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An Elastoplastic Model Simulation to Investigate the Bending Load on Lattice Structures

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Abstract: ***Over the past few decades, there has been significant growth in latticing techniques, resulting in the development of various core shapes with different properties in this fabrication method. This paper utilizes the finite element method to investigate the strength of a curved beam subjected to three-point bending conditions. It focuses on the maximum stress distribution in the concept of frictional contact between elements of an elastic material and three rigids, aiming to provide a constitutive geometrical model that mitigates the effects of bending and shear stresses. Cellular structure objects offer a promising and excellent solution for this purpose. The study includes a comprehensive comparison between solid-made beams and different lattice structures made of titanium alloy. The lattice specimen is modeled, and Abaqus software is employed for the coupled analysis to study the static strength. Recognizing the importance of relative density on the flexural properties of lattice structures, the critical zones are thoroughly examined, and an optimized model is proposed based on the obtained plots. Finally, conclusions are drawn based on the results of the numerical simulations. Additionally, a recommended model with maximum resistance against axial and shear loads is suggested for use as UAV landing gear.***

Keywords: bending effect, finite element analysis, lattice structure.

1. Introduction

In the current international landscape, there are several manufacturing methods for producing lattice structures, among them three-dimensional printing (3D printing) has become the prevalent method for making these mechanical parts. According to ASTM, 3D printing refers to the fabrication process of creating a part from a 3D model by adding layers [1]. This technology is particularly advantageous for producing complex geometries, offering benefits such as cost-effectiveness, reduced manufacturing time, and the ability to produce lightweight components. Traditional manufacturing methods, such as hot or cold extrusion [2], weaving [3], hot clinching [4], laser cutting [5], water cutting, and assembly [6, 7], pose challenges when dealing with intricate designs. The use of additive manufacturing, especially in the production of lattice structures, has gained significant attention due to its potential for achieving high structural efficiency with minimal material usage, which is economically advantageous for low-volume production [8-10]. Lattice structures have found commercial applications in aerospace and other engineering fields.

Over the past four decades, researchers have conducted studies on the behavior, mechanical characterization, and deformation of diverse lattice structures made from different materials, including metals [11-14] and composite [15]. The mechanical properties of lattice structures are influenced by factors such as the shape and size of the unit cell core and relative density. Numerous reports have studied the mechanical response of different lattice core geometries, including body-centered cubic (BCC), face-centered cubic (FCC), hexagonal closest packed (HCP), gyroid cellular (GC), rhombic dodecahedron (RD), and hollow spherical lattice cell [16-22]. Sypeck [23, 24] proposed various manufacturing methods for truss core sandwich structures, such as open-cell aluminum foam, foam-filled tubes, and metal textile laminates, to determine their stiffness and reliability under mechanical loads. Compression properties based on tensile tests have been established to evaluate the effect of compression on lattice structures [25]. Flexural properties, including flexural strength and flexural modulus, are adjusted by altering cell sizes and relative densities [26, 27]. Tian et al. [28] modified the porosity ratio and studied the linear and nonlinear behavior of the relationship between flexural strength and relative density of cellular structures using 3-point bending tests. The loading direction on lattice core samples has been analyzed extensively by Doroszko et al. [29] and Zhang et al. [30] to understand its impact on the resistance of lightweight materials. Barton et al. [31] compared finite element and experimental surveys to examine the elastic and plastic properties of selective laser melted (SLM) cellular lattice structures in three different orientations under quasi-static loading conditions. When considering latticing, the flexibility of the structures is a crucial parameter to be evaluated. Minimizing the bending effects on various structures may involve challenges such as revising the dimensions of the geometry and increasing the beam thickness, which directly influences the weight of the structure. Regular periodic structures, consisting of models made from stronger and more flexible materials with a low-density core, are commonly used in the production of lightweight structures. Their mechanical characterization can be related to the lattice topology, and they can be manufactured using 3D printers, CNC Machining, or casting depending on the material type, geometry, etc. Zhang et al. [32] compared finite element numerical simulations with manufactured sandwich panels that have varying core angles to investigate their influence on structural integrity during 3-point bending tests. The failure mechanisms of the models were measured to understand the bending effects on sandwich panels with different core angles. Some notable researchers have presented a comprehensive analysis of the mechanical response of lattice structures subjected to destructive testing. These studies provide insights into the failure mechanisms, strain ratios, and deformation behavior of these lattice members, contributing to the understanding and optimization of their performance in engineering applications [33].

This research focuses on investigating the flexural behavior of low-density hexagonal lattice structures under three-point bending test conditions. The objectives of this study are threefold:

1) Analyzing the flexural strength parameters and identifying the most critical zones of solid ellipsoidal and trapezoid arch beams under a concentrated midpoint load.
2) Exploring the use of cellular lattice core curved spars as a means to minimize the bending effects by leveraging their flexibility advantage. This includes studying the impact of reducing the density of the lattice structure and conducting simulation analyses on the stiffness of UAV landing gear.
3) Identifying potential design modifications based on the current designs to meet the desired requirements. Since the specifications of the object are designed for use as UAV landing gear, in this case, stiffness significantly impacts landing time. Lattice structures, with their higher flexibility and lower weight, offer advantages over solid structures in terms of improved shock absorption and reduced landing time.

