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Hybrid design and energy absorption of luffa-sponge-like hierarchical cellular structures

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ABSTRACT

Luffa sponge has hierarchical cellular structure with macro-pores and micro-pores. Its strength is greatly enhanced by the stiff inner-surface layer around the macro-pores. This hierarchical bio-cellular structure was mimicked to construct a hierarchical aluminum foam cylinder reinforced by stiff thin-walled carbon fiber reinforced plastic (CFRP) tubes. Compression behaviors of the luffa-sponge-like hierarchical foam cylindrical structures were revealed and it is found that the specific energy absorption (SEA) of the hierarchical structure is greatly improved compared with the pure aluminum foam cylinder. Interaction between the CFRP tube and the aluminum foam lets the SEA of the hierarchical cylinder is greater than the linear summation of the SEA of each component in the hierarchical foam. Through hybrid and hierarchical design, an ultra-light composite cellular structure with excellent energy absorption was developed.

1. Introduction

Hierarchical structures usually possess excellent mechanical behaviors [1–4]. Through hierarchical topology, structures usually get ultra-light and possess greater anti-buckling ability [5] and more excellent energy absorption [6–9]. Research group of Fan et al. [6–9] have made various hierarchical lattice composite structures and revealed their priority in SEA. Sun. et al. [6] found the hierarchical lattice tube have hierarchical fold mechanism which enhances the SEA of the tube. Woven sandwich wall in the honeycomb induces stable deformation plateau for hierarchical composite honeycombs [7–9].

Foam materials also have excellent energy absorbing ability, but the strength of the foam is usually not desirable. To improve the strength and energy absorption of the foam, metal tubes [10,11], bamboo tubes [12] and composite tubes [13] were applied to reinforce the foams. For polymer foams, metal tubes are too strong and too heavy. The tube and the foam have little interaction with each other for the great discrepancy between their strengths. Reasonable composite scheme is that the two components have comparable strength [14].

Another attracting material is natural hierarchical material [15], such as bio-cellular luffa sponges [16–21]. The luffa sponge has great porosity and stable deformation plateau in crushing. It is a hierarchical bio-cellular material. It has four-level hierarchy [22]. Mechanical properties of luffa sponge are also influenced by the moisture [16]. Shen et al. [16] monitored the humidity during the test. They also pointed out that luffa sponges have water-responsive rapid recovery ability [17] and this behavior was also revealed by An et al. [22].

In this research, bio-mimetic technique was applied to construct ultra-light hierarchical aluminum foam structure based on the topology of the luffa sponge cylinders.

2. Bio-cellular luffa sponges

As shown in Fig. 1, the luffa sponge has hierarchical cellular structure [22]. Luffa sponges were bought from Shi Wang Enterprise Co., Ltd. (China). These sponges are usually used as cleaning materials in China. Macroscopically, the luffa sponge is a cylinder (the 1s^{t} order structure) and the cylinder contains macro-pore structures with three parts (the 2nd order structure): a cylindrical shell, a core structure, and three or four macro-cavities, forming a hollow cellular cylinder, as shown in Fig. 1. Mesoscopically, the shell and the core have cellular structures (the 3rd order structure), containing interconnected struts and open meso-pores, as shown in Fig. 1. Microscopically, the strut of the luffa sponge exhibits a two-order

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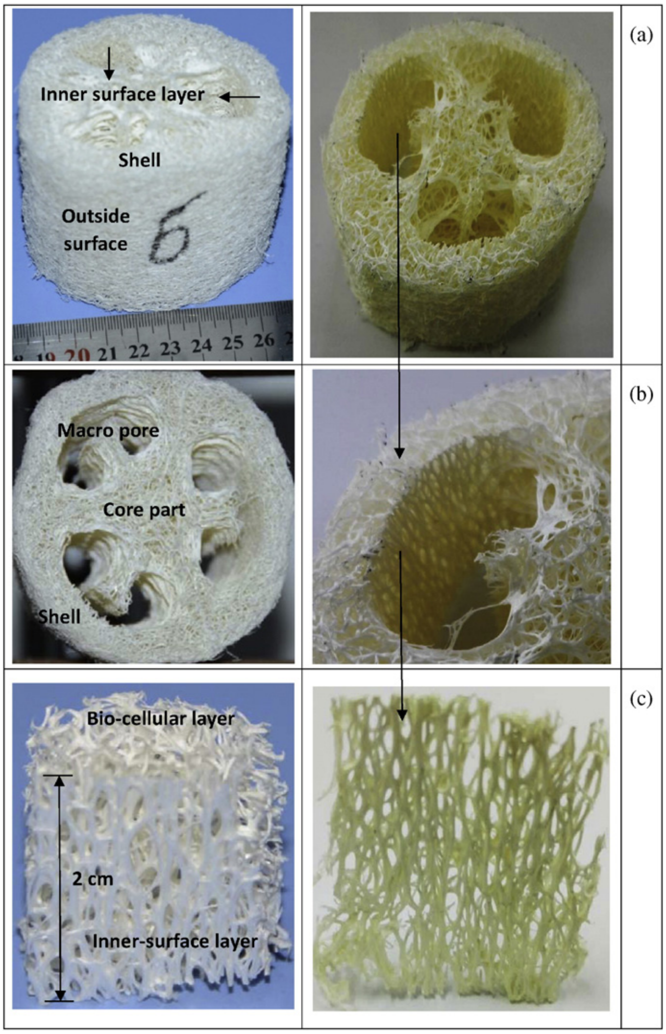

Fig. 1. Macro-structure of luffa sponge viewing from (a) outside surface, (b) cross section and (c) stiff inner-surface [22].

hierarchical hollow cellular tube (the 4th order structure), as suggested by An et al. [22]. Considering the strut material scale, the hierarchy is even higher than 4 scales. Multi-level hierarchical topology makes the luffa sponge ultra-light and usually lighter than 0.1 g/cm^3.

To understand the mechanical performances of luffa sponges, uniaxial compression experiments were performed using an Instron (USA) test machine at a loading rate of 1 mm/min. The most important load-resistant fibers locate at the inner surface of the macro-pores. These axially distributed fibers are stiff and make the luff cylinder have different crushing behaviors as shown in Fig. 2. Characteristics of luffa sponge cylinders are listed in Table 1.

When the stiff inner surface is kept, the deformation of the luffa sponge cylinder has greater strength companying with stable deformation plateau. When the stiff inner surface removed, the luffa sponge cylinder is soft companying with quasi-linear large deformation. As an ultra-thin layer, the inner-surface cannot resist compression dependently. It behaves as a membrane supported by the shell matrix. The interaction effect between the stiff inner-surface layer and the thick shell matrix obviously enhance the specific energy absorption (SEA) at a ratio over 100%, although the mass ratio of the inner layer is only 15% of the total luffa sponge, as listed in Table 2.

Through the research, it indicates that inserting a stiff layer into the luffa-sponge-like cylinder could greatly strengthen the hierarchical structure and improve the SEA.

3. Luffa-sponge-like hierarchical aluminum cellular structures

3.1. Hybrid design

Topology of the luffa sponge is imitated to develop a novel bio-mimetic ultra-light energy-absorbing structure. Aluminum foam is weight-efficient in energy absorption. CFRP is ultra-light with much greater modulus and strength. Combining these two materials, a luffa-sponge-like hierarchical foam structure has been constructed, as shown in Fig. 3. Aluminum foam cylinder is applied to mimic the bio-cellular cylindrical matrix. The aluminum cylinder has 25 macro-pores mimicking the macro-pores in the luffa sponge and thin-walled CFRP tubes are inserted into the cavity to mimic the stiff inner layer around the macro-pores of the luffa sponge. The luffa sponge has high level microstructures, but for us it is difficult to make hierarchical over two levels. So in this research a two-level cylinder is constructed based on foams with distributed macro-pores.

