Design, manufacture and crushing behaviors of buckling-inspired auxetic meta-lattice structures

Jianhua Dong#, Gaoyuan Ye#, Yongjun Wang, Fengnian Jin and Hualin Fan

#State Key Laboratory for Disaster Prevention & Mitigation of Explosion & Impact, Army Engineering University of PLA, Nanjing, China; #Engineering Research Center of Advanced Wooden Materials of Ministry of Education, College of Material Science and Engineering, Northeast Forestry University, Harbin, China; State Key Laboratory of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Nanjing, China

ABSTRACT
Introducing buckling pattern into straight-walled lattice structure, an novel buckling inspired lattice meta-structure (BILM) was designed and fabricated using polylactic acid (PLA) by three-dimensional (3D) printing technology. The square lattice structure with positive Poisson’s ratio (PPR) is transformed into negative Poisson’s ratio (NPR) structure by buckling induction. Curved struts decrease the maximum strain, prohibit strut fracture, increase strut contact and induce ductile bending deformation. The meta-topology changes the crushing pattern from brittle layer-by-layer fracture, hybrid crushing pattern to stable plastic crushing when increasing the central angle from 0° to 120°. Buckling inspired meta-lattice structures can obviously improve the energy absorption (EA) performance through reducing the initial peak force (IPF) while increasing the EA, specific energy absorption (SEA) and crushing force efficiency (CFE). Ductile crushing endows BILM excellent EA.

CONTACT Hualin Fan, fh15@nuaa.edu.cn, State Key Laboratory of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Nanjing, China

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1 Introduction

In recent years, many scholars have devoted to develop auxetic structures. Compared with materials with positive Poisson’s ratio, auxetic structures with negative Poisson’s ratio [1–4] have advantages in shear resistance [5], fracture resistance [6], indentation resistance [7], synclastic behavior [8], variable permeability [9] and energy absorption [10–13] 2015–2021–2425–27. ‘Auxetic’ was first introduced by Evans in 1991, deriving from the Greek word– ‘auxetikos’ [14]. Auxetic structures can be divided into four categories: chiral structures [], reentrant structures [], rotating rigid structures [] and other types of auxetic structures [28]. Among them, reentrant structure is atypical auxetic structure, which has negative angle elements in the periodic structure [29]. Reentrant structure was firstly proposed in 1982 by Gibson [30]. Since then, many scholars have studied this kind of structures through experiments, simulations and theoretical formulas. Hu etal. [31,32] theoretically researched the dynamic crushing and indentation responses of 2D reentrant structures. The finite element method (FEM) has been successfully utilized to investigate the effects of hierarchy order on Poisson’s ratio and energy absorption capacity [33]. Li etal. [34] introduced augmented cell walls into 2D reentrant structure and double arrowhead structure in the principle direction to enhance the mechanical properties: the Young’s modulus and strength in the principle direction. Yang etal. [35] and Wang etal. [36] comprehensively and systematically investigated the typical 3D reentrant auxetic structure. Based on double-V auxetic structures, double-U structures were created through tailoring the geometry parameters by Yang etal. [37]. They concluded that double-U auxetic structures with smooth geometry distinctly reduced stress concentration under elastic loading.

In this research, anew type of buckling-inspired lattice meta-structure (BILM) was designed. The deformation mechanism was investigated through quasi-static in-plane compression experiments. In addition, the crashworthiness and the energy absorption (EA) of the structure with different central angle were discussed.

2 Structural design based on buckling analysis

2.1 Buckling topology

General lattice structures exhibit a high IPF but a lower mean crushing force (MCF) in crushing. Here, finite element analysis was firstly applied to get the buckling topology of general square lattice structure. The buckling mode is shown in Figure 1(a) and 1(b). It is found that the buckling-inspired lattice structure is similar to the reentrant structure in a certain buckling

Figure 1. Buckling analysis of lattice structure from (a) oblique view and (b) front view and (c) designing BILM through introducing buckling mode into straight-walled lattice.
mode. Thus, the buckling mode was applied to construct meta-lattice structure made up of curved struts in the manner of the buckling mode, as shown in Figure1(c). In the buckling analysis, the bending degree of each rod in the lattice structure is different. However, in order to simplify the complexity of modeling and the difficulty of specimen production, some simplifications were adopted, such as keeping the curvature of each rod consistent. This novel lattice is called BILM. The purpose is to avoid abrupt jumping from compression deformation to bending deformation, reduce the IPF and increase the crushing force efficiency (CFE).