2. Statement of the problem

2.1 Methods and Materials

Ti-6Al-4V, also known as Ti64, [34] is an α-β titanium alloy implemented in this simulation analysis which is highly valued in the industry due to its exceptional properties. To begin with, Ti-6Al-4V provides a favorable blend of remarkable strength and reduced weight, making it a prime choice for manufacturing lightweight parts that possess exceptional structural soundness. Additionally, this alloy showcases outstanding resistance against corrosion, rendering it suitable for deployment in challenging surroundings. Moreover, the aerospace industry necessitates materials that exhibit both lightness and robustness, and Ti-6Al-4V fulfills these criteria flawlessly. It allows for the creation of intricate and elaborate designs with exceptional accuracy, establishing it as a versatile material across diverse industries. Tables 1 and 2 show mechanical properties and elemental composition predicted for the as-deigned parts respectively.

Table 1: Mechanical Properties of Ti-6Al-4V.

Tensile strength, Ultimate	980 MPa
Yield stress, Re	920 MPa
Elongation	14%
Hardness Knoop	334
Shear modulus	44 GPa
Modulus of Elasticity	110 GPa
Poisson’s ratio	0.342
Density	4.43 g/cm^3

Table 2: Chemical composition of Ti6Al-4V.

Elements	Al	V	Fe	C	Ti
Value	6.40	3.89	0.16	0.002	Balance

The simulations incorporated the aforementioned material properties provided above, emphasizing high specific stiffness and strength. However, variations were observed in the design, cell numbers, and dimensions. The density was treated as a variable parameter, as indicated by equation 1, which illustrates the density ratio where:

ρ_l - The density of a cell wall lattice.

ρ_s - The density of a cell wall solid.

l -strut length

t - the thickness of the strut

$$\frac{\rho_l}{\rho_s} = \frac{2}{\sqrt{3}}\left(\frac{t}{l}\right)\left(1 - \frac{1}{2\sqrt{3}}\frac{t}{l}\right) \tag{1}$$

A low value of relative density indicates high porosity, meanwhile, a high value of that indicates low porosity. The equations below are employed to determine the stiffness of solid and lattice respectively.

$$K_s = 2.3E\left(\frac{t}{l}\right)^3 \tag{2}$$

$$K_l = (E \times A)/l \tag{3}$$

The flexibility of a lattice structure compared to a solid structure can be mathematically explained by examining their respective stiffness properties. In a solid structure, the stiffness is primarily determined by its material properties and geometry. The stiffness (K) of a solid structure is proportional to its Young's modulus (E) and inversely proportional to its cross-sectional area (A). Therefore, a solid structure with a larger cross-sectional area will have higher stiffness and less flexibility.

Generally, the above statements determine the stiffness of solid and lattice structures respectively, where E is Young's modulus of the material, A is the cross-sectional area of the lattice member and l is the length of the lattice member. On the other hand, a lattice structure is characterized by its intricate network of interconnected struts or beams, which introduces additional degrees of freedom and allows for more flexibility. The flexibility of a lattice structure can be quantified by its effective stiffness, which takes into account the geometry, material properties, and connectivity of the lattice. The effective stiffness of a lattice structure is typically lower than that of a solid structure with the same material, resulting in increased flexibility.

2.2. Geometry of the models

The analysis of an arched beam under three-point bending involves considering factors such as the beam's material properties, cross-sectional geometry, curvature, and loading conditions. Numerical methods like finite element analysis (FEA) or analytical calculations can be used to predict the beam's behavior and estimate its structural response under different loading scenarios. The three-point bending configuration is a common design used in landing gear systems to provide stability and ensure a safe touchdown and rollout of the drone. An arched beam under a three-point bending test condition is subjected to a bending force at two points, creating a bending moment along its length. The three-point bending test is a commonly available way to evaluate the mechanical behavior and strength of beams or structural elements. In the test, the arched beam is supported at two points, typically at its ends, while a load is applied at the center point (Fig 1). This load creates a bending moment that causes the beam to deflect or bend. The behavior of the arched beam

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under this bending condition can be analyzed to understand its structural response and properties. The curvature of the arched beam influences its mechanical behavior. The curvature affects the distribution of stresses and strains within the beam, resulting in different deformation patterns compared to a lattice beam. The arched shape can provide advantages such as increased load-carrying capacity, improved stiffness, and enhanced resistance to buckling or failure. During the three-point bending test, various parameters can be measured, including the deflection or displacement of the beam, the applied load, and the resulting stress and strain distribution. These measurements help in assessing the beam's structural performance, such as its stiffness, strength, and ability to withstand bending loads.

In the three-point bending configuration, the landing gear consists of three support points, typically located at the front and rear of the main body or fuselage of the UAV, and at the midpoint of the landing gear structure. This configuration allows for a stable and balanced support system during ground operations and prevents excessive tilting or tipping of the aircraft. During landing, the landing gear system is subjected to the forces and loads generated by the touchdown impact and the deceleration of the UAV.

