FLAX FIBER REINFORCED COMPOSITE LATTICE CORES: DESIGN, FABRICATION AND MECHANICAL TESTS

Xiang Gao[1,2], Jianxing Hu[1,2], Sha Yin[1,2,3] and Jun Xu[1,2,3,4*]

[1] Department of Automotive Engineering, School of Transportation Science and Engineering, Beihang University, Beijing, China, 100191

[2] Advanced Vehicle Research Center, Beihang University, Beijing, China, 100191

[3] State Key Laboratory for Strength and Vibration of Mechanical Structures, School of Aerospace Engineering, Xi'an Jiaotong University, Xi'an, China, 710049

[4] State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing, China, 100084

Keywords: Natural fibers, Mechanical properties

ABSTRACT

Lightweight, low-cost and recyclability are priorities in various types of material selections. To this end, in the present study, flax fiber reinforced lattice cores with redesigned lattice geometry were developed, and then manufactured by vacuum assisted resin infusion (VARI) and slot assembly method. Then, lattice structures with composites and foam sandwich trusses were fabricated and compressed, respectively. The specific nominal stiffness and strength values of the latter ones were about 1.5 and 2 times of those of their monolithic counterparts. A property-cost chart was specially created and the flax fiber reinforced lattice cores were shown to be promising candidates for automotive lightweight industry considering economy and recyclability.

1 INTRODUCTION

Energy and environment sustainability becomes a top priority in human society such that light-weight, low-cost and recyclability are most intriguing material properties for various large-scale industries, e.g. automotive industry and aerospace industry [1]. To answer the environmentally friendly request, natural fiber reinforced composite materials have gained promising applications due to their attractive properties such as low cost, degradability, high specific strength and stiffness, thermal and acoustic insulation, etc. More importantly, emerging studies have given studies of natural fibers special attention.

On the other hand, cellular materials, such as metal foam, aluminum honeycomb and lattice structures are increasingly popular in mechanical structures. Studies were firstly carried out on metallic lattice structure about the fabrication approaches [2] and the mechanical properties as a structure [3]. Soon, composite lattice structure became available with even higher strength-to-density ratio as well as thermal shielding and corrosion resistance.

However, studies on how to take the advantage of natural fiber as reinforced composite lattice structure are still lacking. Flax fibers, due to their unique properties, low cost, health advantages and environmental impact, is one of the promising candidates among available bio-fibers, and several related works have already been carried out [4]. Thus, in the present study, flax fiber reinforced composite lattice materials will be designed with additionally horizontal beams of variable length for optimized overall mechanical properties, and then fabricated via a low-cost vacuum assisted resin infusion (VARI) and slot assembly process. Monolithic lattice cores with pure composites trusses and hierarchical ones with foam sandwich trusses will be fabricated and through-thickness compressed, respectively.

2 EXPERIMENTAL

2.1 Fabrication

(1)Raw material selection

Flax fiber plain weave fabrics (purchased from Linyi City, Shandong Province, China) were selected as reinforcement phase of composites. An epoxy resin system (LY1564/Aradur22962, Huntsman) was selected for the composites fabrication. The epoxy-hardener ratio is 4:1 by weight, and the viscosity and glass transition temperature of the resin system are 450 MPa.s and 140 ^{o}C, per supplier specifications. The fabrication process should be finished within 120 minutes outside the heating oven, otherwise the resin will cure spontaneously. Also, a closed-cell rigid foam (Rohacell-51 WF) based on PMI (polymethacrylimide) was selected to fabricate foam sandwich panel. The mechanical properties of PMI and PMI foam are presented in Table 1 as followed.

Materials	Density (kg/m^3)	Elastic modulus (MPa)	Compressive strength (MPa)
PMI	1200	5200	90
Foam	52	75	0.8

Table 1. Mechanical properties of PMI material and foam.

(2) Fabrication of laminates and foam sandwich panels

Vacuum assisted resin infusion (VARI) process was used to fabricate flax fiber reinforced laminates and foam sandwich composite panels. The details about the composite layup schemes are presented in Figure 1. Firstly, after painting mold release agent, flax fabrics, demoulding cloth and flow medium were laid up on an aluminum sheet. Specifically, four plies of flax fabrics were used for Type I and two for Types II and III (in Table 2), while one plies of flax fabric was applied as face sheet for foam sandwich panels. Then two spiral pipes were put aside fabrics as illustrated and the whole assembly was vacuum bagged (>28 in. Hg). Bagged samples were debulked for 20 minutes at room temperature to remove trapped air. Secondly, the epoxy resin solution was infused into the vacuum bagged assembly until fully saturating the fabrics, and then the whole assembly was transferred into an oven curing at 80^{o}C for 2 hours and 120^{o}C for 3 hours. Finally, the flax fiber reinforced laminates and foam sandwich panels were obtained after demoulding from the aluminum sheet.