### 2.2 Structural design and manufacture

The designed BILM structure is displayed in Figure1(c). The topology is named as bending-dominated periodic lattice by Wang et al. [38]. The height of the BILM, $H$, is 82mm. The thickness of the lattice plate, $T$, is 16mm. The length of each strut, $L$, is 16mm and the thickness, $t$, is 2mm. The central angle, $\alpha$, controls the amplitude of the waviness and changes from $0°$, $30°$, $45°$, $60°$, $90°$ to $120°$, as listed in Table 1.

The samples were made through fused deposition modeling (FDM) rapid prototyping technology by a3D printer, Raise 3D Pro2 Plus. The nozzle diameter is 0.4mm, with a layer height of 0.2mm and infill of 100%. The printing speed is 50mm/min. Instead of ductile iron material [39], in this research Polylactic Acid (PLA) was chosen as the matrix to print the sample. Mechanical parameters were extracted from the engineering stress–strain

| Central Angle (°) | 0° | 30° | 45° | 60° | 90° | 120° |
|-------------------|----|-----|-----|-----|-----|------|
| ![Schematic diagram of lattice meta-structure with different central angles.](image)

Table 1: Schematic diagram of lattice meta-structure with different central angles.

![Figure 2. Tensile stress–strain curve of PLA.](image)
curve, as shown in Figure 2. The yield strength ($\sigma_y$) is 42.24 MPa. The ultimate strength ($\sigma_u$) is 35.59 MPa. The elastic modulus is 1100 MPa. The ultimate strain ($\varepsilon_u$) is 0.11275. The plastic stress ($\sigma_0$) is 31.72 MPa. The density of the PLA is 1.08 g/cm$^3$.

All samples were printed without any support. The thickness of each sample is 16 mm. Six sets of structures were printed, and the printed samples are shown in Table 1. Three repeated samples were printed for each model. The printing scheme of all samples is shown in Figure 3.

3 Quasi-static in-plane compression experiments

3.1 Crushing performances

Six groups of BILMs were printed and three testing samples were prepared for each group. The compression experiments were conducted at a loading rate of 2 mm/min on a 5-ton universal test machine. The load cell was connected to the top platen and the bottom platen moved upwards. The load–displacement curves recorded by the testing machine are shown in Figure 4.

Three crushing patterns were revealed, changing from brittle layer-by-layer fracture pattern, hybrid crushing pattern to stable plastic crushing pattern accompanying with central angle improving from 0° to 120°, as shown in Figures 4 and 5.

When the strut curvature is small, (that is, when the central angle is small), the lattices will be crushed by layer-by-layer fractures. The force-displacement curves have dramatic zigzag jumps, as shown in Figure 4(a) and 4(b). For the straight-walled lattice, the struts are compression dominated. The bottom layer was firstly compressed to fracture, as shown in Figure 5(a), then other layers were crushed layer-by-layer, resulting in zig-zag compression curves. When the central angle is 30°, the IPF is reduced as the curved struts are compressed and deflected simultaneously. As the waviness is not serious, the struts are still compression-dominated and the lattice is directly compressed to fracture layer-by-layer, as shown in Figure 5(b). The lattice still has zig-zag compression curve. Under these circumstances, the lattices are not ideal for EA.

![Figure 3](https://example.com/figure3.png)

Figure 3. Printing lattice with thickness of (a) 2mm, (b) 5mm, (c) 10mm, and (d) 16mm.
When the central angle is increased to 45°, the waviness of the strut changes the crushing pattern. The crushing curve is more stable accompanying with zig-zags, as shown in Figure 4(c). The crushing initiated from the central three layers, as shown in Figure 5(c). The boundary layers were crushed after the central three layers were densified.