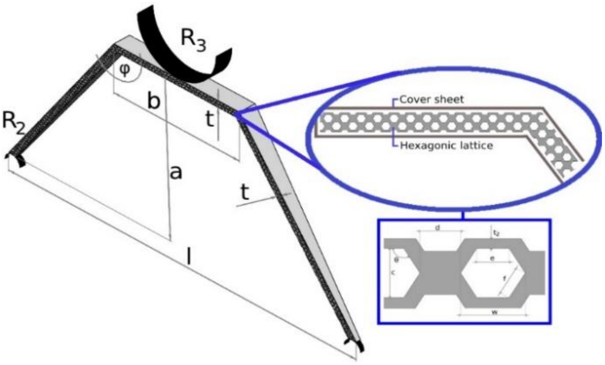

Figure 1: Trapezoid lattice model under 3-point bending test condition

In Table 3 the geometry of unit cells and the whole structure dimension is given when the arch has a trapezoid shape. The table presented below depicts the mass differences among different product cases, where Case 1 represents a solid model while the remaining cases involve lattice models. The mass variations between the different product configurations indicate the impact of utilizing lattice structures instead of solid components (Table 4). The lattice designs offer the advantage of significantly reducing the overall mass of the product compared to the solid model. The decrease in weight can yield various advantages, including enhanced mobility, heightened effectiveness, and improved structural capabilities.

Table 3: Trapezoid cell measurements

Parameter	a	b	l	R2	R3	t	φ
Dimensions [mm]	100	80	220	5	25	4	125

Models	c	d	e	f	w	t2	θ
Case2	1	1.67	0.58	0.58	1.15	0.8	120
Case3	1.43	0.37	0.87	0.78	1.73	0.4	120

Table 4: The difference between trapezoid models

Variants	Case 1	Case 2	Case 3
Mass [Gram]	41.77	35.15	25.66
Volume [Cubic millimeters]	9433.09	7937.67	5795.44
Surface area [Square millimeters]	7285.17	13067.15	17290.70

Figure 2 highlights the potential weight savings achievable through the implementation of lattice structures in product design and manufacturing.

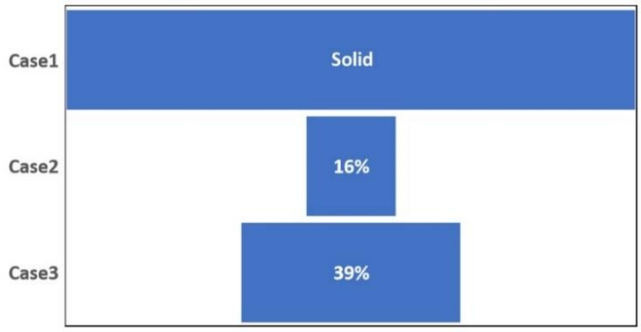

Figure 2: Mass reduction between solid and lattice structure trapezoid models

The detailed 3-point bending test boundary conditions have been exclusively applied to the ellipsoidal lattice model (Fig. 3). This specific lattice configuration was chosen to investigate the mechanical behavior and performance under bending loads. The ellipsoidal lattice model offers unique geometric characteristics that make it suitable for this type of analysis. By subjecting the ellipsoidal lattice model to the 3-point bending test, we can gain valuable insights into its deformation patterns, load distribution, and overall structural response. This focused approach allows for a comprehensive understanding of how the ellipsoidal lattice structure performs under bending conditions, aiding in the evaluation and optimization of its mechanical properties.

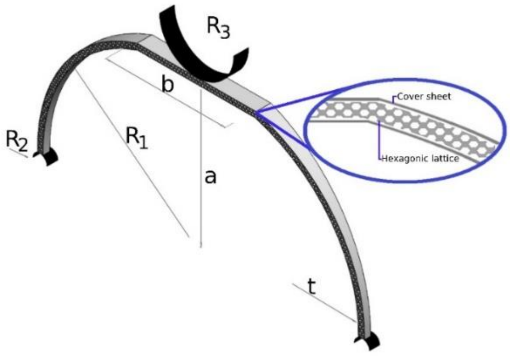

Figure 3: Ellipsoidal lattice model under 3-point bending test condition

The difference between the masses of the ellipsoid models is due to the unit cell variables (Table 5).

Table 5: The difference between ellipsoidal models

Variants	Case 1	Case 2	Case 3
Mass [Gram]	38.24	32.75	27.34
Volume [Cubic millimeters]	8635.21	7395.99	6174.19
Surface area [Square millimeters]	7020.03	12867.57	15326.53

