Simulation of Compression Properties of Pyramidal Sandwich Panels of TC4 Titanium Alloy

H Wang[1], K X Zhao[1], B Zhao[2], X R Chu[1] and J Gao[1, *]

[1]School of Mechanical, Electrical&Information Engineering, Shandong University, Weihai, Weihai 264209, Shandong, China;
[2]Beijing Aeronautical Manufacturing Technology Research Institute, Beijing 100024, China

Corresponding author and e-mail: J Gao, shdgj@sdu.edu.cn

Abstract. As a functional structural material, the mechanical properties determine the application of three-dimensional lattice structure. The panel thickness, core plate thickness, ribs width, and unit size affect the mechanical properties of the pyramid lattice structure. In this work, to give guidance for the design of pyramid lattice structure, the influences of the above factors were studied through numerical simulation.

1. Introduction

As a new type of sandwich material, the key consideration of three-dimensional lattice structure in its application is the mechanical properties. The static characteristics of three-dimensional lattice structures mainly include flat compression, shear and bending. According to the experimental results, the failure mechanism mainly includes panel wrinkling, core buckling and joint shedding and so on.

The mechanical properties of 6061 aluminum alloy tetrahedron lattice structure are tested by Kooistra [1]. It is proved that the lattice structure of aluminum alloy tetrahedron is superior to that of aluminum foam. In order to improve the stability of nodes, Queheillalt [2] proposed a pyramid structure with node plane. Xue [3] and Yungwirth [4] have studied the ability of impact resistance of three-dimensional lattice structure. It is pointed out that the energy absorption characteristics of lattice structures are better than that of honeycomb structures when the impact energy is high. Bele [5] and Bouwhuis [6] used finite element simulation to optimize the molding process for aluminium alloy pyramid core, and optimized the forming process. Numerical simulation is carried out to study the free vibration problems of AISI 304 stainless steel sandwich beams with pyramidal truss core by Lou [7] and the results are compared with theoretical solutions, it is found that theoretical solutions agree well with numerical results. The vibration characteristics of the composite pyramidal truss core sandwich plate with multiple piezoelectric actuator/sensor pairs were examined in the study by Li et al.[8] Founded that the vibration level of the composite pyramidal truss core sandwich panel can be effectively suppressed through the proposed piezoelectric actuator/sensor pairs using the velocity feedback control and LQR control methods.

Wang, H., Zhao, K., Zhao, B., Chu, X. and Gao, J.
Simulation of Compression Properties of Pyramidal Sandwich Panels of TC4 Titanium Alloy.
In *Proceedings of the International Workshop on Materials, Chemistry and Engineering (IWMCE 2018)*, pages 107-114
ISBN: 978-989-758-346-9

In this work, in order to give guidance for the design of the pyramid lattice structure, the influences of panel thickness, core plate thickness, ribs width, and unit size on the compression properties were studied numerical simulation.

2. Numerical simulation of compression properties

Pyramid lattice is a periodically distributed truss structure. The single-core modelling is used for numerical simulation because the force condition of each core unit is the same when a uniform pressure load is applied.

2.1. Introduction of numerical model

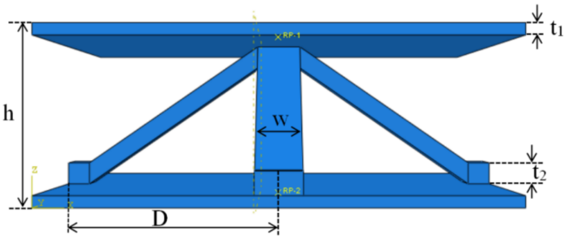

Figure 1. Pyramid pressure model assembly drawing.

The numerical model of the pyramidal structure for flat press is shown in Figure 1. The core height (including upper and lower panels) is set to 15mm. The tie constraint is used between the core and the upper and lower panels. The lower panel is subjected to a complete fixed constraint. The upper panel is controlled by displacement, other degrees of freedom are restricted and the down press forming process is completed through the displacement of Z direction. The tangential friction coefficient was set to 0.36. The density of TC4 sheet is 4.4g/cm^3, the Poisson's ratio is 0.34, the elastic modulus and plastic data are obtained by tensile test at room temperature. The elastic modulus of the material is 109715 MPa.

2.2. Pyramid structure relative density calculation

The relative density of the lattice structure refers to the ratio of the volume of the core material to the volume of space it occupies. For the nodal depressing process, the formed core does not have a regular geometry due to the non-uniformity of the material flow. Therefore, the calculation of relative density will be based on the geometric parameters of pre-formed panels before forming, as shown in Figure 2.