Figure 4. Force–displacement curves of BILMs with different curvature (central angle): (a) 0°, (b) 30°, (c) 45°, (d) 60°, (e) 90° and (f) 120°.
The struts are compressed and deflected simultaneously. But the flexure deformation is more important. The IPF is further reduced. It is a hybrid crushing mode. In this instance, the BILM is still not an ideal energy absorber.

Further increasing the central angles, the curved struts completely change the crushing pattern from compression to bending. The force–displacement curves have three typical stages: elastic deformation, deformation plateau and densification, as shown in Figure 4(d) to 4(f). The IPF is further reduced. The curves are smooth with soft zigzags. All
the five layers were almost crushed simultaneously. Plastic hinges formed in the crushing, as shown in Figure 5(d) to 5(f). After contact, the horizontal struts will be flattened and more energy will be absorbed. Strut contact greatly attenuates the opportunity of brittle fracture and endows the BILM ductile deformation. Under these circumstances, the BILMs become excellent energy absorbers.

3.2 Negative Poisson’s ratio

The buckled topology induces negative Poisson’s ratio, which was observed in the experiment, as shown in Figure 5, especially for BILMs with central angle of 60°, 90° and 120°. The BILM is compressed along axis Y and the strain is compressive. Along axis X, the BILM also has macroscopic compression deformation, especially in the middle of the BILM. Figure 6 clearly shows the selected reference point position.

The Poisson’s ratio is negative, as shown in Figure 7 to 8. Figure 7 reveals the development of the equivalent strains of the BILM. refers to the strain in the ydirection. In this article, the strain in the ydirection only considers the strain in the ydirection of the overall structure, that is, the strain between the upper and lower horizontal planes. refers to the strain in the xdirection. The midpoint of the outermost wall of each layer is selected as the reference point to calculate the five sets of strains in the xdirection, \( \varepsilon_y, \varepsilon_x \).

Figure 8 clearly reveals the development of the Poisson’s ratio. Considering the boundary effect of the upper and lower layers of the structure, we choose the transverse strain of the central layer as the transverse strain of the whole structure to calculate the Poisson’s ratio of the structure. Initially, the Poisson’s ratio of the central layer is close to \(-2.0\). In the crushing, the Poisson’s ratio is enlarged to \(-0.5\), representing topology transformation.

Transverse contraction and longitudinal compression change the configuration of the cellular structure, as shown in Figure 9. Before compression, the cellular structure is a square cell with four curved walls. In compression, accompanying with the transverse contraction
Figure 7. Strain development in crushing for BILMs with central angle of (a) 45°, (b) 60°, (c) 90° and (d) 120°.
contraction and the longitudinal compression, neighboring struts gradually contact with each other. After strut contact, the representative curved-walled square cell turns to two curved-walled triangular cells. As triangular cell is astatically determinate structure, the Poisson’s ratio changes to positive and the crushing force will be enhanced.

4 Structural crashworthiness evaluation

For an energy absorbing device, several factors should be comprehensively considered to evaluate its energy absorption (EA) performance, as shown in Figure10. Specific energy absorption (SEA), that is, the energy absorbed by the energy absorber per unit mass, is a measure of the structure utilization efficiency in the crushing process, and

\[
SEA = \frac{E}{m}
\]

(1)

where \(m\) is the mass of the energy-absorbing structure and \(E\) is the internal energy absorbed by the energy-absorbing mechanism, which can be calculated by

\[
E = \int_0^d F(x)\,dx
\]

(2)

where \(d\) is the effective crushing distance and \(F\) is the impact force. The MCF, , represents the average value of the load during the entire energy dissipation process. Its characterization is related to the EA and deformation distance. The larger is the value, the better is the EA. It is defined as \(P_m\)

\[
P_m = \frac{E}{d}
\]