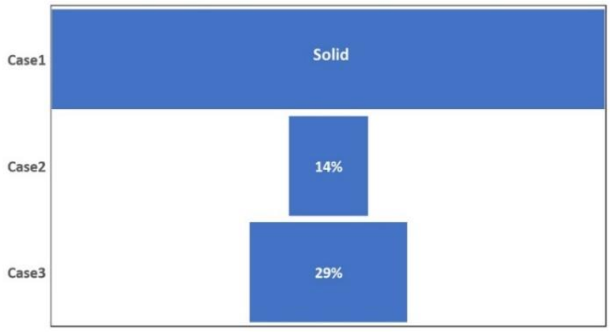

Figure 4: Mass reduction between solid and lattice structure ellipsoidal models

The mass reduction between a solid structure and a lattice structure can be significant, depending on the specific design and material used (Fig 4). Lattice structures are characterized by their intricate network of interconnected beams or struts, which create a lightweight and open framework. In contrast, solid structures are composed of continuous material throughout, resulting in a higher overall mass. The lattice structure's open design inherently reduces the overall density of the structure. This is because the volume of material used in a lattice structure is significantly less compared to a solid structure of the same size. As a result, the mass of the lattice structure is substantially lower. In this study three cases are analyzed, case 1 is a solid arched beam, and the second and third cases are both lattices but in different cell numbers and cell sizes. The figures depict the disparity among the samples.

2.3. FE models

Finite Element (FE) simulation serves as a valuable asset in measuring the stress distribution, plastic occurrence, and the critical zones that lead to structural failure. Within the realm of stress distribution, FE simulation facilitates the visualization and measurement of stress concentrations, pinpointing vulnerable regions that are susceptible to failure. This process deepens comprehension of structural behavior and fosters the development of more resilient engineering solutions. In essence, FE simulation plays a pivotal role in the analysis of stress distribution and failure mechanisms, ultimately contributing to the creation of safer and more effective designs.

Table 6: The element numbers of each model

Case 1	Case 2	Case 3
8212 elements	20356 elements	20334 elements

Trapezoid models

Case 1	Case 2	Case 3
8360 elements	20188 elements	20428 elements

Ellipsoidal models

Here the complex geometry has been divided into a series of smaller elements. A finer mesh with smaller element sizes can provide more accurate results by capturing localized stress concentrations and complex geometries. However, this can also increase the computational cost and time required for the simulation. The element numbers are provided in Table 6. CPS4R which is a 4-node reduced integration bilinear plane stress element type in Abaqus is used. Additionally, in this simulation in which the structure is subjected to a large load and in the case where the material undergoes significant deformation, nonlinear analysis is considered which allows for a more accurate representation of the behavior of the structure under load.

2.4 Boundary condition

In the numerical simulation of a lattice arched beam under 3-point bending, specific boundary conditions are applied to accurately model the behavior of the structure. The lattice-arched beam is typically supported at two points on one side, acting as fixed or clamped supports, while the third point applies a concentrated force at the midpoint of the opposite side. For this simulation, a concentrated force with a magnitude of 80KN is applied at the midpoint. The fixed or clamped supports at the two points restrain the beam from any translational or rotational movement, providing stability during the bending test. These boundary conditions effectively limit the degrees of freedom of the beam and allow for controlled bending deformation when the concentrated force is applied.

The concentrated force applied at the midpoint induces a moment that leads to the bending deformation of the lattice-arched beam. Through the numerical simulation, the displacements and stress distribution throughout the structure can be determined, providing insights into the mechanical response and deformation patterns. By carefully specifying the boundary conditions and applying the concentrated force at the midpoint in the numerical simulation, it is possible to study the structural behavior, stress distribution, and failure mechanisms of lattice-arched beams under 3-point bending. This simulation approach helps in understanding the performance and optimizing the design of such beams in various engineering applications. This problem is a combination of segment-to-segment interaction between elements of a deformable body and three rigids and self-contact through lattice cells by themselves. The penalty method has been used to realize the interaction between bodies, and the frictional coefficient is taken as 0.3. The loading is continued till the occurrence of plastic deformation. In this FEA damaged element deletion technique is used to remove the elements that have been excessively damaged during the analysis. By removing damaged elements, the accuracy and efficiency of the analysis can be improved, allowing for more reliable and efficient simulation results.

3. Presentation of results

In a 3-point bending test, a comparison between a solid and lattice cellular core arched beam can reveal distinct force-displacement relationships. When a solid beam is subjected to the test, it exhibits a relatively linear relationship between the applied force and resulting displacement until it reaches its yield point. Beyond the yield point, the solid beam undergoes plastic deformation, leading to a significant increase in displacement for a relatively small increase in force. On the other hand, a lattice cellular core arched beam demonstrates a more complex force-displacement relationship. Initially, it behaves similarly to the solid beam, with a linear relationship between force and displacement. However, as the force increases, the lattice structure undergoes a combination of elastic deformation and localized failure of lattice members. This results in a nonlinear force-displacement curve

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influenced by its unique structural characteristics, such as the lattice geometry, cell size, and material properties. The force-displacement relationship provides valuable insights into the load-bearing capacity, stiffness, and failure mechanism of both solid and lattice cellular core arched beams under 3-point bending conditions.

In Figure 5 the Force-Displacement curve represents the mechanical response of the selected structure to the applied load. In case 1 which is the solid model the peak force on the curve represents the material's ultimate strength, while the area under the curve represents the energy absorbed by the material during deformation. The post-peak behavior of the curve provides information about the material's ductility, or its ability to deform plastically without fracturing. But in case 2 at the specifically applied load, there is no permanent deformation or fracturing effect on the lattice. In case, 3 cells before reaching the tensile strength have failed because of their thin thickness.

