the component surface, and the unit cells are then mapped onto these meshes. This methodology eliminates the incomplete cells as observed in the uniform vortex technique. This makes conformally latticed structures more resilient. Compressive strength varies based on whether the lattice shows bending-dominated or stretch-dominated behavior. Stretch-dominated behavior shows greater strength as compared to bending-dominated. [10] However, it must be noted that conformal latticing ensures that lattice structures in the same layer are fully connected and provide strength in the direction of the connections. If loads come from other directions, the structure could be weakened. So, engineers should accurately determine the loading directions before orienting the lattices within the structure for optimal performance. In this paper, we have latticed the backrest, cushion, and hand rest of the aircraft seat. The conformal latticing technique was used on topology Platform™ software. To compare the different lattice unit cells, we replicated them along with material properties on Solidworks and tested them in Ansys. The CAD model of the components was designed on Solidworks. The CAD files were imported onto the nTopology platform and then converted to implicit bodies. A volume mesh had to be created to lattice the structure. While latticing the edge length, the lattice cell shape was altered in different iterations. The edge length was set as 25mm. The Triangular Honeycomb (THC), Octet, Body Centred Cubic (BCC), Face Centred Cubic (FCC), Diamond and Kelvin Cell lattices were tested.

2.5 MATERIAL SELECTION

The rigid aromatic rings in high-temperature thermoplastics help them withstand high temperatures. The aromatic rings hinder the backbone chain’s movement since two chemical links have to break for a chain break to occur. This is better than aliphatic structures since they require only one link to be broken for chain breaks. Thus, mechanical properties, high-temperature capability, and chemical resistance are greatly enhanced and even better than crosslinked, thermosetting polymers.

ULTEM™ 9085 resin is a Polyetherimide resin that is a flame-retardant, high-performance thermoplastic. It has a high strength-to-weight ratio, excellent impact strength, and high heat resistance. In addition, it has an optimal flame, smoke, and toxicity (FST) properties. ULTEM™ 9085 resin CG meets stringent test criteria and retains traceability required by the aerospace industry. Polyetherimide (PEI) is also a widely used high-temperature thermoplastic in the aircraft industry. PEI is selected for internal aircraft applications for its inherent flame retardancy and low smoke emissions. It also has excellent chemical resistance to fuels and fluids used in the aircraft industry. Its heat deflection temperature (HDT) is approximately 153°C. ULTEM 9085 has a flexural strength of 16200 psi, making it resistant to fatigue failure. Furthermore, ULTEM-9085 is compatible with FDM 3D printing technology, making it an appropriate choice since 3D printing is majorly used in the seat’s manufacturing.

3. RESULTS AND DISCUSSION

3.1 ANSYS WORKBENCH – TOPOLOGY OPTIMIZATION SETUP

Topology optimization in Ansys Workbench was carried out in 4 iterations to reduce mass: 10%, 15%, 20%, and 25% mass retained. The results can be seen in Fig 1. It can be inferred that optimizing the
geometry with 10% and 15% mass retention resulted in several imperfections around the upper holes. The iteration with 25% mass retention shows a promising structure with minor imperfections. However, this iteration does not efficiently reduce weight to a minimal amount. The iteration with 20% mass retention generated nearly 500g of weight reduction compared to the iteration with 25% mass retained while maintaining mesh consistency, strength, and minor imperfections. Hence, further optimization was executed to reduce additional weight. However, before optimizing the geometry further, the Aluminium grades 7075-T76511, 7050-T7651, 6061-T89, and 2024-T861 were finalized among 15 grades due to various factors, including density, yield strength, and availability.

3.1.1 POST PROCESSING AND STRUCTURAL ANALYSIS IN ANSYS SPACECLAIM

Before analyzing the four grades in Ansys, the optimized geometry was post-processed in the Ansys Spaceclaim modeler. The generated design was smoothened, shrink-wrapped and auto-fixed to make it compatible with additive manufacturing requirements, as shown in figure 2(b). Figure 2(a) shows the aircraft seat leg’s structural analysis with the four materials mentioned earlier. Three factors, mainly total deformation, maximum elastic equivalent strain and maximum equivalent stress, were analyzed. The four materials showed similar results since their structural and mechanical properties nearly the same with minor differences. It was inferred that Al 7075-T76511 showed the minimum deformation while Al 6061-T89 experienced minimum equivalent stress. Consequently, Al 6061-T89 was finalized attributed to lower density (2700kg/m^3) than the other three grades. Based on the mentioned results, the grade Al 6061-T89 was finalized.