Figure 1. The sketch of Vacuum assisted resin infusion (VARI) process

(3) Fabrication of lattice cores

Pyramidal lattice cores with additionally horizontal trusses of variable length were designed in this study with the aim to optimize the overall mechanical properties with better shear performance. The length of the horizontal trusses is flexible and the optimal length value could be specified by considering both compression and shear performance. The representative volume cells for monolithic and hierarchical lattice structures are shown in Figure 2 together with the corresponding geometrical parameters, respectively.Both monolithic and hierarchical lattice cores were fabricated by interlocking process that had been introduced in the previous publication [5]. Four types of lattice structures were fabricated including those with composite trusses and foam sandwich trusses, and the geometric parameters were summarized in Table 2. Types I, II and III represent monolithic lattice cores with pure composites trusses of different relative densities, and Type IV stands for those with foam sandwich trusses. All the lattice cores were subsequently glued with two composite face sheets forming sandwich structures as shown in Figure 3a-d for the following compression testing.

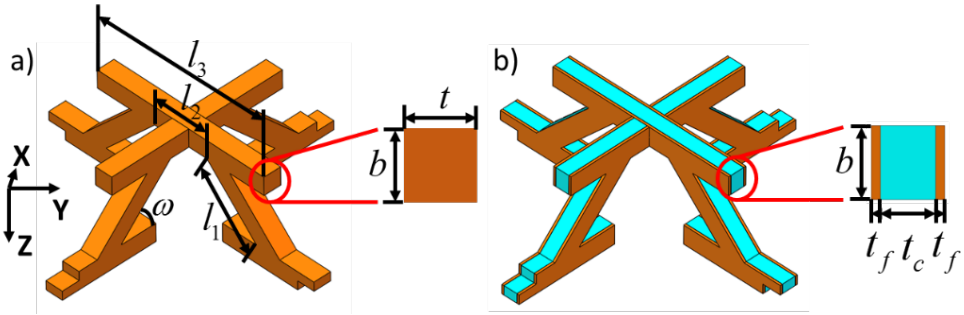

Figure 2. The representative unit cells (RUC) for the redesigned pyramidal lattice structures with a) pure composite trusses; b) foam sandwich trusses with geometrical parameter illustrations.

Type		l_1 (mm)	l_2 (mm)	l_3 (mm)	ω	b (mm)	t (mm)	
Monolithic	I	8.94	6.34	30.34	$\pi/4$	2	2.43	
	II	8.94	6.34	12	$\pi/4$	2	1.23	
	III	12.73	9.51	18	$\pi/4$	3	1.23	
Hierarchical	IV	12.73	9.51	18	$\pi/4$	3	t_f	t_c
							0.5	4

Table 2. Geometric parameters for the four types of lattice structures.

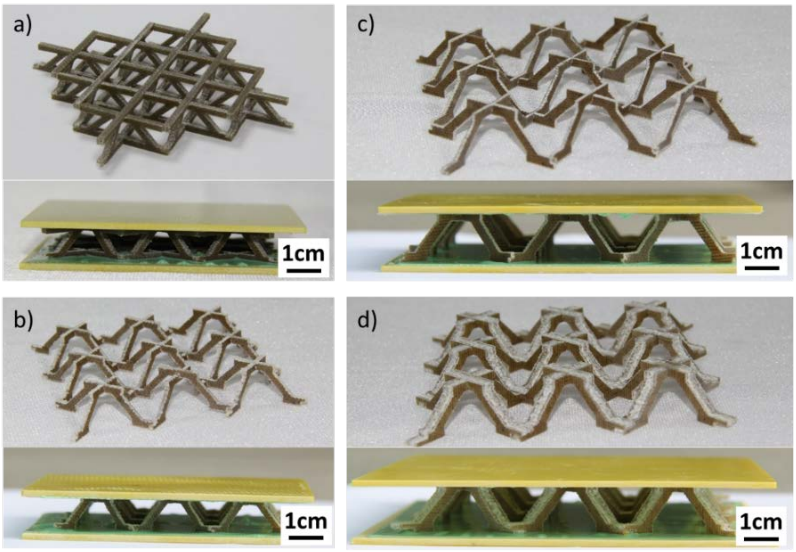

Figure 3 Sandwich structures for compression testing: a), b), c) monolithic lattice structures with pure composite trusses with different geometric parameters; d) hierarchical lattice structure with foam sandwich trusses.