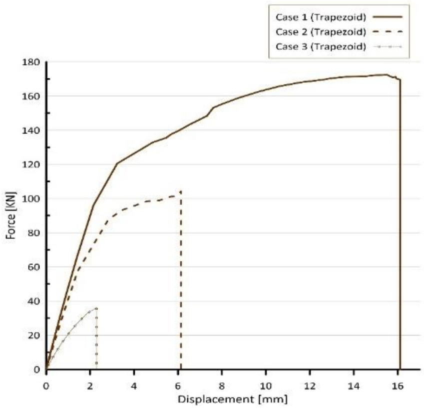

Figure 5: Force-displacement relationship in trapezoid models

By analyzing the principal stress distribution, (Fig. 6) critical regions where the maximum principal stress occurs are identified. These regions are susceptible to failure, such as crack initiation or propagation during the bending process. Moreover, the availability of both maximum and minimum principal stress values provides us with the means to evaluate the structural response and make well-informed choices to guarantee the dependability and integrity of the system and performance of the component or optimize the cell numbers, and their thickness.

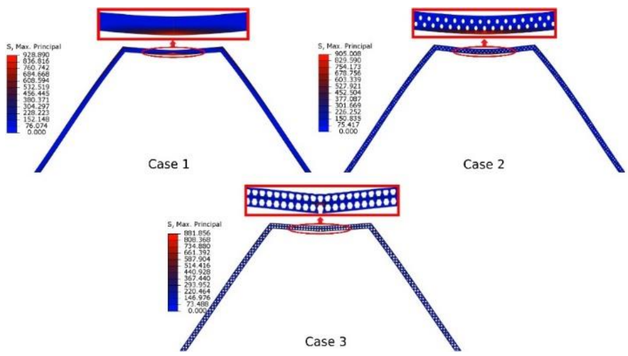

Figure 6: Principal stress distribution

Under the applied load, the solid model (case 1) due to its limited flexibility undergoes deformation, resulting in plastic deformation in certain regions. This highlights one of the advantages of lattice structures over solid models, as lattices offer higher flexibility, allowing them to absorb and distribute loads more effectively without undergoing excessive plastic deformation. This enhanced flexibility of lattice structures contributes to their improved resilience and resistance to failure under varying loading conditions. In the simulation, (Fig. 7) the occurrence of structural failure in case 3 before reaching the plastic limit can be observed in specific critical zones. These areas are characterized by high-stress concentrations or inadequate load-bearing capacity, highlighting the need for further analysis and reinforcement to ensure the overall integrity and durability of the lattice structure.

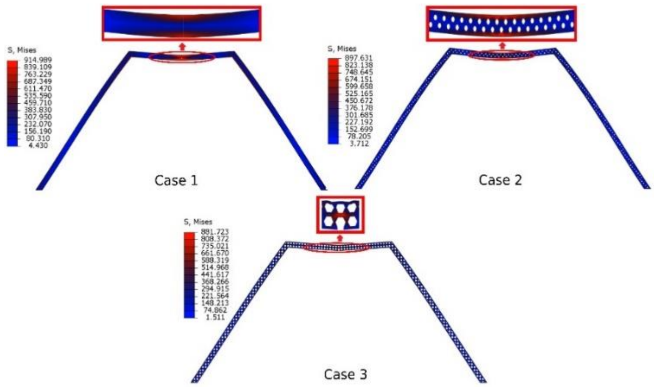

Figure 7: Von Mises stress distribution

Due to the application of a large magnitude of force, the model has undergone significant plastic deformation. The deformation observed in the model indicates (Fig. 8) that the material has exceeded its elastic limit and entered the plastic range.

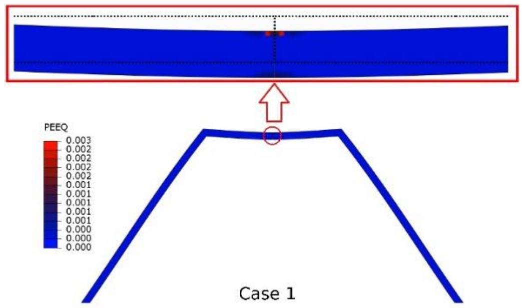

Figure 8: Plastic deformation occurred on the critical elements of the trapezoid model

The distribution of damage in the utilized specimens provides valuable insights into the behavior of the material under the detailed loading condition. As depicted in Fig 9, in the third case, the leg of the lattice cells has experienced a fracture, indicating the occurrence of structural failure in those regions. The fracture of the cell legs is a significant observation as it suggests that the applied load has exceeded the material's strength or the structural design's limitations. This type of damage can lead to a loss of load-carrying capacity and a decrease in the overall structural performance. Understanding the specific locations where the fracture occurred provides valuable insights for further analysis and optimization of the lattice structure, aiming to enhance its strength and durability.