3.2. Properties of hierarchical structure

Strength of the aluminum foam, σ_{AF}, is usually expressed by

$$\sigma_{AF} = A\sigma_{Al}(\overline{\rho}_{AF})^m, \tag{1}$$

where σ_{Al} is the strength of the matrix of the aluminum foam. $\overline{\rho}_{AF}$ is the relative density of the aluminum foam. A and m are constants. Usually $m>1$. SEA of the aluminum foam, SEA_{AF}, is given by

$$SEA_{AF} = \sigma_{AF}\varepsilon_{AF} = A\sigma_{Al}(\overline{\rho}_{AF})^m\varepsilon_{AF}, \tag{2}$$

where ε_{AF} is the densification strain of the aluminum foam.

Adopting bio-mimetic technique, thin-walled CFRP tubes with diameter, d, and thickness, t, were inserted into the foam cylinder with diameter, D, and height, H, as shown in Fig. 3. Strength of the hierarchical aluminum foam, σ_{HF}, is given by

$$\sigma_{HF} = A\sigma_{Al}(\overline{\rho}_{AF})^m\overline{\rho}_{HF} + \sigma_{CF}\overline{\rho}_{CF}(1-\overline{\rho}_{HF}), \tag{3}$$

with

$$\overline{\rho}_{HF} = 1-n\left(\frac{d}{D}\right)^2, \overline{\rho}_{CF} = 1-\left(1-2\frac{t}{d}\right)^2 \approx \frac{4t}{d}, \tag{4}$$

where σ_{CF} is the strength of the CFRP. $\overline{\rho}_{HF}$ is the relative density of the hierarchical foam. $\overline{\rho}_{CF}$ is the relative density of the CFRP tube and n is the number of CFRP tubes. SEA of the hierarchical aluminum foam, SEA_{HF}, is given by

$$SEA_{HF} = \sigma_{HF}\varepsilon_{HF} = A\sigma_{Al}(\overline{\rho}_{AF})^m\overline{\rho}_{HF}\varepsilon_{HF} + \eta\sigma_{CF}\overline{\rho}_{CF}(1-\overline{\rho}_{HF})\varepsilon_{HF}, \tag{5}$$

where ε_{HF} is the densification strain of the hierarchical foam. η is a coefficient representing the strength discount of the deformation plateau of CFRP tubes. Usually $\eta<1$.

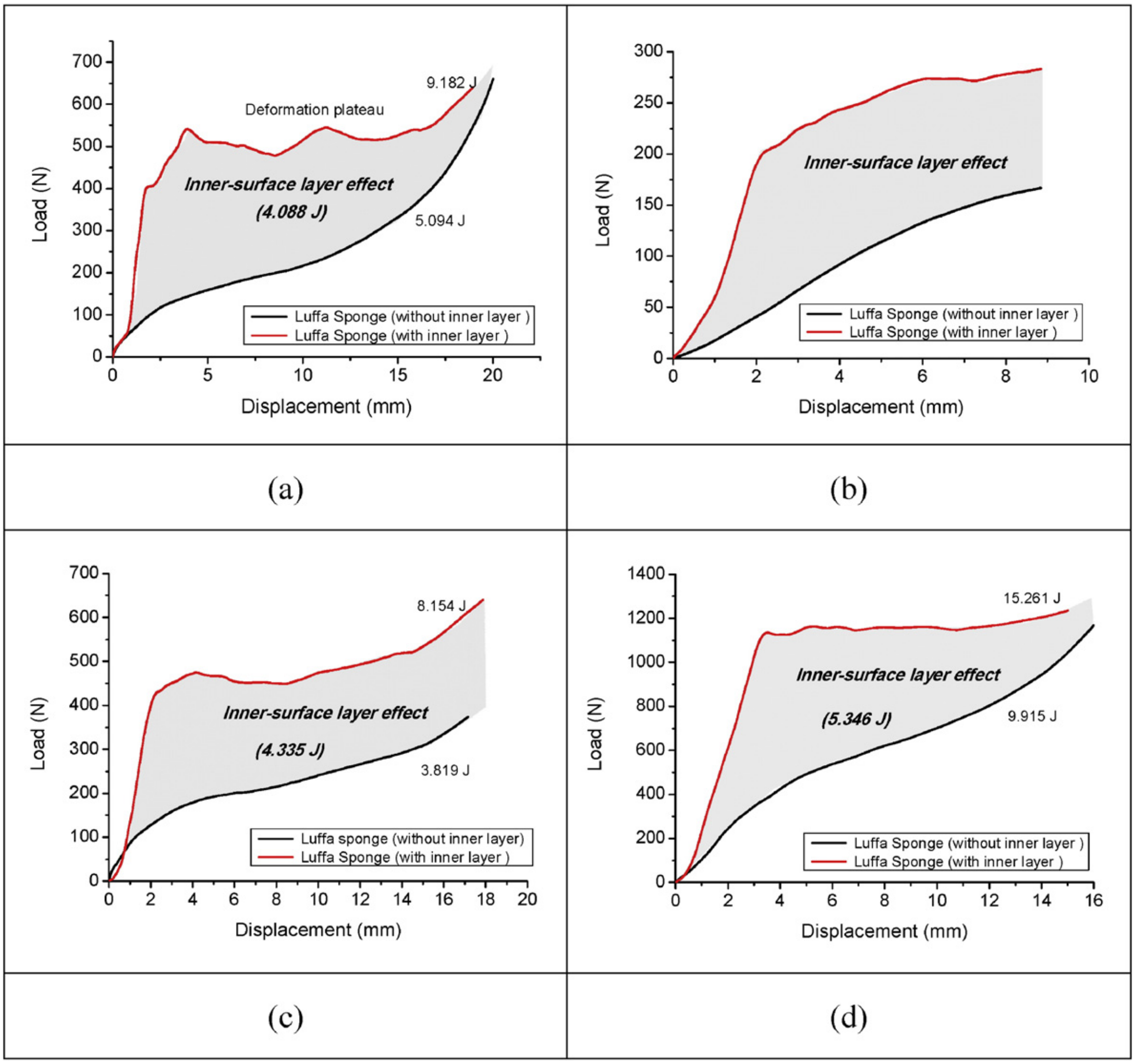

Fig. 2. Typical compression behaviors of luffa sponge cylinders when the stiff inner-surface layer kept or removed: (a) A1, (b) A2, (c) A3 and (d) A4.

Having identical mass, the relative densities have bellowing relation:

$$\bar{\rho}_{AF}\rho_{Al} = \bar{\rho}_{CF}\rho_{CF}, \tag{6}$$

where ρ_{Al} and ρ_{CF} denote the density of the aluminum and the CFRP, respectively. Dimension of the CFRP tube is determined by

$$d = \frac{4\rho_{CF}}{\bar{\rho}_{AF}\rho_{Al}} t. \tag{7}$$

Table 1
Characteristics of luffa sponge cylinders.

