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AN INVESTIGATION ON INTERNAL LIGHTWEIGHT LOAD BEARING STRUCTURES

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This paper investigates the differences in structural response of lightweight internal structures using finite element (FE) simulation to provide quantitative comparison of the advantages of each type of structure. Various configurations, corresponding to different amounts of weight savings, were studied under distributed pressure loading and bending moment loading conditions. It was found that for configurations with less weight savings, the kagome possesses better performance than the honeycomb structure. However, as the amount of weight savings increase, the trend was observed to be reversed, with the honeycomb structure providing much better performance than the kagome structure. In general, it was shown that the honeycomb structure possesses better performance than the kagome structure under cantilever loading conditions.

Keywords: Lightweight Internal Structures; Kagome; Honeycomb; FE Analysis

1. Introduction

In the design of structural components, we often have to strike a balance between form, functionality and costs. Higher utilization of materials yield better structural properties, but increase weight and thus production and operational costs. On the other hand, weight reduction would lead to higher cost efficiency, which however, compromises structural integrity.

Depending on the geometry, the core material can be classified as foam or lattice structures. Foam structures are of stochastic nature and hence possess a certain degree of randomness. On the other hand, lattice structures possess very regular configurations, displaying tessellations of particular unit cells. Generally, lattice structures have properties that are superior to other structures which make them viable for use in an array of applications, such as flexible actuation [1], heat exchangers [2], heat transfer enhancement [3] and energy absorbers [3-5].

While there have been may works studying and characterizing different types of internal structures, such as the honeycomb structure [5-8], the kagome structure [9, 10] and rib and spar structure [11, 12]. There exists very few literature comparing the relative performance of the different types of internal structures, with the exception of the recent work by Li and Wang [5].

In this paper, we will study the different kinds of core structures, focusing on regular lattice structures. This allows a deterministic approach as compared to irregular structures which require a stochastic approach. Both 2D and 3D lattice structures will be investigated to determine which lattice structure is able to fulfil the requirements mentioned by performing structural analysis using finite element modelling on shortlisted lattice structures chosen based on previous studies by researchers and using the results obtained for justification.

2. Numerical model

2.1. *Lattice structures to be investigated*

In the current work, we focus on the regular lattice structures, which can be analyzed in a deterministic approach, as compared to irregular structures which require a stochastic approach in the analysis. Both 2D and 3D structures will be investigated using commercial finite element software ANSYS Workbench.

Studies have shown that lattice-based open-cell structures have higher specific strength as compared to closed-cell structures and are in general more effective for compression as well as bending [13] which is crucial in the design of the internal structure of a wing.

Amongst the existing open-cell structures, several studies have indicated that the kagome structure has been superior in its properties. Results from a study on lattice structures which have high values in elastic performance - 3D Kagome, Hexagonal Diamond and 3D Pyramidal Structure - showed that the 3D Kagome structure does have the highest load capacity among the three truss structures, being able to withstand the highest compression stress of 0.65 MPa at a strain of 3.8% [13]. Another study on the compression for tetrahedral and kagome cores also showed that the kagome structure, in particular, has a greater load capacity and has shown to be a superior structure for ultra-light panels [14].

Amongst the closed-cell lattices, the honeycomb structure is well known for its strength and advantages in being light-weight. The honeycomb structure has high strength-to-weight ratio and has good compressive strength, resulting in applications in a wide array of fields spanning engineering to medicine [15]. Some applications of honeycomb include enhancing heat transfer [3], Currently, in wing designs, laminated honeycomb panels are being used as the stress skins due to the mentioned advantages in its strength and weight. The honeycomb structure is also being utilized in other parts of the wing as well such as the leading edge.

As such, the honeycomb structure is chosen to be structurally analyzed alongside the Kagome lattice structure for this work. Figure 1 shows the unit cells of both internal structures.