![Figure 1](image1.png)

**Figure 1:** Topology Optimisation of Supporting Leg on Ansys Workbench with mass retention of a) 10% b) 15% c) 20% d) 25%
Table 1: Comparison of mechanical behaviour between several materials for the aircraft seat leg

| Material | Total Deformation (mm) | Maximum Equivalent Elastic Strain | Maximum Equivalent Stress (MPa) | Yield Strength (MPa) |
|----------|------------------------|-----------------------------------|-------------------------------|---------------------|
| Al 7075-T6511 | 0.026453 | 8.5567E-05 | 5.9799716 | 510 |
| 7050-T7651    | 0.026851 | 8.5567E-05 | 5.9799716 | 500 |
| 6061-T89      | 0.027479 | 8.7547E-05 | 5.8791732 | 370 |
| 2024-T861     | 0.026705 | 8.5081E-05 | 5.8891731 | 490 |

Figure 2: (a) Structural analysis of the topology optimised structure (b) Post processing of the topology optimised structure

3.1.2 TOPOLOGY OPTIMIZATION IN AUTODESK FUSION 360

The leg was further optimized using the shape optimization tool in Autodesk Fusion 360 software. Instead of importing a solid model, the resultant topology optimized model in Ansys was used for subsequent analysis and optimization. The four iterations of simulations based on load path criticality in Fusion 360 can be seen in figure 3. It can be inferred that in all 4 cases, material from the middle portion of the leg has been removed since that particular area experiences minimal stress as compared to other portions, thereby reducing more weight. After carefully analyzing the equivalent stress in every region of the optimized design, it was concluded that the iteration with a 0.8 load path criticality would best suit optimization. This version was post-processed in Solidworks, and fillets were added to the edges for weight reduction and minimizing stress concentration around sharp corners.
3.1.3 STATIC STRUCTURAL ANALYSIS IN ANSYS WORKBENCH

Afterward, the thickness of the leg was varied between 0.5 and 1 inches for further optimization. The results of the structural analyses of the leg variations of 3 thicknesses are shown in Table 2. It can be inferred that the leg with thicknesses 1 in and 0.75 in are overdesigned. Despite having a thickness of 1 in, the maximum equivalent stress experienced by it is roughly 10 MPa less than that experienced by the leg having a thickness of 0.5 inches. It is also evident that the leg with a thickness of 0.5 inches weighs around 1.2 kg lesser than the leg with a thickness of 1 in, proving that it is a valid, optimized design while maintaining structural strength and durability. It also shows a considerable deformation value coming out to be 0.54081 mm. Hence, after a series of simulations and further modifications, the final optimized design is shown in Figure 4(a).

Table 2. Mechanical behaviour of aircraft seat leg iterations with different thicknesses

| Thickness of Leg (in) | Total Deformation (mm) | Maximum Equivalent Elastic Strain | Maximum Equivalent Stress (MPa) | Factor of Safety | WEIGHT (kg) |
|-----------------------|------------------------|----------------------------------|---------------------------------|------------------|-------------|
| 1                     | 0.28149                | 2.9578E-04                       | 20.991                          | 17.62744164      | 2.37        |
| 0.75                  | 0.37116                | 2.9545E-04                       | 21.175                          | 17.47343566      | 1.79        |
| 0.5                   | 0.54081                | 4.3066E-04                       | 30.876                          | 11.98341754      | 1.21        |
3.2 FINDINGS AND INFERENCES FROM 8 GENERATIVE DESIGN OUTCOMES

Numerous conclusions can be drawn after analyzing the structure, durability, reliability, and other structural results. A comprehensive comparison of various characteristics of the eight iterations is listed in Table 3. According to the results listed in Table 3, it can be inferred that the designs for Al 7075 T6 and Al 6061 T6 (unrestricted manufacturing method) show the least global displacement among all other iterations. They also exhibit a high and reliable factory of safety. On the other hand, optimized designs (b) and (f) show the maximum global deformation of 0.54mm and 0.98mm, respectively, amongst all other outcomes, which prove unreliable and easily deformable. These designs also have a minimum factor of safety of 2 since their orientations for additive manufacturing are incompatible with the loads experienced. Hence (b) and (f) cannot be post-processed further for 3D printing.