Sample	Length (cm)	Cylinder dimensions (long axis, short axis; cm)	Pore dimensions (long axis, short axis; cm)	Weight (with, without; g)
A1	3.0	(7.1, 6.5)	(3.0, 1.8);(2.6, 1.8);(3.0, 1.8)	(3.8, 3.4)
A2	3.0	(6.0, 6.0)	(2.1, 1.3);(1.6, 1.3);(1.9, 1.6)	(2.6, 2.2)
A3	3.0	(6.5, 5.6)	(2.1, 1.6);(2.4, 1.7);(1.7, 1.4)	(3.1, 3.1)
A4	3.0	(7.6, 7.2)	(3.0, 2.1);(3.0, 1.6);(2.7, 2.0)	(6.2, 4.8)

Accordingly,

$$\bar{\rho}_{HF} = 1-n\left(\frac{4\rho_{CF}}{\bar{\rho}_{AF}\rho_{Al}}\frac{t}{D}\right)^2, \bar{\rho}_{CF} = 1-\left(1-2\frac{t}{d}\right)^2 \approx \frac{\bar{\rho}_{AF}\rho_{Al}}{\rho_{CF}}, \tag{8}$$

and

$$\sigma_{HF} = A\sigma_{Al}(\bar{\rho}_{AF})^m\left[1-n\left(\frac{4\rho_{CF}}{\bar{\rho}_{AF}\rho_{Al}}\frac{t}{D}\right)^2\right] + 16n\sigma_{CF}\frac{\rho_{CF}}{\bar{\rho}_{AF}\rho_{Al}}\left(\frac{t}{D}\right)^2. \tag{9}$$

Table 2
Mass of the luffa sponge.

Sample	Mass of luffa sponge (g)	Mass of luffa sponge removing inner surface layer (g)	Mass of inner surface layer (g)	Mass fraction of inner surface layer
1	6.38	5.43	0.95	0.149
2	5.35	4.55	0.80	0.156
3	4.81	3.97	0.84	0.175
4	6.67	5.67	1.00	0.150

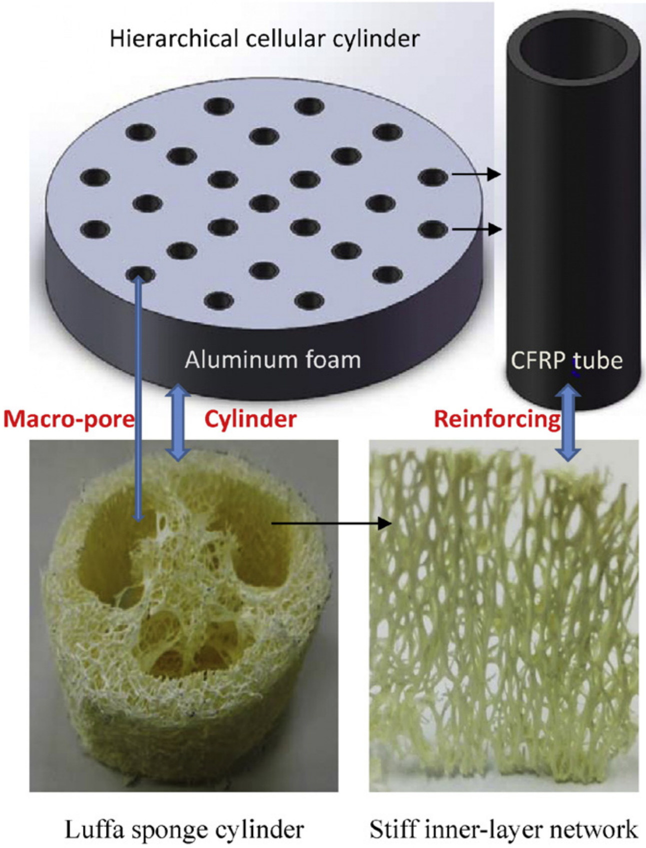

Fig. 3. Bio-inspired hierarchical cellular structure.

3.3. Fabrication

In this research, the mass of the aluminum foam cylinder is 300 g, varying from 287.8 (0.542 g/cm^3) g to 343.8 g (0.648 g/cm^3). The diameter of the cylinder is 150 mm and the height is 30 mm. The diameter of the CFRP tube is 10 mm and the thickness is 1 mm according to Eq. (7), as the density of the CFRP is 1.8 g/cm^3. Each tube has mass 1.53 g. There are twenty-five macro-cavities for inserting CFRP tubes, as shown in Fig. 3.

To make the luffa-sponge-like hierarchical aluminum cellular cylinder, cylinder with diameter of 150 mm and height of 30 mm was firstly cut from an aluminum foam plate whose designed density is 0.648 g/cm^3. Then the cylinder was fixed on a drilling machine to punch 25 macro cylindrical pores with diameter of 10 mm. Finally, 25 CFRP tubes were inserted into and adhere with the macro-pores. Fabricated hierarchical foam cylinder is displayed in Fig. 4. The mass of the hierarchical foam cylinder varies from 289.8 g (0.546 g/cm^3) to 336 g (0.633 g/cm^3). Details of the foam cylinders are listed in Table 3.

4. Compression behaviors

4.1. Foam cylinder

Quasi-static axial compression experiments were carried out on a 2000 kN universal testing machine at a loading rate of 1 mm/min to investigate the crushing behaviors of Aluminum foam cylinders, as shown in Fig. 5(a). The foam cylinders exhibit energy absorbing ability with stable deformation plateau. The yield strength varies from 6.4 MPa to 11.3 MPa due to the variation of the foam density. With macro-pores, the strength of the foam decreases to 5.6 MPa or 8.0 MPa. Yield force (YF) and mean crushing force (MCF) of the foam cylinders are listed in Table 4.

4.2. CFRP tube

CFRP tubes were compressed at a loading rate of 1 mm/min and crushed at splaying progressive crushing mode. The deformation curve has stable deformation plateau, but there is an abrupt load-dropping after the peak force (PF) induced by the splitting of the CFRP tube, as shown in Fig. 6. The peak force (PF) varies from 7.14 MPa to 9.38 MPa, while the MCF has little variation, from 5.23 MPa to 5.99 MPa, as listed in Table 4.

The four deformation curves are linear added to get an average curve. The average PF is 7.8 kN (279.4 MPa). The stress of the deformation plateau is 199.8 MPa (5.72 kN, MCF). So that $\eta = 0.73$.

4.3. Hierarchical cellular cylinder

Hierarchical cellular cylinders display excellent energy absorbing ability with enhanced yield load and stable deformation plateau, as shown in Fig. 7. The composite effect is amazing as pointed out by the grey area in Fig. 7, which represent the extra energy absorbed by the hierarchical cylinder of the same density. As show in Fig. 8, the improvement of the YF and the MCF of the hierarchical cellular varied from 40.0% (the greatest density) to 73.0% (the lowest density).

YF and MCF of the luffa-sponge-like hierarchical foam cylinders are listed in Tables 4 and 5. As the weight ratio of the CFRP tubes is only 15%, the improvement of the MCF varies from 38.1% to 73%, while the improvement of the YF varies from 67.1% to 134.2%, as listed in Table 4.

Theoretically, the improvement, ξ, is given by

$$\xi = \frac{PF_{HF}}{PF_{AF}} = \frac{\sigma_{HF}}{\sigma_{AF}} - 1 = (1 - \overline{\rho}_{HF})\left(\frac{\sigma_{CT}}{\sigma_{AF}} - 1\right), \tag{10}$$

where σ_{CT} is the equivalent strength of the CFRP tube and $\sigma_{CT} = \sigma_{CF}\overline{\rho}_{CF}$. Increasing the fraction of CFRP tubes enhances the strength of the hierarchical foam, as well as the strength ratio of the CFRP tube to the aluminum foam. With $\overline{\rho}_{HF} = 1 - 25\left(\frac{10}{150}\right)^2 = 0.889$ and $\sigma_{CT} = \frac{7800}{25\pi} = 99.3\text{MPa}$, the improvement coefficient is given by

$$\xi = 0.111\left(\frac{99.3}{\sigma_{AF}} - 1\right) \text{ for } \sigma_{AF} \in (6.0\text{MPa}, 12.0\text{MPa}). \tag{11}$$

As shown in Fig. 9, Eq. (11) correctly predicts the actual improvement of the strength.