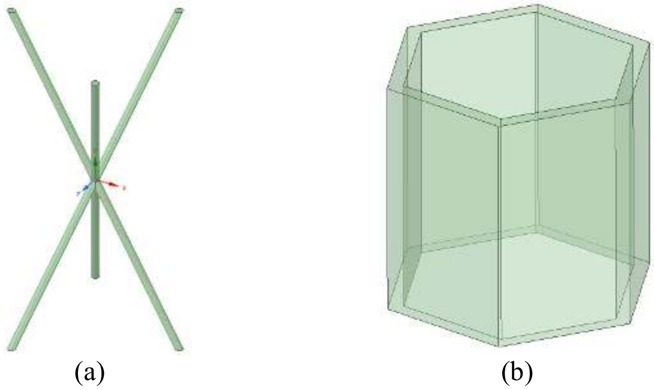

(a) (b)

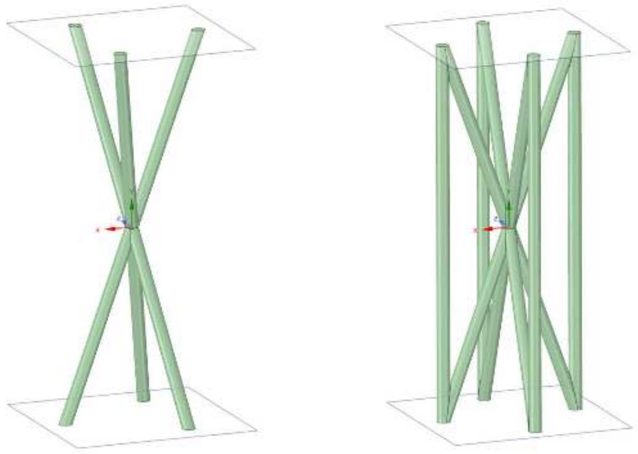
Figure 1: Unit cell of (a) kagome structure and (b) honeycomb structure.

The kagome and honeycomb structures, representing 3D and 2D lattice structures respectively, will be varied based on size parameters, keeping volume constant for a direct comparison between the two types of structures. Both the lattice structures will be sandwiched between skins with thickness of 1 mm. The overall size of the models will be 50 mm by 43.30 mm by 8 mm. A length of 50 mm was chosen based on a scaled dimension of the length of the actual wing of the UAV. The width of 43.30 mm was dimensioned based on the number of unit cells in each model. A nominal height of 8 mm was chosen. More details on the dimensions of the unit cells to be compared are illustrated in the following sub-sections.

2.1.1. *Kagome Lattice Structure with Vertical Trusses*

Experimental results from a study on the compression of kagome structures have shown that the addition of vertical strands offer much more attractive mechanical properties [16]. Therefore, vertical strands will be included in the unit cell of the kagome structure.

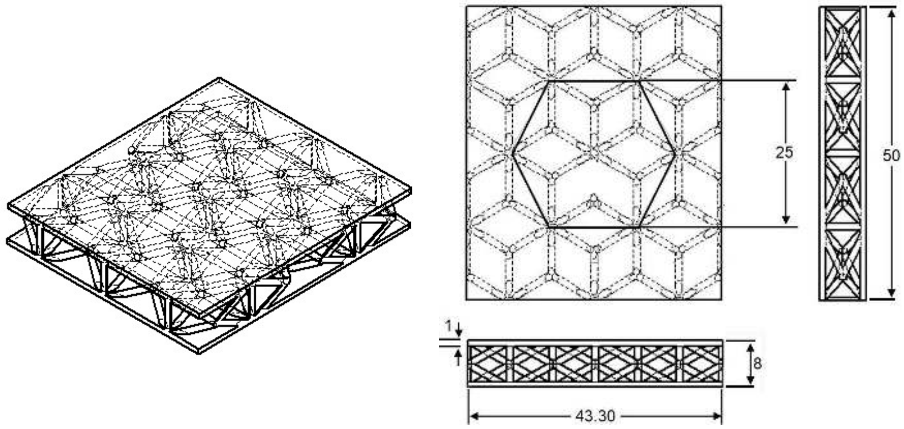
This difference of a lattice structure with and without the vertical strands is represented visually in Figure 2.