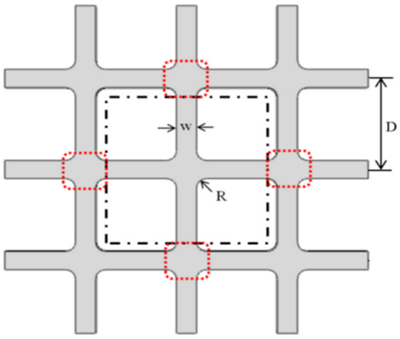

Figure 2. Pre-formed panels geometry figure.

The area in the black wireframe shown in Figure 2 is unique to a pyramidal unit, and the nodes in the red wireframe are shared by four units. So the volume of core material is:

$$V_1=\{2[(w+2R)^2-\pi R^2]+4w(\mathrm{D}-w-2R)\}t_2 \tag{1}$$

Where, w is rids width and R is the radius of the circular corner, D is the unit size and t_2 is the thickness of the sheet metal.

Simplified the formula, it can be obtained:

$$V_1=(8-2\pi)R^2t_2-2w^2t_2+4wDt_2 \tag{2}$$

The volume of the formed core is:

$$V_2=4\mathrm{D}^2h \tag{3}$$

Where, D is the unit size and h is the core height.

Therefore, the formula of relative density of pyramid structure is as follows:

$$\bar{\rho}=\frac{(8-2\pi)R^2t_2-2w^2t_2+4wlt_2}{4D^2h} \tag{4}$$

2.3. Influence of structural parameters

2.3.1. Influence of Panel thickness. To study the panel thickness t_1 influence, core plate thickness t_2, the ribs width w and the unit size D are set to 2mm, 4mm and 20mm, respectively. The simulation results with different panel thickness of 0.5 mm, 1 mm, 1.5 mm and 2 mm are shown in Figure 3.

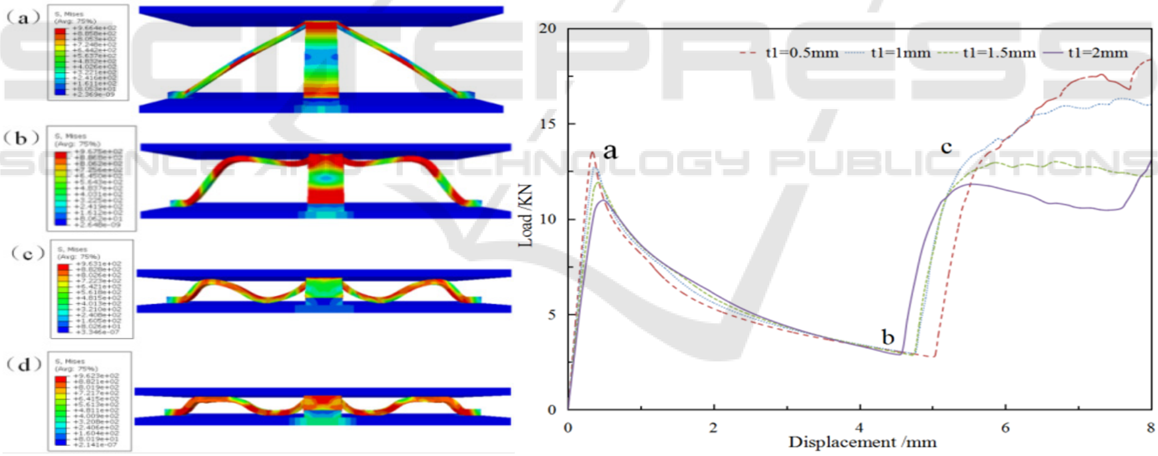

Figure 3. Failure process of flat pressure and its load-displacement curve.

As shown in Figure 3, the compression process of the pyramid lattice structure can be divided into four stages: (a) resistance to deformation, (b) buckling instability, (c) contact strengthening and (d) densification. Corresponding to this, the flat pressure load also presents the four obvious stage characteristics: firstly, before point a, the truss is stable and the load increases linearly (stage 0 to a); secondly, the first plastic hinge appears at point a, truss rod buckling instability appears and the load begins to decrease (stage a to b); thirdly, when the panel presses down to point b, the plastic hinges contacts with the upper panel, the flat pressure load rises again, with the press continues, the plastic hinges contacts with the lower panel, and the press load continues arising (stage b to c); finally, after point c, the truss is completely destroyed, a large number of trusses contact with the panel occurs which leads to the densification stage and the flat compression load increases further.