5. Hierarchical effects

5.1. Linear summation effect

The hierarchical cellular cylinder has two components: aluminum foam and CFRP tubes. According to linear summation effect, the energy absorbed by the hierarchical structure is equal to the summation of the energies absorbed by the aluminum foam and the CFRP tubes, expressed as

$$SEA_{HF} = SEA_{AF} + nSEA_{CF}. \tag{12}$$

According to this linear rule, we get the deformation curves, as shown in Fig. 10. Interestingly, the deformation plateau of these superposed curves is lower than the tested curve of the hierarchical structure.

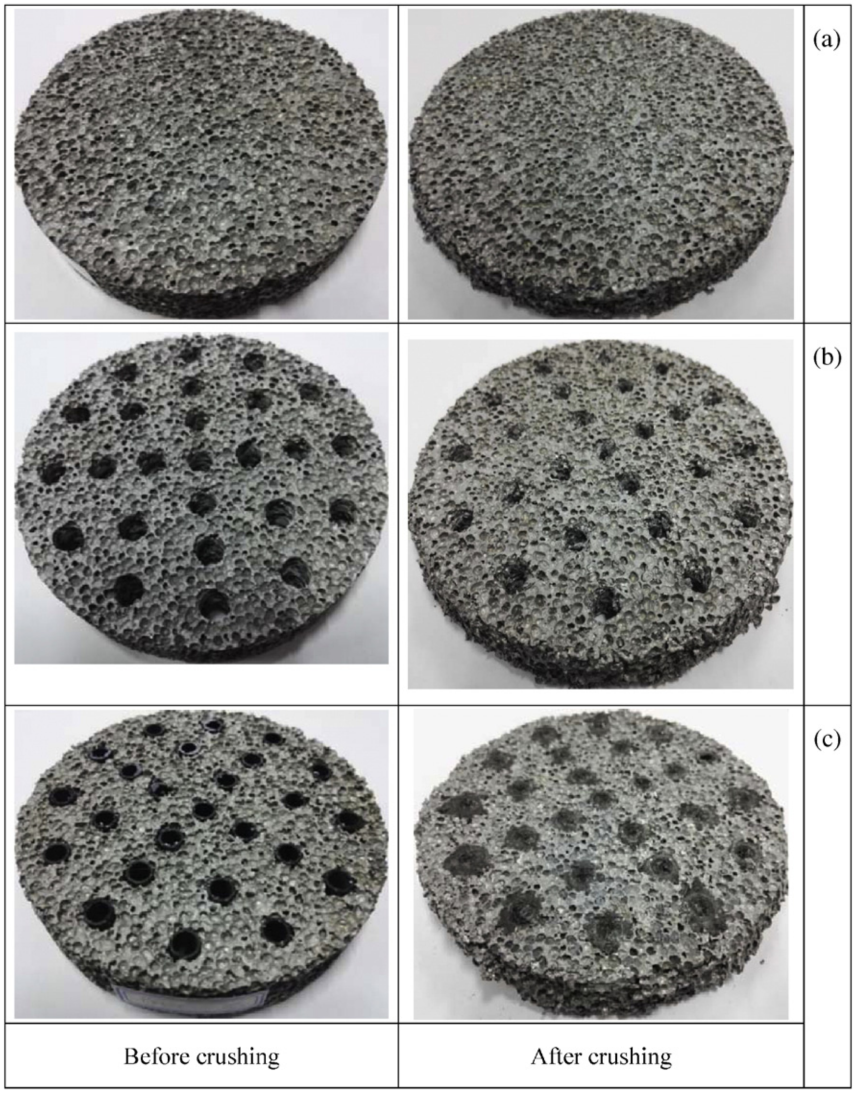

Fig. 4. Hierarchical foam cylinder: (a) Foam cylinder; (b) foam cylinder with hierarchical cavities; (c) CFRP tube reinforced hierarchical foam cylinder.

It indicates that another effect would exist and play an important role in enhancing the SEA.

According to linear summation effect, the strength or YF of the hierarchical structure (PF_{HF}) is equal to the summation of the strength or YF of the aluminum foam (PF_{AF}) and the CFRP tubes (PF_{CF}), expressed as

$$PF_{HF} = PF_{AF} + nPF_{CF}. \tag{13}$$

As shown in Fig. 11(a), the linear rule consistently predicts the PF of the hierarchical cylinder.

Linearly, the mean crushing force (MCF) of the hierarchical structure (MCF_{HF}) is equal to the summation of the MCF of the aluminum foam (MCF_{AF}) and the CFRP tubes (MCF_{CF}), expressed as

$$MCF_{HF} = MCF_{AF} + nMCF_{CF}. \tag{14}$$

Table 3
Mechanical properties of the cellular structures.

	Foam cylinder			Foam cylinder with macro-pores			Hierarchical cylinder			Improvement to foam cylinder	
Sample	Mass (g)	YF (kN)	MCF (kN)	Mass (g)	YF (kN)	MCF (kN)	Mass (g)	YF (kN)	MCF (kN)	YF (%)	MCF (%)
1	343.8	180.4	243.2	285.5	147.2	151.9	336.0	325.7	340.4	80.5	40.0
2	310.0	199.7	212.8	260.9	106.3	133.0	304.0	333.9	293.9	67.2	38.1
3	303.8	195.6	191.5	252.5	124.5	137.7	301.2	326.9	300.8	67.1	57.1
4	287.8	122.9	163.1	249.6	118.8	125.1	289.8	287.8	282.2	134.2	73.0

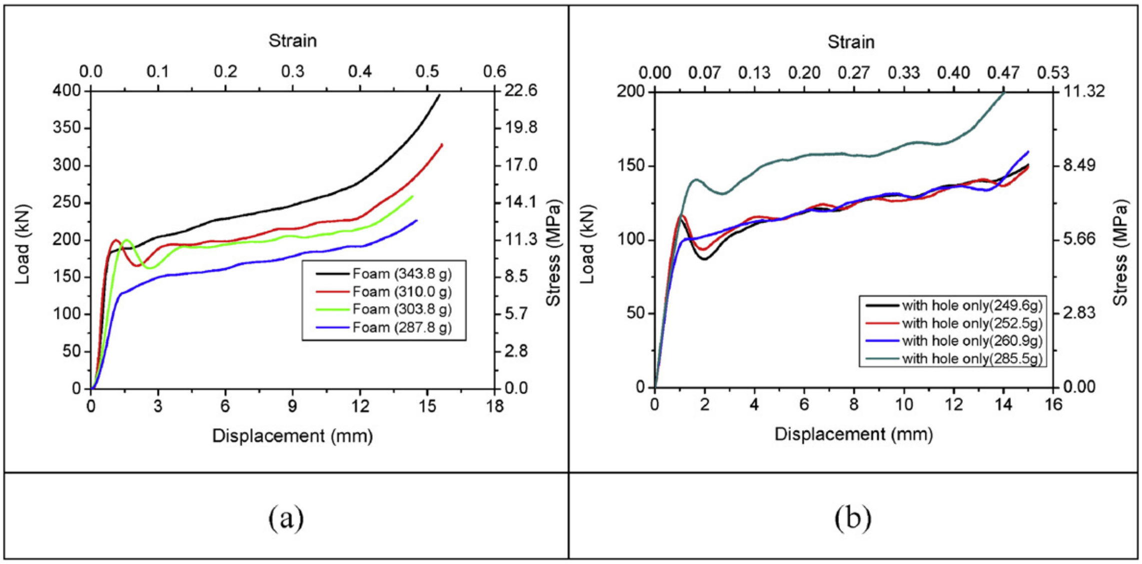

Fig. 5. Compression curves of (a) foam cylinders and (b) cylinders with macro-pores.