3.2.1 COMPARATIVE ANALYSIS OF THE RESULTS

One iteration each (for AL7075 T6 and 6061 T6), as shown in figure 5 (a and e), was performed irrespective of the required manufacturing method required. The remaining six designs were generated based on a motive for subsequent 3D printing in the X, Y, and Z directions. Figure 5(b c d) and figure 5(f g h) show the design optimization for additive manufacturing in the X, Y, and Z direction for Al7075 T6 and Al6061 T6, respectively. Furthermore, designs (b), (c), (f), and (g) show geometry inconsistencies in load-bearing areas, such as the two holes on the top and one hole at the bottom. Although designs (c) and (g) show a moderate deformation of 0.5mm and 0.17mm, they lack the geometry to be manufactured without post-processing irregularities and eliminated from the others. Concerning maximum weight reduced, designs (e) and (h) show the most promising results having a weight of 1.566kg and 1.571kg, respectively. The software’s designs were tailored to be 3D printed in the Z+ direction concerning their isometric view. On the other hand, iterations (a) and (d) also resulted in considerable weight reduction, with the final mass of each outcome being 1.632kg and 1.636kg, respectively. It is also evident from the diagram that iterations tailored to be 3D printed subsequently in the Z+ direction showed the most optimized and safe results along with geometry compatibility. However, while comparing outcomes (a), (d), (e), and (h), it is clear that Al 6061 T6, which is to be further 3D printed in the Z+ direction, experienced the maximum equivalent stress of 8.4MPa as compared to the other three outcomes. Finally, after finally narrowing down to the parameters of weight, maximum equivalent stress, global deformation, and the generative design tool’s percentage recommendation, iteration (e) was finalized and considered for further post-processing.
Table 3. Comparison of Generative Design outcomes based on material properties and manufacturing techniques

| Outcome | Material   | Manufacturing Method | Orientation | Iteration | Mass (kg) | Maximum Von Mises Stress (MPa) | Minimum Factor of Safety | Maximum Global Displacement (mm) | Recommendation by Autodesk Fusion 360 Software (%) |
|---------|------------|----------------------|-------------|-----------|-----------|-------------------------------|--------------------------|----------------------------------|---------------------------------------------------|
| a       | Al 7075   | Unrestricted         | -           | 36        | 1.632     | 4.4                           | 32.96                    | 0.04                             | 91                                                |
| b       | Al 7075   | Additive Manufacturing | X+          | 41        | 2.15      | 72.5                          | 2                        | 0.54                             | 43                                                |
| c       | Al 7075   | Additive Manufacturing | Y+          | 39        | 2.214     | 50.3                          | 2.88                     | 0.50                             | 19                                                |
| d       | Al 7075   | Additive Manufacturing | Z+          | 45        | 1.636     | 5.4                           | 26.85                    | 0.08                             | 70                                                |
| e       | Al 6061   | Unrestricted         | -           | 42        | 1.566     | 4.8                           | 57.02                    | 0.04                             | 92                                                |
| f       | Al 6061   | Additive Manufacturing | X+          | 40        | 2.055     | 137.5                         | 2                      | 0.98                             | 49                                                |
| g       | Al 6061   | Additive Manufacturing | Y+          | 39        | 2.113     | 40.9                          | 6.72                     | 0.17                             | 41                                                |
| h       | Al 6061   | Additive Manufacturing | Z+          | 46        | 1.571     | 8.4                           | 32.61                    | 0.09                             | 71                                                |

3.3 LATTICE STRUCTURE COMPARISONS ON ANSYS AND NTOPOLOGY PLATFORM

The tables below depict the analysis results for the compared lattice structures. The weights of the latticed components are also shown.