Usually the lattice structural failure occurs when the truss undergoes plastic yield instability and the corresponding strength is compressive strength. The equivalent flat compressive strength formula can be defined as:

$$\sigma = \frac{F}{4D^2} \tag{5}$$

Where, F is the peak load of plastic yield instability, D is the unit size.

The formula for calculating the equivalent modulus of flat compression is as follows:

$$\bar{E} = \frac{\sigma}{(\delta/h)} \tag{6}$$

Where, δ is the pressing height of linear stage and h is the original lattice height. According to numerical simulation results and the formulas (5) and (6).

The equivalent flat compressive strength and modulus under different panel thickness are obtained as shown in Table 1. As the thickness of the panel increases, the equivalent flat compressive strength and modulus of the pyramidal element decrease. This is because under the condition of constant height, the panel thickness increases and the truss rid tilt angle decreases, resulting in a reduction in the ability of the truss rid to resist vertical downward loading. Figure 4 is the comparison of tilt angles of truss rods for panel thicknesses of 1mm and 2mm. The larger tilt angle makes the core unit with a panel thickness of 1 mm more efficient, resulting in a greater equivalent compressive modulus with a lower relative density, indicating that by increasing the tilt angle, the compression performance of the pyramid lattice can be improved.

Table 1. Equivalent flat compressive strength and modulus under different panel thickness.

Panel thickness(mm)	0.5	1	1.5	3
Relative density (%)	2.60	2.80	3.03	3.31
Equivalent flat compressive strength (MPa)	8.44	7.93	7.45	6.86
Equivalent flat compressive modulus (MPa)	379	339.9	268	209.86
Strength-to-density ratio(MPa)	3.25	2.83	2.46	2.07
Modulus-to-density ratio(MPa)	145.77	121.39	88.45	63.40

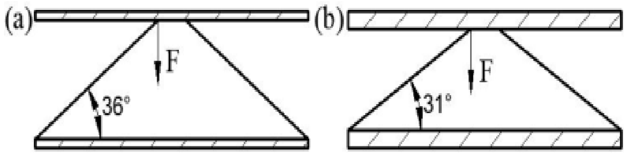

Figure 4. Effect of panel thickness on tilting angle of truss rid (a) t_l=1mm, (b) t_l=2mm.

2.3.2. Influence of Core plate thickness. The thickness of the panel t_l, the width of the ribs w, and the unit size D are set to 1mm, 4mm, 20mm, respectively and the thickness of the core plate is taken as 0.6mm, 1mm. 1.5mm, 2mm to study the influence of the core plate thickness.

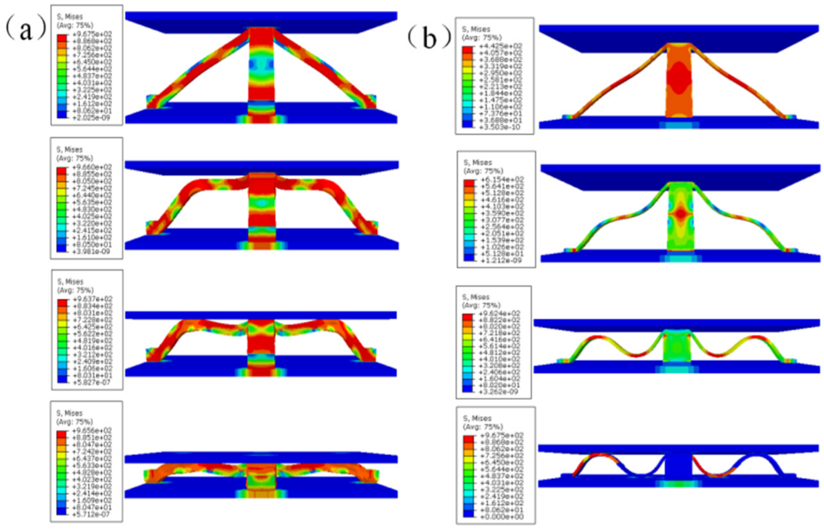

Figure 5. The influence of core plate thickness on the process of flat compression (a) t2=2mm, (b) t2=0.6mm.