As shown in Fig. 11(b), the linear rule underestimates the MCF of the hierarchical cellular structures, just as the SEA. As listed in Table 5, the underestimated level varies from 15.8% to 45.5%.

5.2. Interaction effect

As shown in Fig. 12(a), (b) and (c), CFRP tubes encased in the aluminum foam display different crushing mode. Pure CFRP tube has splaying progressive crushing mode, as shown in Fig. 6 (a). Splitting will be restricted by the surrounded aluminum foam. Under circumferential stresses, the CFRP tube is progressively crushed at fragmentation mode, as shown in Fig. 12(d). The CFRP tube was squashed into carbon powders filled into the uncrushed segment of the tube. The interaction between the aluminum foam and the CFRP tube improves the post-failure strength of the CFRP tube to the level of the PF, so that the MCF of the hierarchical structure is greater than the linear summation of the perforated foam and the tubes, as shown in Figs. 10, 11(b) and 12(d). But the interaction has little effect on the PF.

The MCF of the hierarchical structure comes from the perforated foam, the CFRP tubes and the interaction effect. It is expressed by

$$MCF_{HF} = MCF_{AF} + nMCF_{CF} + MCF_{In}, \tag{15}$$

where MCF_{In} denotes the contribution from the interaction effect. Assuming the post-failure stress of the CFRP tube is equal to its failure strength and the densification strain is identical, the interaction effect is evaluated by

$$MCF_{In} = \frac{1-\eta}{\eta} nMCF_{CF}, \tag{16}$$

so that

$$MCF_{HF} = MCF_{AF} + \frac{1}{\eta} nMCF_{CF}. \tag{17}$$

Eq. (17) reflects the interaction between the foam and the tube. Prediction by Eq. (17) is a little greater than the tested data, as shown in Fig. 11(b).

The energy absorbed by the hierarchical structure includes three parts, SEA of the perforated foam, SEA of the CFRP tubes and SEA contributed by the interaction effect. It is expressed by.

$$SEA_{HF} = SEA_{AF} + nSEA_{CF} + SEA_{In}, \tag{18}$$

where SEA_{In} denotes the contribution from the interaction effect and.

$$SEA_{In} = \frac{1-\eta}{\eta} nSEA_{CF}, \tag{19}$$

so that

$$SEA_{HF} = SEA_{AF} + \frac{1}{\eta} nSEA_{CF}. \tag{20}$$

Eq. (20) reflects the interaction between the foam and the tube. Prediction by Eq. (20) is a little greater than the tested data, as shown in Fig. 13(a).

Table 4
Mechanical properties of the CFRP tubes.

Sample	PF (kN)	MCF (kN)
1	8.26	5.70
2	9.38	5.23
3	7.14	5.99
4	9.26	5.75
Average curve	7.8	5.72

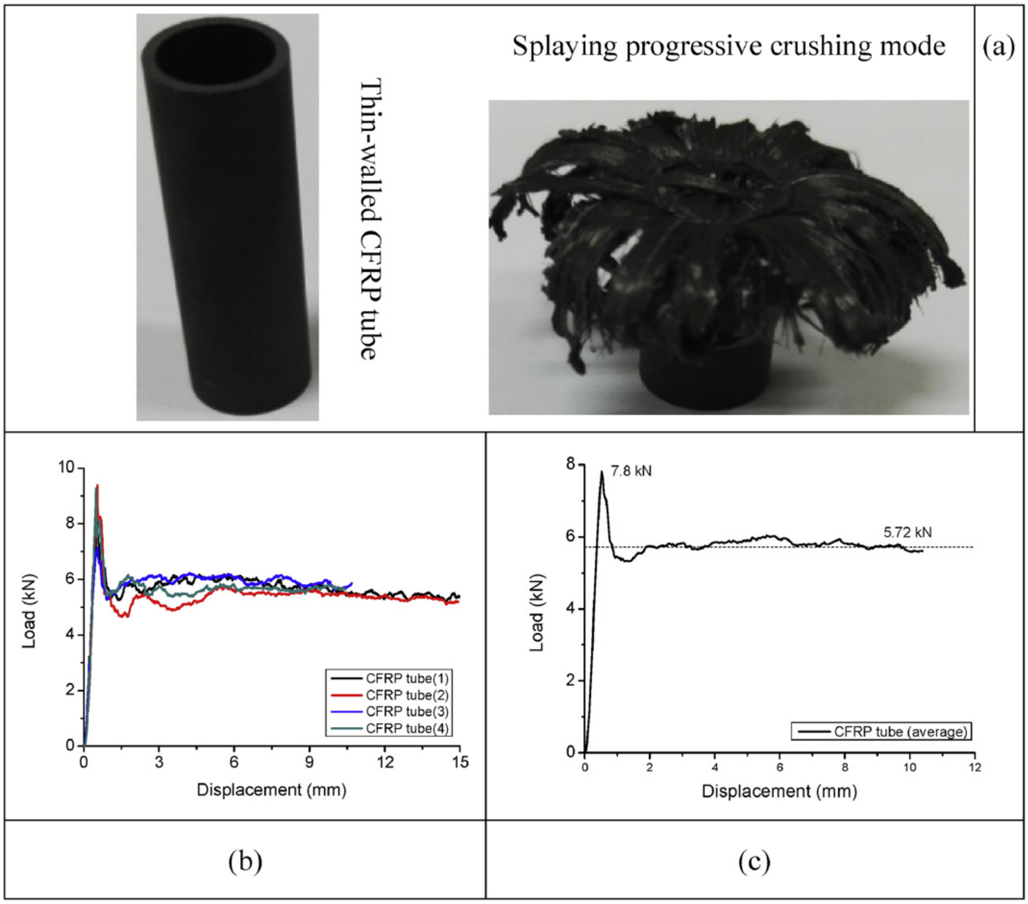

Fig. 6. CFRP tube: (a) Splaying progressive crushing mode, (b) compression curves and (c) average compression curve.