(a) (b)

Figure 2: Comparison of modified Kagome structures with (a) no vertical strands, and (b) added vertical strands.

Figure 3 shows the detailed dimensions of the kagome structure that will be used. For this lattice structure, the diameter, D, of the individual rods will be varied. Table 1 then summarizes the variation of the diameter as well as the corresponding volumes of the structures to be tested.



(a) (b)

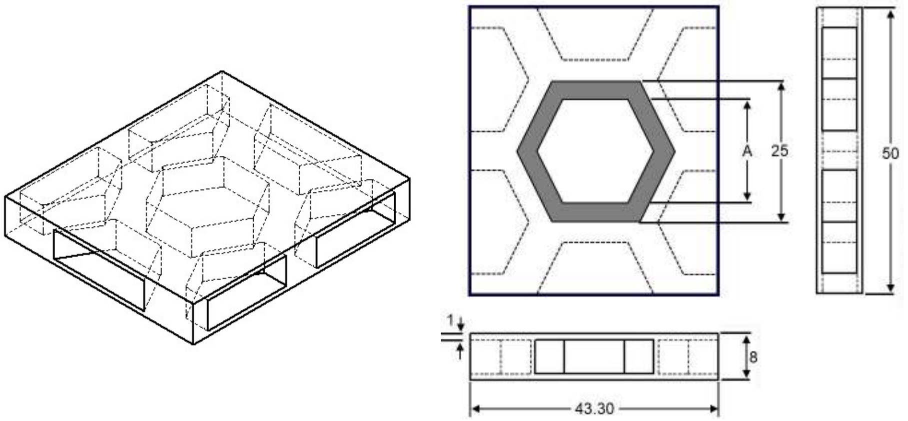
Figure 3 (a) Isometric projection and (b) dimensions of kagome sandwich panel.

Table 1: Parameters of kagome lattice structures.

Configuration	Diameter, D (mm)	Volume (mm^3)
1	3.10	10551.08
2	2.60	9029.38
3	1.95	7180.16
4	1.15	5380.16

2.1.2. *2.4.2 Honeycomb Structure*

The following CAD drawings show in detail the honeycomb structure that will be used. For this lattice structure, the distance between two parallel sides of the inner hexagon, labelled as dimension ‘A’ will be varied. Table 2 summarizes the variation of the parameter ‘A’ as well as the corresponding volume of the structure to be tested.



(a) (b)

Figure 4: (a) Isometric projection and (b) dimensions of honeycomb sandwich panel, with greyed area the unit cell of the honeycomb structure.

Table 2: Variation of dimension 'A' and volume of honeycomb lattice

Configuration	Parameter A (mm)	Volume (mm^3)
1	18.0	10586.29
2	20.0	9006.66
3	22.0	7260.76
4	24.0	5348.57

2.2. ***Material properties***

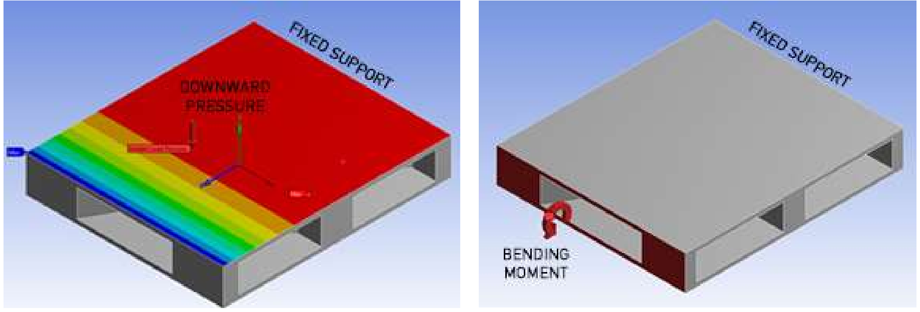
Linear isotropic elastic material properties based on Acrylonitrile Styrene Acrylate (ASA) are assumed in the simulation of the lattice structures, with Young’s modulus of 1.6 GPa and Poisson’s ratio of 0.331.