2.2 Testing

Through-thickness compression tests for the pyramidal lattice cores were performed on a hydraulic servo testing machine (MTS 810) at a displacement rate of 0.5mm/min following ASTM C365/C365M [6]. Samples with 3*3 unit cells were prepared and at least two repeated tests for each type of structure were carried out to ensure the repeatability. The compression force was read from the load cell while the compression displacement was measured using a laser extensometer.

3 RESULTS AND DISCUSSION

3.1 Compressive properties of lattice cores

All the four types of lattice structures were tested under through-thickness compression and the stress-strain curves were compared in Figure 4. All the curves have initially elastic linear increasing stages from which the nominal compressive modulus of structure is determined. A relatively long strain softening stage followed by the peak point appears in monolithic lattice structures while the stress decreases sharper for hierarchical lattice structures (Type IV). For Type I, the struts fail by Euler buckling which may be attributed to the low moment of inertia caused by the slender shape and relatively poor compressive stiffness of the parent material, i.e. flax fiber reinforced composite sheet compared with carbon fiber counterparts. Types II and III show the same failure mode but the struts buckle in different directions compared to Type I. As for Type IV, the governing failure mode of the lattice truss core sandwich structures is shear buckling. Compared to the previous work [5], the structure here doesn't fail by face sheet wrinkle, which should be attributed to the better interfacial property by resin infusion process.

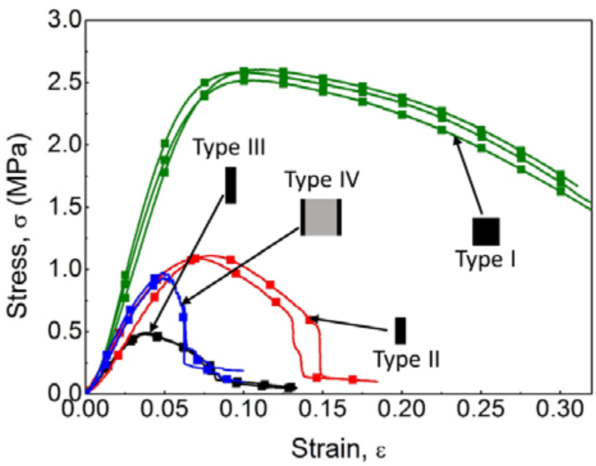

Figure 4. Compressive stress-strain curves of four different types of lattice structures.

The compressive properties were summarized in Table 3 along with the specific stiffness and strength. For monolithic lattice cores, the nominal compressive strength and stiffness varies linearly with the equivalent density (Type I to III) while for hierarchical lattice cores, the nominal compressive strength and stiffness values are greater than monolithic ones (Type III) with comparable relative density by 94% and 44%. The utilization of foam increases the compressive strength and stiffness with a relatively low equivalent density. After dividing the strength and modulus by the equivalent density, the changing tendency among four types is different. Type II reaches the maximum specific strength among monolithic structures, determined directly by the corresponding radius of inertia. As for Type IV, the specific nominal stiffness and strength values are the highest, and about 1.5 and 2 times of those for monolithic lattice cores.

Type	ρ_{equ} (g/cm^3)	Nominal strength (MPa)	Nominal stiffness (MPa)	Specific strength $(\mathrm{MPa}\cdot\mathrm{m}^3/\mathrm{kg})$	Specific stiffness $(\mathrm{MPa}\cdot\mathrm{m}^3/\mathrm{kg})$
I	0.182	2.56±0.03	42.76±1.64	1.41×10^{-2}	0.235

II	0.057	1.1±0.01	21.58±0.98	1.93×10^{-2}	0.379
III	0.035	0.49±0.005	16.29±0.43	1.40×10^{-2}	0.465
IV	0.033	0.95±0.02	23.45±0.49	2.88×10^{-2}	0.711

Table 3. Through-thickness compressive properties and equivalent density

3.2 Compare with other materials

The comparison between the hierarchical lattice structure (Type IV) and other typical cellular materials are summarized in Table 4. The specific strength of the hierarchical structures in the present study is superior to that of steel lattice and Al foam-filled corrugated core and competitive with Nomex honeycombs.