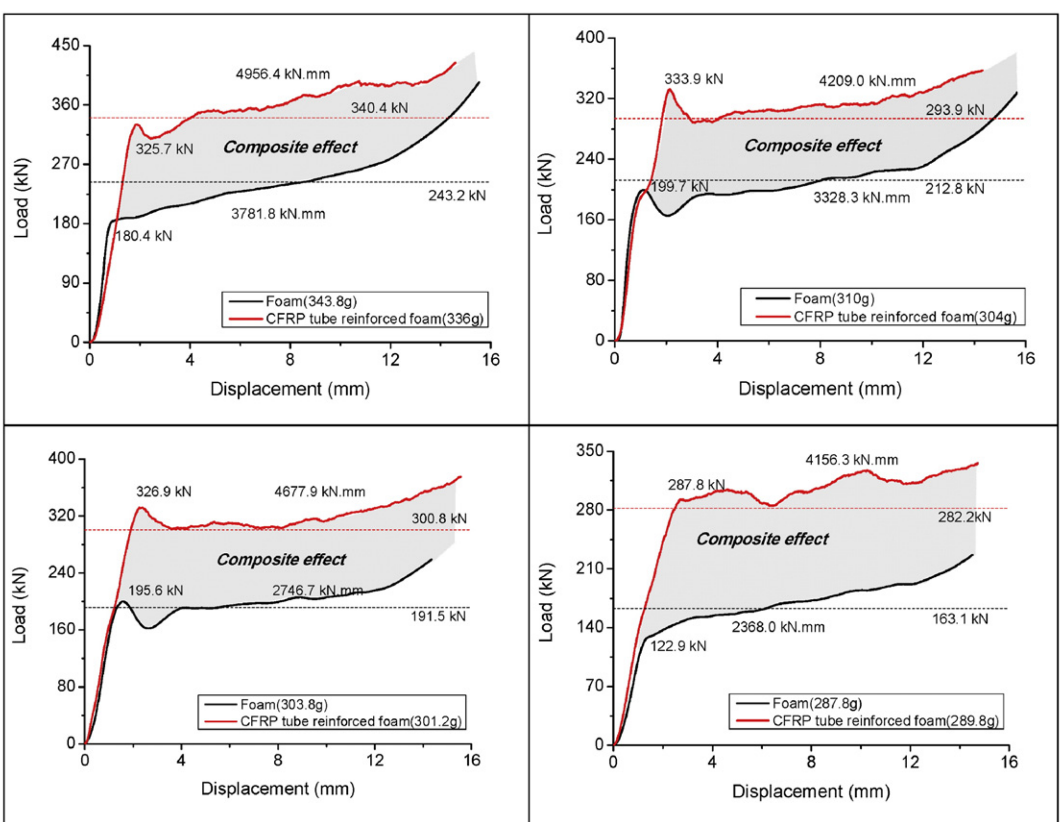

Fig. 7. Typical compression behaviors of CFRP tube reinforced foam cylinders.

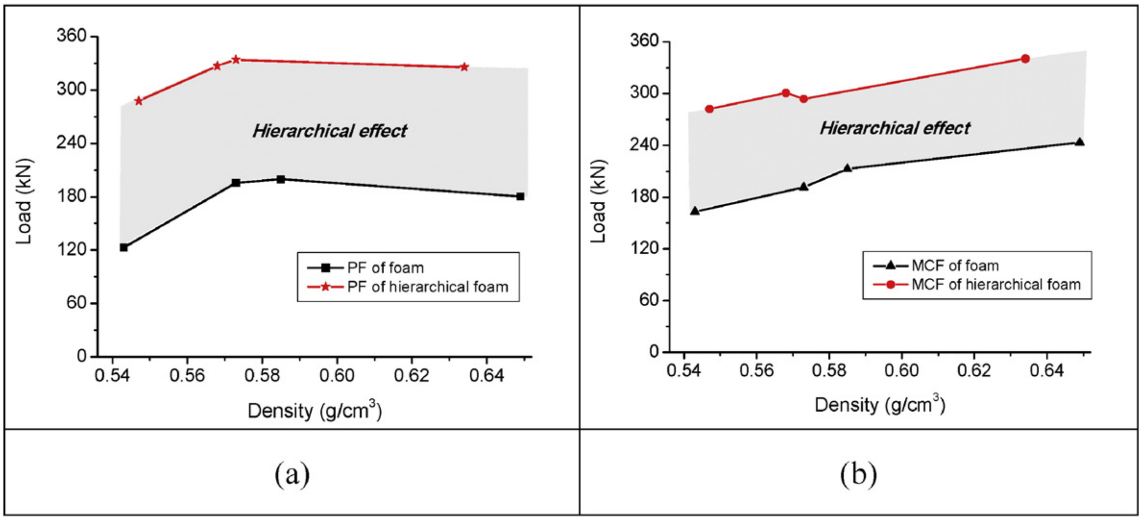

Fig. 8. Improvement of (a) YF and (b) MCF of the hierarchical foam.

Table 5
Interaction effect of the hierarchical cellular structures.

Sample	Foam cylinder with macro-pores		Linear summation		Hierarchical cylinder		Mass ratio of CFRP tubes in hierarchical cylinder	Interaction effect (Increment)	
	YF (kN)	MCF (kN)	YF (kN)	MCF (kN)	YF (kN)	MCF (kN)		YF (kN)	MCF (kN)
1	147.2	151.9	342.2	294.9	325.7	340.4	0.152	−16.5	45.5
2	106.3	133.0	301.3	266.1	333.9	293.9	0.145	32.6	27.8
3	124.5	137.7	319.5	269.9	326.9	300.8	0.161	7.4	30.9
4	118.8	125.1	323.8	266.4	287.8	282.2	0.139	−36.0	15.8

Theoretically, the improvement of the mean crushing strength or force, ξ, is given by

$$\xi = \frac{\sigma_{MHF}}{\sigma_{MAP}/\overline{\rho}_{HF}} - 1 = \frac{\sigma_{MCT}(1-\overline{\rho}_{HF}) + \sigma_{MAP}}{\sigma_{MAP}/\overline{\rho}_{HF}} - 1 = (1-\overline{\rho}_{HF})\left(\frac{\sigma_{MCT}}{\sigma_{MAP}} - 1\right), \tag{21}$$

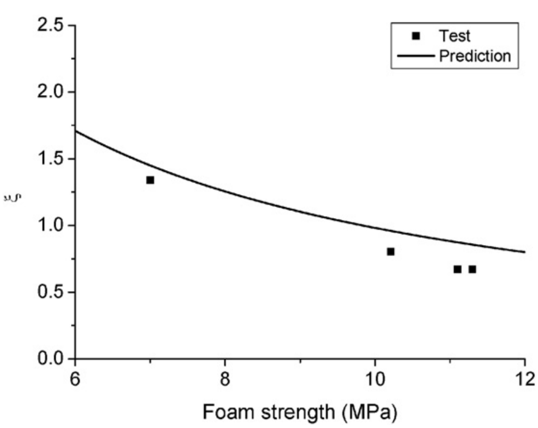

Fig. 9. Improvement prediction of the YF of the hierarchical foam.

where σ_{MHF} is the mean crushing strength of the hierarchical foam and σ_{MHF} is the mean crushing strength of foam matrix in the hierarchical foam. σ_{MCT} is the equivalent mean crushing strength of the CFRP tube and $\sigma_{MCT} = \eta\sigma_{CT}$.

According to the linear summation rule as shown in Fig. 6(c), $\eta = 0.73$. With $\overline{\rho}_{HF} = 0.889$ and $\sigma_{CT} = 99.3$MPa, the improvement coefficient is given by

$$\xi = 0.111\left(\frac{72.5}{\sigma_{MAP}} - 1\right). \tag{22}$$

Eq. (22) denotes linear summation. As shown in Fig. 13(b), Eq. (22) underestimates the improvement of the MCF.

According to the interaction effect as shown in Fig. 12(d), the mean crushing strength of the CFRP tube is lifted to the level of the peak strength of the CFRP tube and η is lifted to 1.0. With $\eta = 1.0$, the improvement is given by

$$\xi = 0.111\left(\frac{99.3}{\sigma_{MAP}} - 1\right). \tag{23}$$

As shown in Fig. 13(b), Eq. (22) fits the test data very well, validating the existence of the interaction effect.