2.3. *Loads and boundary conditions*

The sandwich structures are tested on cantilever boundary conditions and subjected to two types of load cases. The first being a distributed pressure load, much akin to the aerodynamic load distribution found on aircraft wings, which are generally distributed elliptically spanwise.

This normal stress then causes a bending moment acting on the wing. This results in bending of the wing which leads to compressive and tensile stresses between the top and bottom surfaces.

The models are given cantilever boundary conditions, simplifying the conditions experienced by an aircraft wing. In addition to a spatially distributed pressure load, the effects of a bending moment load are also studied. Figure 5 provides a visual representation of the boundary condition and loads.



(a) (b)

Figure 5 : Loads and boundary condition for (a) distributed pressure load, (b) bending moment load.

Figure 6 shows the pressure distribution applied on the structure, equivalent to a lift force of 20N while the resultant moment applied is 0.465 Nm.

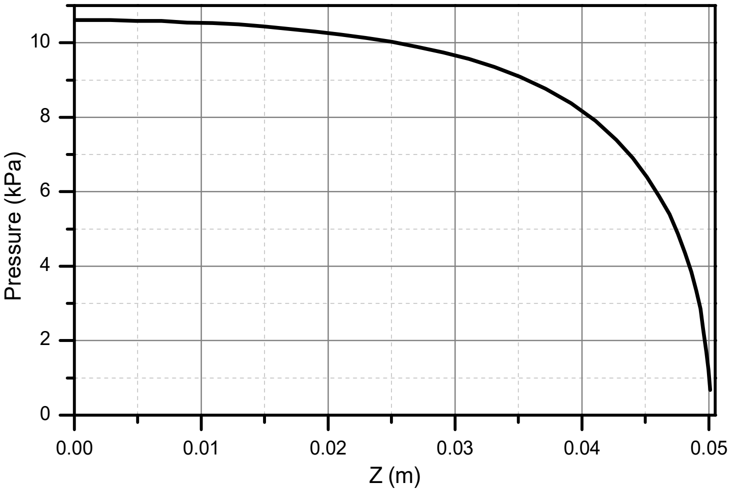
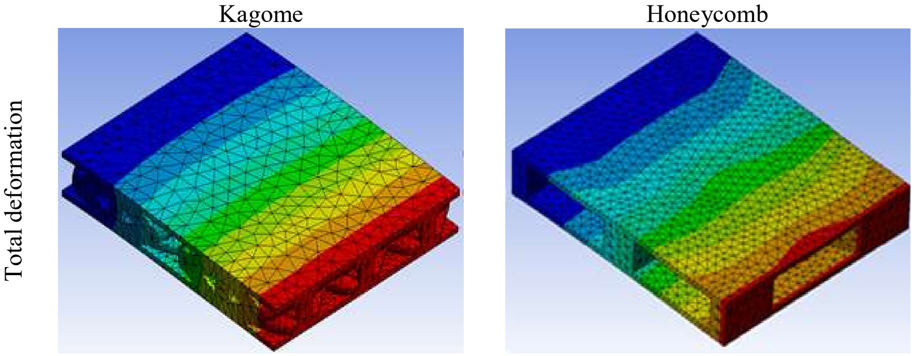


Figure 6: Pressure distribution along the length of the models

3. Results and discussion

3.1. *Distributed pressure load*

Figure 7 and 8 show the displacement, equivalent stress and equivalent strain response of both sandwich panels with Configuration 1 under distributed pressure loading and bending moment loading respectively. These responses are representative of the general reponses for all four volume configurations investigated.