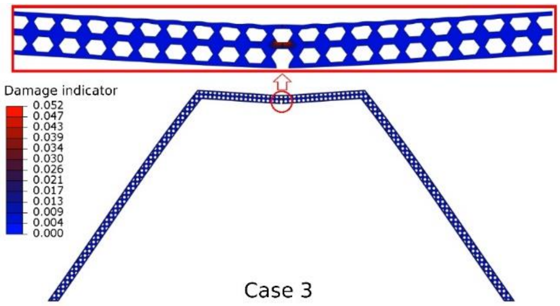

Figure 9: Damage distribution in the utilized specimens

In the second type, three ellipsoidal arched beams are modeled and again the force-displacement curve (Fig. 10) is illustrated, in case 1 it indicates that the structure is exhibiting a greater resistance to deformation, but above 80KN, plastic deformation has occurred, and then because of large deformation the linear relationship has been replaced by entirely curve line. If the force-displacement curve is higher, it indicates that the structure or material is exhibiting a greater resistance to deformation. This can be attributed to factors such as increased stiffness, higher strength, or improved structural integrity. A higher force-displacement curve suggests that the structure can withstand larger forces or deformations before reaching failure or yielding. It may indicate a more robust or durable material or a stronger structural design. However, it is important to analyze the specific context and requirements of the application to determine whether a higher force-displacement curve is desirable or if it signifies excessive rigidity or potential issues such as brittleness.

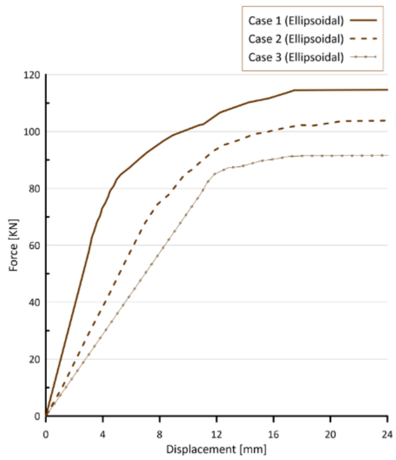

Figure 10: Force-displacement relationship in ellipsoidal models

The flexibility of an ellipsoidal lattice curved beam compared to a trapezoidal lattice curved beam can be attributed to their respective geometric shapes and distributions of stress. In an ellipsoidal lattice curved beam, the curved shape allows for a more uniform distribution of material along the length and cross-section of the beam. This shape provides a balanced distribution of stress and strain during deformation, resulting in increased flexibility and resistance to deformation. The changing cross-sectional shape and uneven material distribution can lead to localized stress concentrations and less flexible behavior. The abrupt changes in geometry and material distribution can result in higher stress concentrations, making the trapezoidal lattice curved beam less flexible compared to the ellipsoidal lattice curved beam. The principal stress distribution, illustrated in Fig. 11, cases 1, and 2 failed because of different reasons. In 1st case which is a solid curved beam the maximum principal stress is extensively higher than the yield point, and in case 2 the beam has the highest thickness, this assumed geometry of cells can result in less flexibility as there are fewer interconnected elements to accommodate deformation. In contrast, a thinner lattice with a higher number of smaller cells allows for more freedom of movement and increased flexibility likewise case 3.

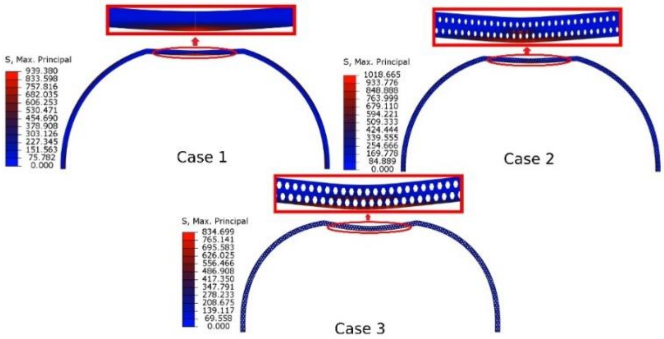

Figure 11: Principal stress distribution

A thicker lattice generally exhibits lower flexibility compared to a thinner lattice due to the differences in stiffness and deformation characteristics

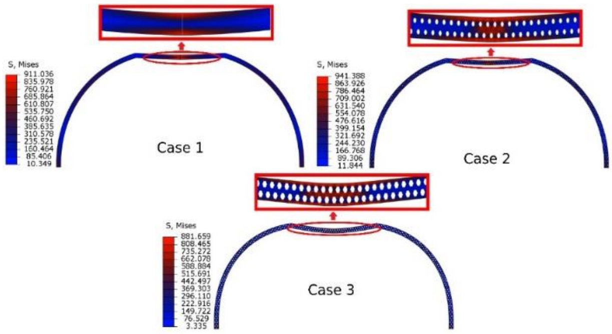

Figure 12: Von Mises stress distribution

Optimization plays a crucial role in the design of lattice structures to achieve the most effective model in terms of stiffness, weight, and flexibility features to find an optimal balance between these factors to meet the desired performance requirements (Fig. 12). Firstly, the stiffness of the lattice is a key consideration in many applications. A highly stiff lattice structure can provide excellent load-bearing capabilities and resist deformations under applied forces. This is particularly important in engineering designs where rigidity and stability are paramount. By optimizing the lattice topology, cell shape, and material distribution, designers can enhance the overall stiffness of the structure. Secondly, weight reduction is a significant advantage of lattice structures compared to solid counterparts. By strategically removing material in non-critical areas and utilizing lightweight materials, the weight of the lattice can be minimized without compromising its strength. This weight optimization is particularly beneficial in industries where weight savings lead to improved energy efficiency, reduced costs, or enhanced mobility. Lastly, flexibility is another crucial aspect to consider in a lattice design. While stiffness is desirable in certain applications, flexibility allows for adaptive responses to dynamic loading conditions or deformations. By carefully designing the lattice geometry and cell connections, it is possible to introduce controlled flexibility while maintaining structural integrity.