5.3. Energy absorption

Adopting hierarchical topology, cellular structure can be further lighter but stronger. This rule is testified once more by the mimetic

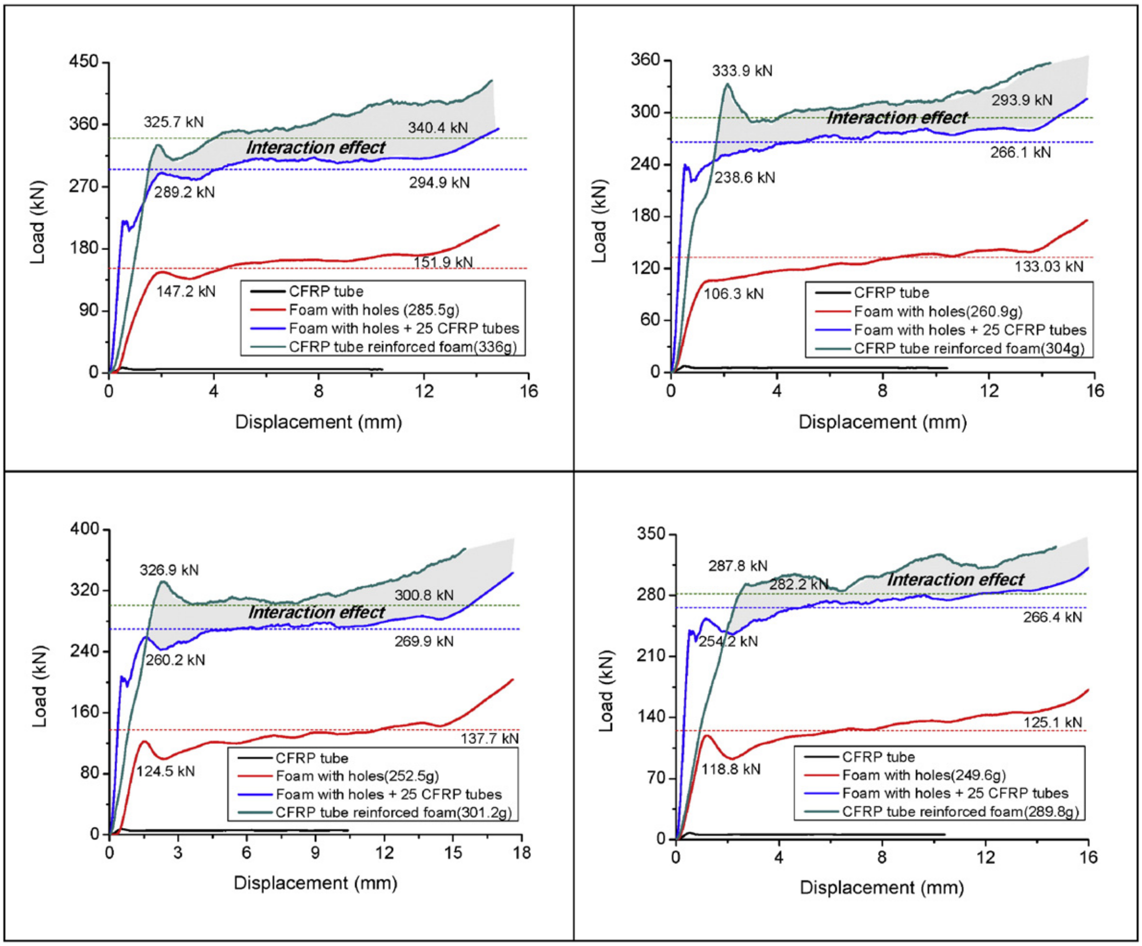

Fig. 10. Compression behaviors of CFRP tube reinforced foam cylinders compared with the linear summation of the components.

hierarchical foam structure. The SEA of the hierarchical structure of the same mass as foams is greatly enhanced at a maximum ratio over 70%. Compared with the attractive light lattice truss materials, the hierarchical foam also possesses excellent energy absorption, as shown in Fig. 14. The SEA is greater than most of the lattice truss materials.

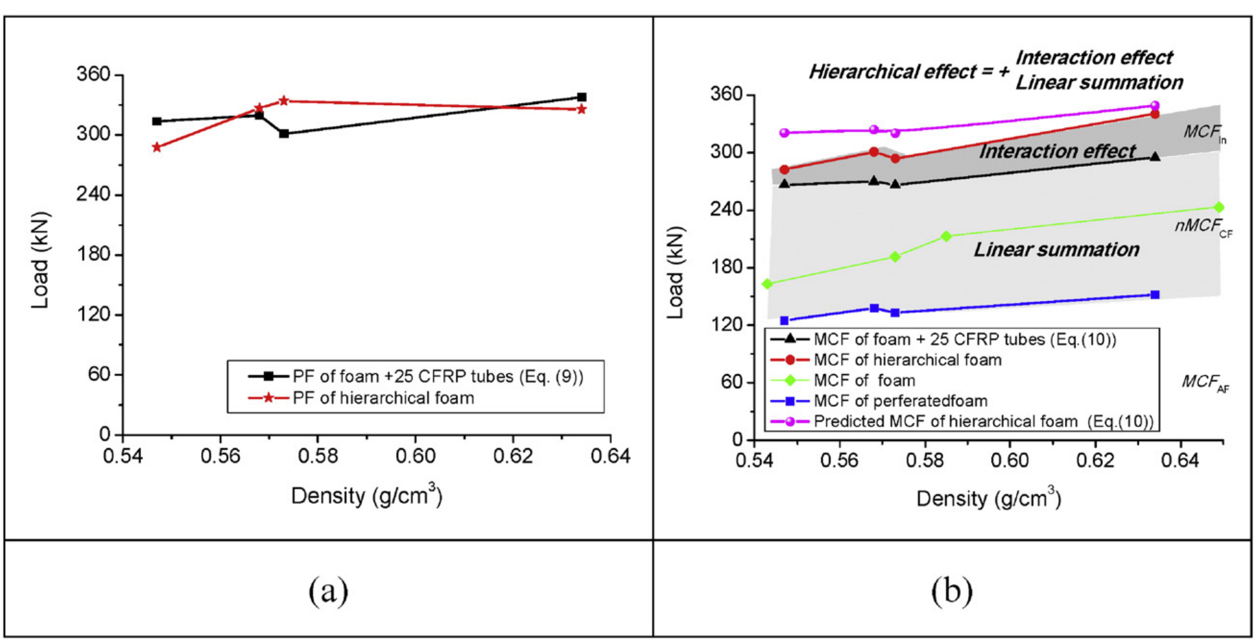

Fig. 11. (a) YF and (b) MCF of CFRP tube reinforced foam cylinders compared with the linear summation of the components.