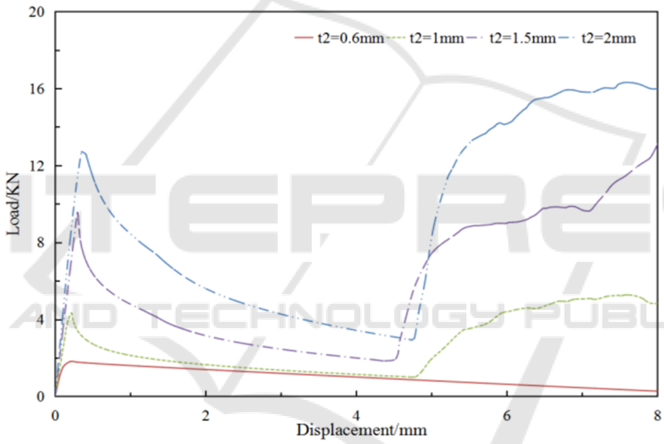

Figure 6. Simulation of load-displacement curve under different core plate thickness.

Figure 5 shows the comparison of stresses states during the pressing process when the core plate thickness is 2mm and 0.6mm. It can be seen that changing the core plate thickness will affect the failure process of the pyramidal core. When the core plate thickness is 2mm, only one plastic hinge appears in the compression process, and the core has strong compressive resistance. When the core plate thickness is 1mm, the core starts to have two plastic hinges. As shown in Figure 5 (b), when the press displacement is 0.2mm, the truss quickly loses stability, two plastic hinges appear at the same time and the ability of pressure resistance continues to decrease. In addition, double plastic hinge also delayed the contact between the panel and the core. The load-displacement curve of different core plate thickness is shown in Figure 6. As can be seen from Figure 6, the core plate thickness has a significant effect on the ability of pressure resistance. By increasing the core plate thickness the deformation resistance performance of the pyramid increases and the modulus of the flat compression increases significantly. According to the formulas (5) and (6), the equivalent flat compressive strength and modulus with different core plate thickness are shown in Table 2. With the increase of core plate thickness, the equivalent flat compressive strength and the equivalent flat compressive modulus increase accordingly. In addition when the core plate thickness increases, the relative density increases correspondingly.

Table 2. Equivalent flat compressive strength and modulus under different core plate thickness.

Core plate thickness (mm)	0.6	1	1.5	2
Relative density (%)	0.84	1.40	2.10	2.80
Equivalent flat compressive strength (MPa)	1.13	2.71	5.97	7.93
Equivalent flat compressive modulus (MPa)	138.32	185.69	299.58	339.90
Strength-to-density ratio(MPa)	1.35	1.94	2.84	2.83
Modulus-to-density ratio(MPa)	164.67	132.64	142.66	121.39

2.3.3. Influence of the rid width. The panel thickness, core plate thickness and the unit size were set to 1mm, 2mm, and 20mm. The width of ribs was set to 2 mm, 4 mm, 6mm, and 8mm respectively. The simulation results show that the failure process is still a classic four-stage form similar to Figure 3: linear strengthening, buckling instability, contact strengthening and densification. It is worth noting that the compression process with different ribs widths all has only one plastic hinge, this means that the ribs width is not a key factor affecting the number of plastic hinges. The load-displacement curve is shown in Figure 7. The equivalent flat compressive strength and modulus are shown in Table 3. It can be seen that increasing the ribs width can significantly improve the pressure resistance performance of the pyramid structure, and the relative density is also increasing to some extent.

Table 3. Comparison of equivalent flat compressive strength and modulus under different ribs width.

Ribs width (mm)	2	4	6	8
Relative density (%)	1.49	2.80	3.96	4.96
Equivalent flat compressive strength (MPa)	2.51	7.93	13.5	18.91
Equivalent flat compressive modulus (MPa)	107.48	339.9	643.18	1044.4
Strength-to-density ratio(MPa)	1.68	2.83	3.41	3.81
Modulus-to-density ratio(MPa)	72.13	121.39	162.42	210.56

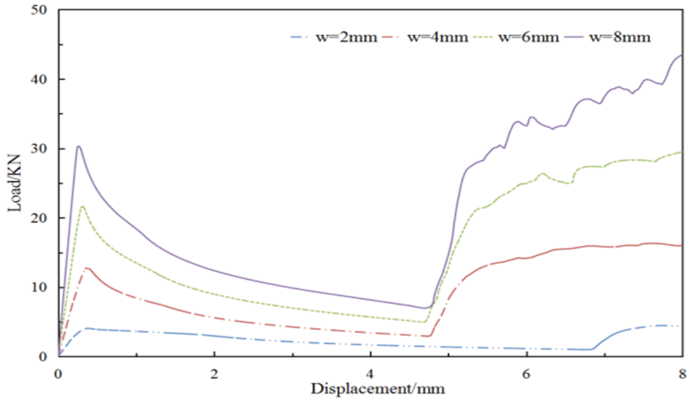

Figure 7. Simulation of load-displacement curves with different ribs width.