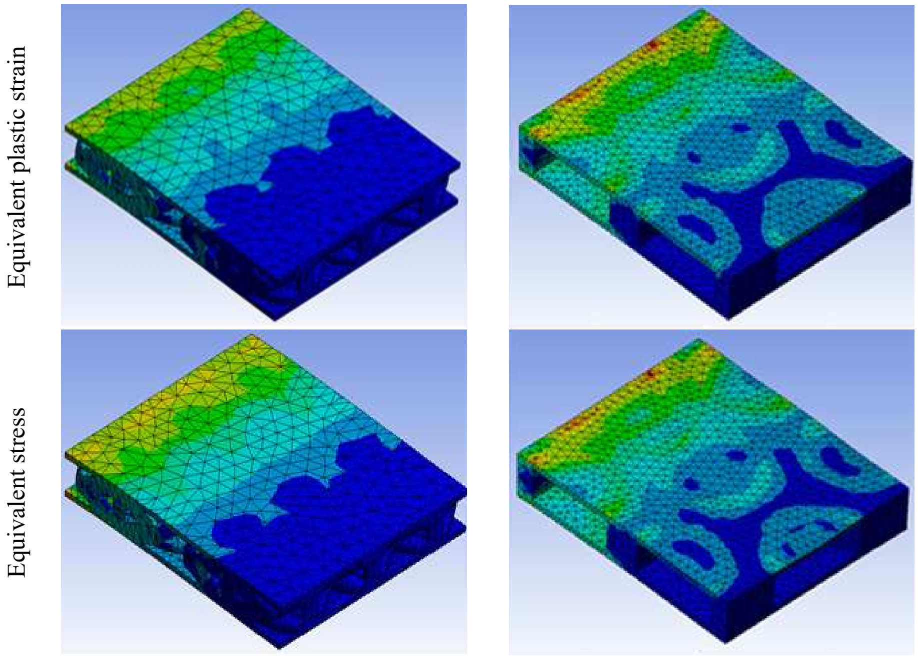
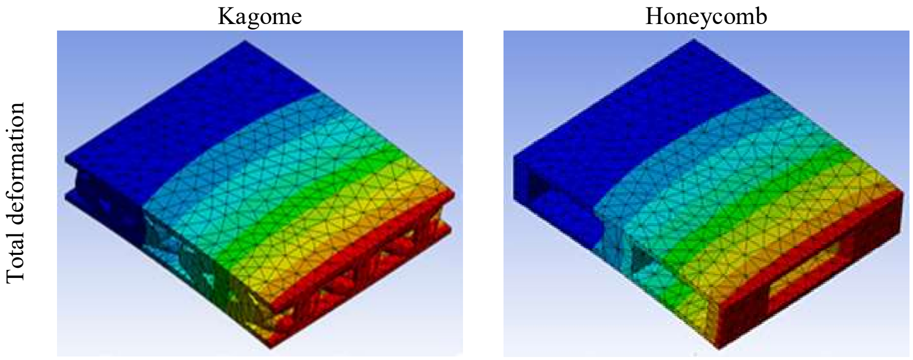