Cellular material	ρ_{equ} (kg/m^3)	Compressive strength (MPa)	Specific strength ($\mathrm{MPa}\cdot\mathrm{m}^3/\mathrm{kg}$)
Lattice cores (Type IV)	33	0.95	0.0288
CFRP tetrahedral lattice[7]	53.82	4.6	0.0855
Al tetrahedral[8]	99.2	6.1	0.0615
Steel pyramidal lattice[9]	210.6	4.32	0.0205
CFPR pyramidal lattice[2]	100	9	0.09
5052Al honeycombs[10]	33	0.91	0.0276
Nomex honeycombs[11]	32	0.85	0.0266
Al foam-filled corrugated cores[12]	1106	25.6	0.0231

Table 4. Measured compressive strength compared with other cellular core materials

4 CONCLUSIONS

Flax fiber reinforced composite lattice materials were developed in the present study. Monolithic and hierarchical composite pyramidal lattice materials were designed and fabricated via a low-cost vacuum assisted resin infusion (VARI) and slot assembly method. And out-of-plane compressive performance were then examined for monolithic and hierarchical lattice core sandwich structures with different geometries. For monolithic lattice cores, the struts tend to fail by Euler buckling along direction with lower moment of inertia while the governing failure mode of the hierarchical cores is truss shear buckling. The specific nominal stiffness and strength values of the hierarchical construction are about 1.5 and 2 times of those for their monolithic counterparts.

The flax fiber reinforced composite lattice structures in the present study could be superior to some metallic lattice structures, foam filled corrugated materials, and competitive with Nomex honeycombs. Results in the present study may shed lights on the possible application of natural fiber lattice materials in automotive industry such as to improve vehicle efficiency and emission. Further efforts about the feasibility of their specific application will be investigated.

ACKNOWLEDGEMENTS

This work is financially supported by the National Natural Science Foundation of China under grant No. 11402012, Young Elite Scientist Sponsorship Program by CAST, Opening fund of State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi'an Jiaotong University (SV2015-KF-07, SV2016-KF-20), Opening fund of State Key Laboratory for Automotive Safety and

Energy, Tsinghua University (Grant No. KF16142), and Beijing Municipal Science & Technology Commission (Grant No.Z161100001416006)

REFERENCES

[1] C. Schilde, H. Nolte, C. Arlt, A. Kwade, Effect of fluid–particle-interactions on dispersing nano-particles in epoxy resins using stirred-media-mills and three-roll-mills. *Composites Science and Technology*, **70**, 2010, 657-63.

[2] K. Finnegan, G. Kooistra, H. G. Wadley, V. S. Deshpande, The compressive response of carbon fiber composite pyramidal truss sandwich cores. *International Journal of Materials Research*, **98**, 2007, 1264-72.

[3] G. J. Mcshane, V. S. Deshpande, N. A. Fleck, Underwater blast response of free-standing sandwich plates with metallic lattice cores, *International Journal of Impact Engineering*, **37**, 2010, 1138-49.

[4] Z. Mahboob, I. E. Sawi, R. Zdero, Z. Fawaz, H. Bougherar, Tensile and compressive damaged response in Flax fibre reinforced epoxy composites, *Composites Part A-Applied Science and Manufacturing*, **92**, 2017, 118-33.

[5] S. Yin, L. Wu, S. R. Nutt. Stretch–bend-hybrid hierarchical composite pyramidal lattice cores. *Composites Structures*, **98**, 2013, 153-9.

[6] Committee CCMAD. Standard Test Method for Flatwise Compressive Properties of Sandwich Cores. 2011.

[7] G. Zhang, L. Ma, B. Wang, L. Wu, Mechanical behaviors of CFRP sandwich structures with tetrahedral lattice truss cores. *Composites Part B-Engineering*, **43**, 2012.

[8] G. W. Kooistra, V. S. Deshpande, H. G. Wadley. Compressive behavior of age hardenable tetrahedral lattice truss structures made from aluminium. *Acta Materialia*, **52**, 2004, 4229-37.

[9] F. W. Zok, S. A. Waltner, Z. Wei, H. J. Rathbun, R. M. Mcmeeking, A. G. Evans. A protocol for characterizing the structural performance of metallic sandwich panels: application to pyramidal truss cores. *International Journal of Solids Structures*, **41**, 2004, 6249-71.

[10] B. Russell, V. Deshpande, H. Wadley, Quasistatic deformation and failure modes of composite square honeycombs. *Journal of Mechanics of Materials & Structures*, **3**, 2008, 1315-40.

[11] X. Z. Wang, L. Z. Wu, S. X. Wang. Tensile and shear properties of aluminium foam. *Materials Technology*, **24**, 2013, 161-5.

[12] L. L. Yan, B. Yu, B. Han, C. Q. Chen, Q. C. Zhang, T, J, L. Compressive strength and energy absorption of sandwich panels with aluminum foam-filled corrugated cores. *Composites Science and Technology*, **86**, 2013, 142-8.