2.3.4. Influence of unit size. The thickness of panel, the core plate thickness and the ribs width were set to 1 mm, 2 mm and 4 mm respectively to study the effect of unit size. The unit sizes were set as 15mm, 20mm, 25mm, and 30mm, respectively. The failure process went through linear strengthening, buckling instability, secondary strengthening, and densification.

Table 4. Comparison of equivalent flat compressive strength and modulus under different unit sizes.

Unit size(mm)	15	20	25	30
Relative density (%)	3.61	2.80	2.29	1.93
Equivalent flat compressive strength (MPa)	16.51	7.93	4.07	2.24
Equivalent flat compressive modulus (MPa)	1042.95	339.9	207.34	51.01
Strength-to-density ratio(MPa)	4.57	2.83	1.78	1.16
Modulus-to-density ratio(MPa)	288.91	121.39	90.54	26.43

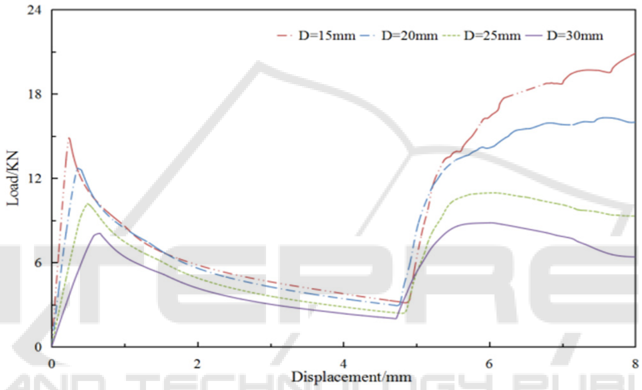

Figure 8. Simulation of load-displacement curve under different unit sizes.

The load-displacement curves are compared as shown in Figure 8 and the equivalent flat compressive strength and modulus are shown in Table 4. It can be seen that the smaller the unit is, the greater the relative density is and the better the compressive performance is. It can be seen that with the decrease of unit size, the compressive strength and the equivalent flat compressive modulus increases, meanwhile, the relative density also increases, in addition, the equivalent flat compressive modulus increase faster than the strength, which means that the unit size have much more influence on the modulus

3. Conclusions

In this paper, finite element simulations of compression Properties of Pyramidal Sandwich Panels of TC4 Titanium Alloy were carried out. The influences of panel thickness, core plate thickness, ribs width, and unit size on the pyramidal sandwich compression properties were obtained. The conclusions are as follows:

The panel is a major part of the weight of the structure but it has little influence on the pressure resistance. The core is the main supporting part of the structure, increasing core plate thickness or ribs width can increase the structure ability of pressure resistance. The smaller the unit is, the greater the relative density and the higher stability of the structure are.

References

[1] Kooistra G W, Deshpande V S and Wadley H N G 2004 Compressive behavior of age hardenable tetrahedral lattice truss structures made from aluminium *J. Acta Materialia* **52**(14) 4229-4237

[2] Queheillalt D T and Wadley H N G 2009 Titanium alloy lattice truss structures *J. Materials & Design* **30**(6) 1966-1975

[3] Xue Z Y and Hutchinson J W 2004 A comparative study of impulse-resistant metal sandwich plates J. *International Journal of Impact Engineering* **30**(10) 1283-1305

[4] Yungwirth C J, Radford D D, Aronson M and et al 2008 Experiment assessment of the ballistic response of composite pyramidal lattice truss structures *J. Composites Part B Engineering* **39**(3) 556-569

[5] Bele E, Bouwhuis B A and Hibbard G D 2012 *Finite Element Analyses of Failure Mechanisms and Structure-Property Relationships in Microtruss Materials J.*

[6] Bouwhuis B A 2010 Microstructural strengthening mechanisms in micro-truss periodic cellular metals *J. Doctoral*

[7] Lou J, Ma L and Wu L Z 2012 Free vibration analysis of simply supported sandwich beams with lattice truss core *Materials Science and Engineering: B*. Nov20 **177**(19) 1712-6

[8] Li M, Li F M and Jing X J 2017 Active vibration control of composite pyramidal lattice truss core sandwich plates *Journal of Aerospace Engineering Dec 9* **31**(2) 04017097