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This flexibility can improve the lattice's ability to absorb energy, withstand vibrations, or accommodate shape changes, making it suitable for applications where adaptability and resilience are key.

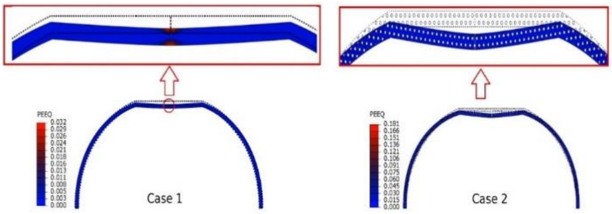

Figure 13: Plastic deformation occurred on the critical elements of ellipsoidal models

Plastic deformation in both cases 1 and 2 are illustrated in Fig 13.

4. Conclusions

(1) The flexibility of a lattice structure arises from its unique design and arrangement, allowing for greater deformation and bending in comparison to a solid structure. The ellipsoidal lattice beam, with its smooth and continuous curvature, facilitates better load distribution, minimizing stress concentrations and promoting flexibility. Conversely, a trapezoidal lattice curved beam exhibits non-uniform material distribution along its length and cross-section. The geometry of the lattice structure can be optimized to enhance its performance under various loading conditions. In a 3-point bending test, the lattice structure evenly distributes the load throughout its structure, resulting in reduced stress concentrations. The comparison of studied cases reveals that as the stiffness of a structure increases, its flexibility decreases, and vice versa.

(2) When designing lattice structures, it is important to find a balance between leg thickness and flexibility. Thick legs can limit flexibility and lead to plastic deformation under loads, while thin legs may be prone to cracking. Achieving an optimal leg thickness is crucial for ensuring both structural integrity and performance.

(3) The selection between lattice and solid structures can significantly impact landing time. Lattice structures, with their higher flexibility, tend to provide better shock absorption and reduce landing time compared to stiffer solid structures that may struggle to absorb impact forces.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] A. Standard, "Standard terminology for additive manufacturing technologies," ASTM International F2792-12a, pp. 1-9, 2012.

[2] W. Zhou, J. Lin, T. A. Dean, and L. Wang, "Feasibility studies of a novel extrusion process for curved profiles: Experimentation and modelling," International Journal of Machine Tools and Manufacture, vol. 126, pp. 27-43, 2018.

[3] H. Cao, W. Lu, M. Yi, and S. Wang, "Deformation and failure by weaving dislocation networks in body-centered-cubic tungsten," Materials & Design, vol. 223, p. 111182, 2022.

[4] D. Berezhnoi and M. Shamim, "Numerical investigation of clinch connection manufacturing process," Procedia Engineering, vol. 206, pp. 1056-1062, 2017.

[5] U. Halm, M. Nießen, and W. Schulz, "Simulation of melt film dynamics in laser fusion cutting using a boundary layer approximation," International Journal of Heat and Mass Transfer, vol. 168, p. 120837, 2021.

[6] M. Luţcanu et al., "Analysis of water jet cutting of metal-ceramic elements made through atmospheric plasma spraying technique," Materials Today: Proceedings, vol. 72, pp. 550-553, 2023.

[7] C. Shet, X. Deng, and A. E. Bayoumi, "Finite element simulation of high-pressure water-jet assisted metal cutting," International Journal of Mechanical Sciences, vol. 45, no. 6-7, pp. 1201-1228, 2003.

[8] J. Ding, M. Baumers, E. A. Clark, and R. D. Wildman, "The economics of additive manufacturing: Towards a general cost model including process failure," International Journal of Production Economics, vol. 237, p. 108087, 2021.

[9] L. Rickenbacher, A. Spierings, and K. Wegener, "An integrated cost-model for selective laser melting (SLM)," Rapid Prototyping Journal, vol. 19, no. 3, pp. 208-214, 2013.

[10] D. Thomas, "Costs, benefits, and adoption of additive manufacturing: a supply chain perspective," The International Journal of Advanced Manufacturing Technology, vol. 85, pp. 1857-1876, 2016.

[11] D. Jiang and F. Ning, "Physical-mechanical behaviors of stainless steel plate-lattice built by material extrusion additive manufacturing," Journal of Materials Processing Technology, vol. 309, p. 117739, 2022.

[12] D. Jiang and F. Ning, "Material extrusion of stainless-steel plate-lattice structure: Part shrinkage, microstructure, and mechanical performance," Manufacturing Letters, vol. 33, pp. 712-718, 2022.