Figure 7: Typical response of kagome sandwich panels under distributed load



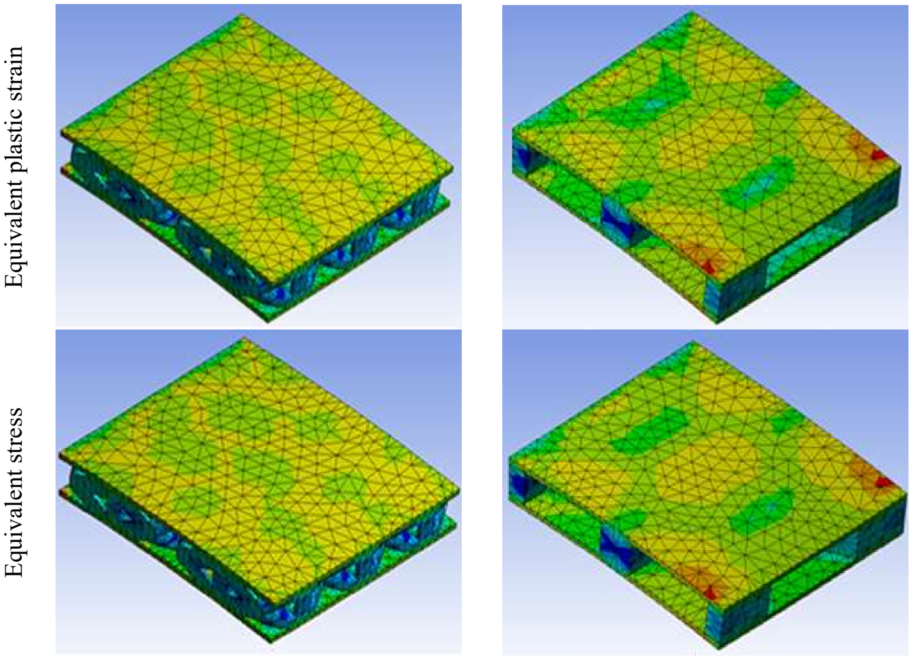


Figure 8 Typical response of honeycomb sandwich panels under bending moment

It is observed that the maximum deformation for both cases occur at the free-end of the model while the equivalent stress and strain however occurs at the supported end. These general results are expected responses of cantilevers under similar loading.

Table 3 and 4 provide comprehensive summaries on the results obtained from the structural analysis with pressure loading applied and bending moment applied, respectively.

Table 3 Summary of data for structures under pressure loading

Configuration	Max. Total Deformation ($\times10^{-4}$ m)		Max. Equivalent Elastic Strain ($\times10^{-3}$)		Max. Equivalent Stress (MPa)	
	Kagome	Honey-comb	Kagome	Honey-comb	Kagome	Honey-comb
1	1.73	1.88	1.49	1.46	2.09	2.32
2	1.91	2.16	1.88	1.55	2.58	2.47
3	2.27	2.54	2.12	1.90	2.87	3.03
4	3.50	3.28	5.11	2.65	7.88	4.23

Table 4 Summary of data for structures under bending moment loading

Configuration	Max. Total Deformation ($\times 10^{-4}$ m)		Max. Equivalent Elastic Strain ($\times 10^{-3}$)		Max. Equivalent Stress (MPa)	
	Kagome	Honeycomb	Kagome	Honeycomb	Kagome	Honeycomb
1	2.82	2.07	1.31	1.31	2.09	2.10
2	2.99	2.84	1.36	1.39	2.18	2.22
3	3.18	3.05	2.34	1.55	3.40	2.47
4	3.33	3.20	6.88	3.17	9.17	4.23

Generally, the honeycomb structure is shown to provide better performance as compared to the kagome structure. This is despite some interesting observations observed in the deformation and stress results. Under distributed pressure loading, it can be seen that the maximum total deformation in the honeycomb structure exceeds that of the kagome structure up to the third configuration while for the structure with the least volume, the honeycomb structure outperforms the kagome structure. This is likely due to the hollow section in the honeycomb lattice being much larger than that of the kagome lattice, which can be inferred from Figure 7, where the maximum deformation occurs at the hollow region. This concentration of excess deformation is less evident in the kagome structure due to the presence of more trusses per unit volume of the unit cell and is thus able to better resist deformation of the skin.

The maximum equivalent stress experienced by the structures under both types of loadings shows similar trend, where the performance of the honeycomb structure only outperforms the kagome structure when the volume of the models decreases. In this comparison, however, the stress per volume experienced by the kagome is about double that of the honeycomb in the fourth volume configuration which further proves the honeycomb’s performance under loadings is much better than that of the kagome, especially when the volumes of the models are small.

Comparing maximum strain results, the honeycomb structure shows consistently better performance than the kagome structure in all test cases except for the case of Configuration 2 under bending moment load. Furthermore, the gap in performance of the structure widens as total volume decreases, giving strong evidence of the superiority of the honeycomb structure over the kagome structure, especially as structural weight is continually being decreased.

4. Conclusion

This paper has investigated the performance of two types of lightweight internal structures, namely the honeycomb structure and the kagome structure, to provide a quantitative comparison between the two different types of structures. The investigation was performed on four weight configurations of honeycomb and kagome structures constrained by cantilever boundary conditions and subjected to pressure and bending moment loads. Analysis was conducted using finite element simulations through commercial finite element software ANSYS.