Table 4. Comparison of Lattice structure performances under service conditions
The seat cushion bears the most load amongst all the latticed components. The best iterations for the seat cushion in terms of Factor of Safety (FoS) were Octet (1.98), Diamond (1.85), and Triangular Honeycomb (1.71). Thus, we considered these lattices for the seat structure. The THC lattice structure had a comparable Factor of Safety but was heavier than Octet and Diamond structures, so it was discarded. The diamond iteration of 2mm beam thickness had the lowest weight (278.3425g). However, we selected the Octet Lattice due to its lower deformation (0.41029 mm) than Diamond (1.0311 mm).

| Lattice type | Thickness | Total Deformation (mm) | Maximum Equivalent Elastic Strain | Maximum Equivalent Stress (MPa) | Factor of Safety |
|--------------|-----------|------------------------|-----------------------------------|---------------------------------|------------------|
| BCC          | 2mm       | 60.552                 | 1.5455                            | 2832.7                          | 0.04             |
|              | 3mm       | 0.12003                | 0.0039757                         | 737.06                          | 0.33             |
|              | 5mm       | 0.1346                 | 0.000848                          | 129.59                          | 1.92             |
| FCC          | 2mm       | 112.12                 | 1.4746                            | 2913.1                          | 0.04             |
|              | 3mm       | 22.08                  | 0.56431                           | 1130.1                          | 0.12             |
|              | 5mm       | 2.956                  | 0.14598                           | 303.33                          | 0.46             |
| OCTET        | 2mm       | 2.9362                 | 0.1747                            | 281.38                          | 0.49             |
|              | 3mm       | 1.2985                 | 0.094068                          | 197.02                          | 0.71             |
|              | 5mm       | 0.41029                | 0.040426                          | 70.432                          | 1.98             |
| TETRAHEDRAL  | 2mm       | 9.7797                 | 0.25217                           | 544.69                          | 0.25             |
|              | 3mm       | 3.9588                 | 0.15568                           | 333.2                           | 0.42             |
|              | 5mm       | 1.5688                 | 0.09556                           | 208.54                          | 0.7              |
| THC          | 2mm       | 1.7115                 | 0.078826                          | 160.38                          | 0.87             |
|              | 3mm       | 0.65104                | 0.040347                          | 81.851                          | 1.71             |
|              | 5mm       | 0.20946                | 0.012388                          | 23.305                          | 6                |
| DIAMOND      | 2mm       | 1.0311                 | 3.92E-02                          | 75.33                           | 1.85             |
|              | 3mm       | 0.7564                 | 3.62E-02                          | 71.456                          | 1.97             |
|              | 5mm       | 0.32575                | 3.24E-02                          | 67.178                          | 2.08             |

Table 5. Comparison of Lattice Structure Weights

| Lattice type | Thickness | Mass of Seat Cushion (g) | Mass of Back Rest (g) | Mass of Hand-rest (g) |
|--------------|-----------|--------------------------|-----------------------|-----------------------|
| BCC          | 2mm       | 841.20554                | 1308.23               | 155.4292              |
|              | 3mm       | 1819.9124                | 2831.59               |                       |
|              | 5mm       | 2814.1625                | 7,392.48              |                       |
| FCC          | 2mm       | 127.9261                 | 1597.39               | 184.4612              |
|              | 3mm       | 227.96                   | 3459.95               |                       |
|              | 5mm       | 401.4139                 | 8817.99               |                       |
| OCTET        | 2mm       | 106.402                  | 3076.95               | 335.0241              |
|              | 3mm       | 225.354                  | 6598.9                |                       |
|              | 5mm       | 489.2857                 | 16124.2               |                       |
| TETRAHEDRAL  | 2mm       | 1234.38                  | 1877.49               | 151.992               |
|              | 3mm       | 2634.62                  | 4029.84               |                       |
|              | 5mm       | 6532.97                  | 10241.1               |                       |
| THC          | 2mm       | 844.972                  | 11738.6               | 646.852               |
|              | 3mm       | 1136.27                  | 24421.8               |                       |
|              | 5mm       | 1819.91                  | 37002.3               |                       |
| DIAMOND      | 2mm       | 278.3425                 | 1289.48               | 156.6279              |
|              | 3mm       | 558.3638                 | 2853.48               |                       |
|              | 5mm       | 662.6248                 | 7,316.89              |                       |
Figure 6: Total deformation on (a) Triangular Honey Comb (b) Octet and (c) Diamond Lattices for Seat Cushion.