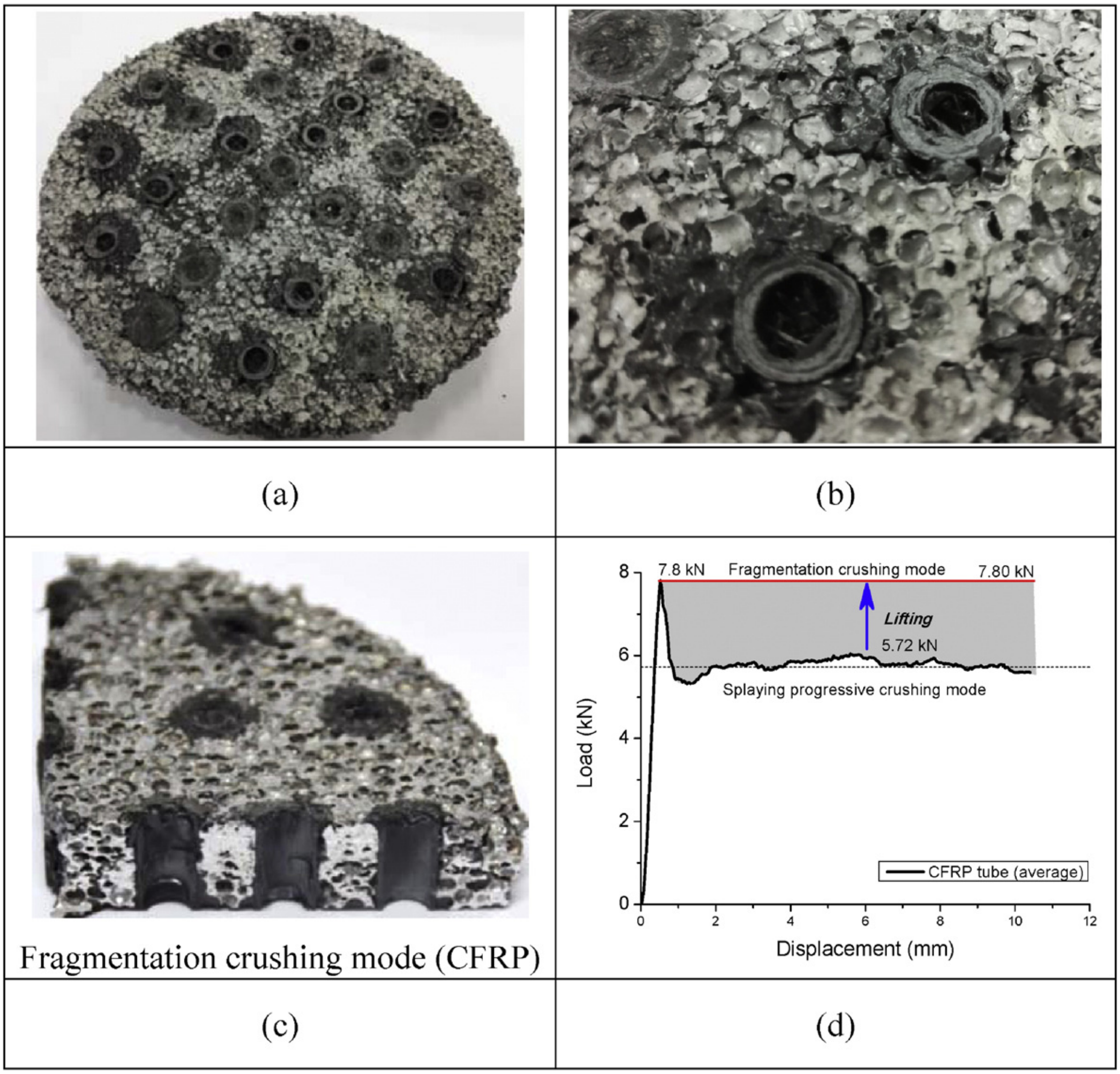

Fig. 12. Crushed mode of CFRP tubes encased in the foam: (a) Hierarchical cylinder; (b) partial enlarged detail; (c) cross-sectional detail and (d) interaction effect.

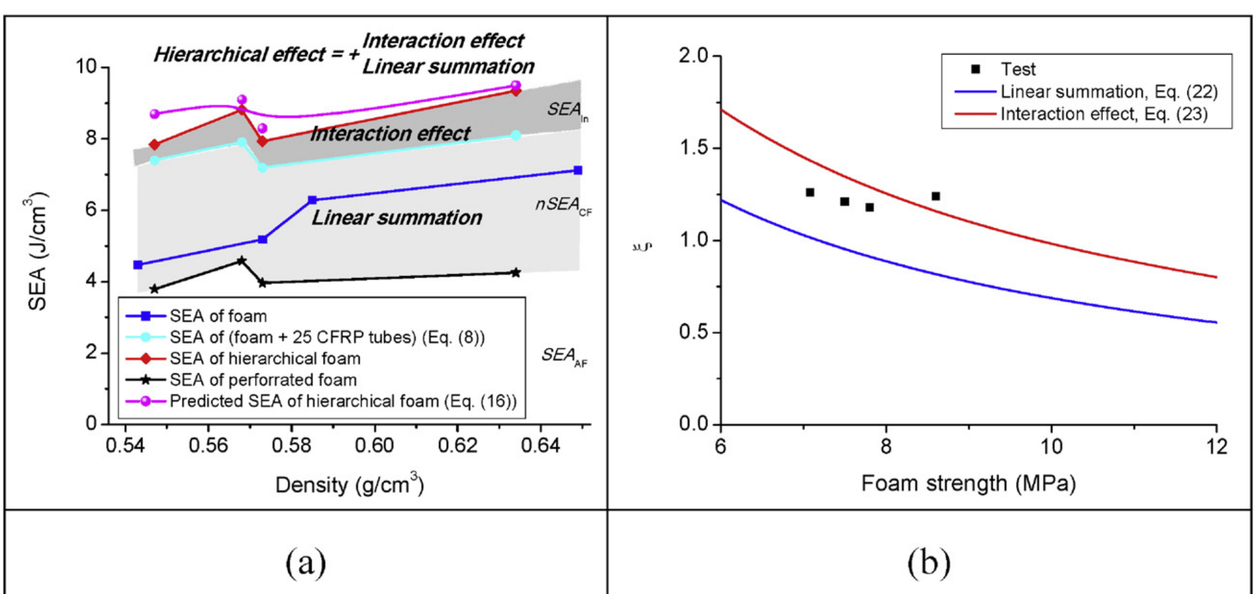

Fig. 13. SEA of (a) hierarchical cellular structure and (b) the improvement prediction.

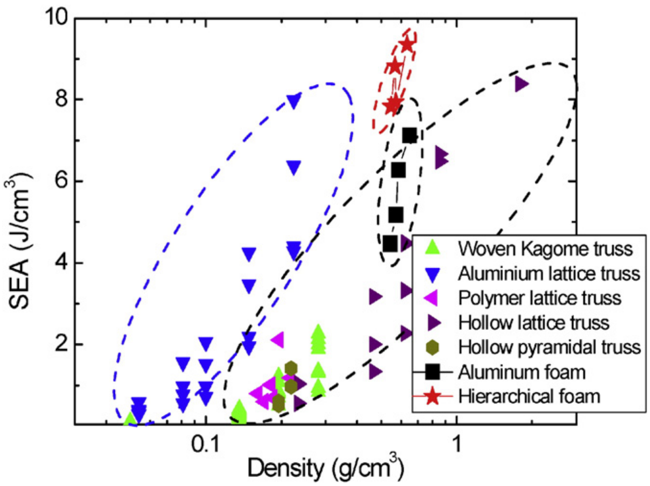

Fig. 14. SEA of hierarchical cellular structure compared with lattice truss materials [23].

6. Conclusions

In this research, hierarchical effect of luffa sponges was revealed by experiments and this bio-cellular topology was inspired to construct a hierarchical cellular structure through inserting thin-walled CFRP tubes into aluminum foams. Through the compression experiments, it is concluded that:

1) The luffa-sponge-like hierarchical topology induces an ultra-light but stronger cellular structure.
2) Thin-walled reinforcing CFRP tubes enhance the strength and the energy absorption of the luffa-sponge-like hierarchical composite foam. At the same time, the density of the foam is not increased.
3) The hierarchical effect comes from the linear summation of the components and the interaction effects between the components.
4) Surrounded by the aluminum foam, the crushing of thin-walled tubes becomes more stable, letting the composite foam has greater energy absorption than the linear summation of the components.

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