[13] T. Zhong, K. He, H. Li, and L. Yang, "Mechanical properties of lightweight 316L stainless steel lattice structures fabricated by selective laser melting," Materials & Design, vol. 181, p. 108076, 2019.

[14] P. Köhnen, C. Haase, J. Bültmann, S. Ziegler, J. H. Schleifenbaum, and W. Bleck, "Mechanical properties and deformation behavior of additively manufactured lattice structures of stainless steel," Materials & Design, vol. 145, pp. 205-217, 2018.

[15] C. J. Hunt, F. Morabito, C. Grace, Y. Zhao, and B. K. Woods, "A review of composite lattice structures," Composite Structures, vol. 284, p. 115120, 2022.

[16] Y. Huang, Y. Xue, X. Wang, and F. Han, "Mechanical behavior of three-dimensional pyramidal aluminum lattice materials," Materials Science and Engineering: A, vol. 696, pp. 520-528, 2017.

[17] S. Morrish, M. Pedersen, K. Wong, I. Todd, and R. Goodall, "Size effects in compression in Electron Beam Melted Ti6Al4V diamond structure lattices," Materials Letters, vol. 190, pp. 138-142, 2017.

[18] L. Yang, "Experimental-assisted design development for an octahedral cellular structure using additive manufacturing," Rapid Prototyping Journal, vol. 21, no. 2, pp. 168-176, 2015.
[19] H. Klippstein, H. Hassanin, A. Diaz De Cerio Sanchez, Y. Zweiri, and L. Seneviratne, "Additive manufacturing of porous structures for unmanned aerial vehicles applications," Advanced Engineering Materials, vol. 20, no. 9, p. 1800290, 2018.
[20] J. Xiong et al., "Advanced micro-lattice materials," Advanced Engineering Materials, vol. 17, no. 9, pp. 1253-1264, 2015.
[21] M. S. Elsayed and D. Pasini, "Analysis of the elastostatic specific stiffness of 2D stretching-dominated lattice materials," Mechanics of Materials, vol. 42, no. 7, pp. 709-725, 2010.
[22] M. Zhao, X. Li, D. Z. Zhang, and W. Zhai, "Design, mechanical properties and optimization of lattice structures with hollow prismatic struts," International Journal of Mechanical Sciences, vol. 238, p. 107842, 2023.
[23] D. J. Sypeck and H. N. Wadley, "Cellular metal truss core sandwich structures," Advanced Engineering Materials, vol. 4, no. 10, pp. 759-764, 2002.
[24] D. J. Sypeck, "Wrought aluminum truss core sandwich structures," Metallurgical and Materials Transactions B, vol. 36, pp. 125-131, 2005.
[25] A. Shitanaka, T. Aoki, and T. Yokozeki, "Comparison of buckling loads of hyperboloidal and cylindrical lattice structures," Composite Structures, vol. 207, pp. 877-888, 2019.
[26] D. Kotzem, T. Arold, K. Bleicher, R. Raveendran, T. Niendorf, and F. Walther, "Ti6Al4V lattice structures manufactured by electron beam powder bed fusion-Microstructural and mechanical characterization based on advanced in situ techniques," journal of materials research and technology, vol. 22, pp. 2111-2130, 2023.
[27] M. Marco, R. Belda, M. H. Miguélez, and E. Giner, "Numerical analysis of mechanical behaviour of lattice and porous structures," Composite Structures, vol. 261, p. 113292, 2021.
[28] C. Tian, X. Li, H. Li, G. Guo, L. Wang, and Y. Rong, "The effect of porosity on the mechanical property of metal-bonded diamond grinding wheel fabricated by selective laser melting (SLM)," Materials Science and Engineering: A, vol. 743, pp. 697-706, 2019.
[29] M. Doroszko, A. Falkowska, and A. Seweryn, "Image-based numerical modeling of the tensile deformation behavior and mechanical properties of additive manufactured Ti–6Al–4V diamond lattice structures," Materials Science and Engineering: A, vol. 818, p. 141362, 2021.
[30] X.-Y. Zhang, G. Fang, S. Leeflang, A. A. Zadpoor, and J. Zhou, "Topological design, permeability and mechanical behavior of additively manufactured functionally graded porous metallic biomaterials," Acta biomaterialia, vol. 84, pp. 437-452, 2019.
[31] N. R. Barton and J. V. Bernier, "A method for intragranular orientation and lattice strain distribution determination," Journal of Applied Crystallography, vol. 45, no. 6, pp. 1145-1155, 2012.
[32] L. Zhang et al., "Bending behavior of lightweight C/SiC pyramidal lattice core sandwich panels," International Journal of Mechanical Sciences, vol. 171, p. 105409, 2020.
[33] W. Radlof, C. Benz, and M. Sander, "Numerical and experimental investigations of additively manufactured lattice structures under quasi-static compression loading," Material Design & Processing Communications, vol. 3, no. 3, p. e164, 2021.
[34] T. DebRoy et al., "Additive manufacturing of metallic components–process, structure and properties," Progress in Materials Science, vol. 92, pp. 112-224, 2018.