Figure 7: Seat cushion with (a) BCC (b) FCC (c) Octet (d) Tetrahedral (e) THC and (f) Diamond lattice.

Figure 8: Total deformation of (a) Diamond 2mm and (b) Diamond 3mm iterations for back-rest.

The Diamond 2mm and 3mm beam thickness iterations had a safety factor of 1.85 and 1.97, respectively. The 2mm iteration was selected for the back-rest latticing on account of its lower weight.

The hand rests of aircrafts seats are usually about 2 inches wide; however, seat manufacturers now make them 1.6 inches wide. Our design is 1.6 inches wide and has been latticed with a 2mm thick shell. The
BCC, FCC, Tetrahedral, and Diamond Lattices had comparable weights of 155.4292g, 184.4612g, 151.992g, and 156.6279g, respectively. The BCC and FCC structures had very high deformation, so these lattices were rejected. The tetrahedral design had 9.7797 mm deformation while the diamond lattice showed just 1.0311 mm deformation. Therefore, it was selected.

![Deformation Diagrams](image)

**Figure 9:** Total deformation of (a) BCC (b) FCC (c) Tetrahedral (d) Diamond lattices for hand rest.

The final latticed components are shown below.

![Final Lattice Structures](image)

**Figure 10:** Finalised lattice structure of the (a) Seat Cushion (b) Hand-rest (c) Back-rest.

The seat cushion was latticed with an octet lattice structure of 5 mm thickness, while the hand rest and backrest were latticed using the diamond lattice structure of 2mm thickness.

### 3.4 ERGONOMICS EVALUATION ON CATIA V5

We tested our design on Catia V5 software to obtain a RULA score. For the evaluation, we considered a passenger that is a 95 percentile American man whose weight is 125 Kg. A RULA score of 3 is preferred, while scores below 3 are okay, and scores above 3 are considered inferior. The figure below shows the results of the ergonomic evaluation. The seat design obtained a score of 3.
4. COMPARISON WITH STANDARD AIRCRAFT SEATS

Standard Aircraft seats weigh about 15 kg on average. The figure above shows that 43% of the seat weight is from aluminum components. Therefore, aluminum components account for about 6.45 kgs of the seat's weight. At the same time, plastic foam contributes to about 3.3 kg of the seat weight.

Table 6: Weight of Optimised Components.

| COMPONENT                  | WEIGHT  |
|----------------------------|---------|
| Supporting Leg             | 1.21 Kg |
| Actuating Mechanism Housing| 1.8 Kg  |
| Hand rest                  | 156.6 g |
| Seat Back Rest             | 1289.48 g |
| Bottom Cushion             | 489.28 g |
| Serving Tray               | 330.45 g |
The table above shows that the optimized designs show a 3.29 kg weight saving for Aluminium components and a 1.1 kg weight reduction for plastic and foam components. They are effectively reducing each seat weight by approximately 4.4 Kg.

5. CONCLUSION

Weight reduction in aircraft components is imperative to improve fuel efficiency. Each seat contributes significantly to the aircraft weight; therefore, we decided to reduce weight on aircraft seats using computational techniques like latticing, topology optimization, and generative design simulations on the seat hand-rest, supporting leg, backrest, housing mechanism, serving tray and bottom cushion. This yielded positive results in the form of a 4.4 kg weight reduction per seat. Since, on average, there are 180 seats within a single passenger aircraft, the total amount of weight reduced will be approximately 800 kg. To summarise, combining different and simple computational & numerical techniques can help design and develop very light aircraft seats. This concept can be extended to other components in the aircraft’s interior as well.

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