It was found that in general, for the same weight, the honeycomb structure outperforms the kagome structure. It is able to better resist the bending moments, especially when less material is being used, as seen from the smaller maximum deformation and strain values. In addition, for the same loads, the maximum stress in the honeycomb structure is generally lower than in the kagome structure. This is especially so when smaller volumes are involved. This implies that the honeycomb wing structure is able to withstand larger loads prior to the point of material failure.

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References

W. Tao, M.C. Leu, Design of lattice structure for additive manufacturing, in: 2016 International Symposium on Flexible Automation (ISFA), 2016, pp. 325-332.

K.J. Maloney, K.D. Fink, T.A. Schaedler, J.A. Kolodziejska, A.J. Jacobsen, C.S. Roper, Multifunctional heat exchangers derived from three-dimensional micro-lattice structures, International Journal of Heat and Mass Transfer, 55 (2012) 2486-2493.

W. Wang, X. Yang, B. Han, Q. Zhang, X. Wang, T. Lu, Analytical design of effective thermal conductivity for fluid-saturated prismatic cellular metal honeycombs, Theoretical and Applied Mechanics Letters, 6 (2016) 69-75.

B. Florijn, C. Coulais, M. van Hecke, Programmable Mechanical Metamaterials, Physical Review Letters, 113 (2014) 175503.

T. Li, L. Wang, Bending behavior of sandwich composite structures with tunable 3D-printed core materials, Composite Structures, 175 (2017) 46-57.

A. Abbadi, Y. Koutsawa, A. Carmasol, S. Belouettar, Z. Azari, Experimental and numerical characterization of honeycomb sandwich composite panels, Simulation Modelling Practice and Theory, 17 (2009) 1533-1547.

M. Giglio, A. Gilioli, A. Manes, Numerical investigation of a three point bending test on sandwich panels with aluminum skins and Nomex™ honeycomb core, Computational Materials Science, 56 (2012) 69-78.

M. Giglio, A. Manes, A. Gilioli, Investigations on sandwich core properties through an experimental–numerical approach, Composites Part B: Engineering, 43 (2012) 361-374.

J.-S. Hwang, T.-G. Choi, D. Lee, M.-Y. Lyu, D.G. Lee, D.-Y. Yang, Dynamic and static characteristics of polypropylene pyramidal kagome structures, Composite Structures, 131 (2015) 17-24.

J.-S. Hwang, T.-G. Choi, D. Lee, M.-Y. Lyu, D.G. Lee, D.-Y. Yang, Development of a bendable pyramidal kagome structure and its structural characteristics, Composite Structures, 142 (2016) 87-95.

B.K. Stanford, P.D. Dunning, Optimal Topology of Aircraft Rib and Spar Structures Under Aeroelastic Loads, Journal of Aircraft, 52 (2014) 1298-1311.

P. Garre, G.V. Arjun, Modeling and Analysis of a RIBS and Spars of An Airplane Wing for Bending and Shear Loads, International Journal for Research in Applied Science & Engineering Technology, 5 (2017) 295-315.

J.-S. Hwang, T.-G. Choi, M.-Y. Lyu, D.-Y. Yang, Investigation for the bending modes of a semi-circular pyramidal kagome sandwich structure and the bending load calculation, Composite Structures, 134 (2015) 10-17.

S. Hyun, A.M. Karlsson, S. Torquato, A.G. Evans, Simulated properties of Kagomé and tetragonal truss core panels, International Journal of Solids and Structures, 40 (2003) 6989-6998.

Q. Zhang, X. Yang, P. Li, G. Huang, S. Feng, C. Shen, B. Han, X. Zhang, F. Jin, F. Xu, T.J. Lu, Bioinspired engineering of honeycomb structure – Using nature to inspire human innovation, Progress in Materials Science, 74 (2015) 332-400.

R. Umer, Z. Barsoum, H.Z. Jishi, K. Ushijima, W.J. Cantwell, Analysis of the compression behaviour of different composite lattice designs, Journal of Composite Materials, 52 (2017) 715-729.