(3)
Figure 9. Structural evolution and Poisson's ratio transformation.
The IPF, is the greatest force in the initial process. It is closely related to personnel injury and damage to objects. The lower is the value of this indicator, the better is the anti-impact performance. The crushing force efficiency (CFE) is an index to evaluate the consistency of the structural load. The most perfect state is that the MCF is equal to the IPF, then the CFE is 100%, which is defined by

\[ CFE = \frac{P_m}{P_{\text{max}}} \]  

Through the experiments, it is found that enlarging the central angle from 0° to 120°, the crushing of the lattice changes from layer-by-layer zigzag crushing, hybrid crushing to stable crushing. The ductility changes better when the strut has larger curvature. In order to simplify the calculation, a theoretical value of is selected as the effective crushing distance (ECD) to calculate the EA. As shown in Figure10, this value is consistent with the experiment. To evaluate the performance, the IPF, the EA, the SEA and the CFE are listed in Table 2.

Introducing buckling mode into the lattice, the IPF is greatly reduced from 6.83 kN to 1.77 kN, a decrease of 74.08%, as compared in Figure11(a). On the contrary, the MCF of the BILM is greatly improved from 1.3 kN of straight-wall lattice to 2.75 kN of BILM with central angle of 120°, as compared in Figure11(b). For BILMs with central angle of 90°, the MCF has a slight drop to 2.4 kN.

The SEA of the BILM is greatly improved from 1.98 J/g of the straight-walled lattice to 3.86 J/g of the BILM with central angle of 60°, as compared in Figure11(c). For BILMs with central angle of 90° and 120°, the SEA has a slight drop to 3.37 J/g and 3.57 J/g, respectively. As shown in Figure11(d), the CFE of the lattice structure is dramatically modified. It is nearly proportional to the central angle, increasing from 0.19 at 0° to 1.56 at 120°. The CFE is tightly relating to the crushing pattern. Lattice with layer-by-layer zigzag crushing mode has CFE smaller than 0.336. Lattice with hybrid crushing mode has CFE nearly 0.544. The CFE of BILMs with stable crushing mode is close to or even much...
Table 2 EA indexes of lattice structures with different central angles.

| BILM | Mass (g) | IPF (kN) | EA (J) | SEA (J/g) | ECC | MCF (kN) | CFE |
|------|----------|----------|--------|-----------|-----|----------|-----|
| 0–1  | 32.76    | 7.012    | 68.26  | 2.08      | 0.61| 1.37     | 0.19|
| 0–2  | 32.78    | 6.736    | 62.03  | 1.89      | 0.61| 1.24     | 0.18|
| 0–3  | 32.66    | 6.737    | 64.26  | 1.97      | 0.61| 1.29     | 0.19|
| 30–1 | 33.01    | 4.453    | 70.66  | 2.14      | 0.61| 1.41     | 0.32|
| 30–2 | 33.05    | 4.404    | 77.24  | 2.34      | 0.61| 1.54     | 0.35|
| 30–3 | 32.95    | 4.363    | 73.89  | 2.24      | 0.61| 1.48     | 0.34|
| 45–1 | 33.65    | 4.181    | 127.06 | 3.78      | 0.61| 2.54     | 0.61|
| 45–2 | 33.58    | 4.238    | 102.01 | 3.04      | 0.61| 2.04     | 0.48|
| 45–3 | 33.67    | 4.209    | 114.54 | 3.40      | 0.61| 2.29     | 0.54|
| 60–1 | 33.68    | 4.998    | 129.40 | 3.84      | 0.61| 2.59     | 0.86|
| 60–2 | 34.18    | 3.148    | 139.68 | 4.09      | 0.61| 2.79     | 0.89|
| 60–3 | 34.14    | 2.966    | 125.08 | 3.66      | 0.61| 2.50     | 0.84|
| 90–1 | 35.76    | 2.102    | 124.91 | 3.49      | 0.61| 2.50     | 1.19|
| 90–2 | 35.50    | 2.018    | 111.41 | 3.14      | 0.61| 2.23     | 1.10|
| 90–3 | 35.80    | 2.178    | 124.02 | 3.46      | 0.61| 2.48     | 1.14|
| 120–1| 38.27    | 1.679    | 126.95 | 3.32      | 0.61| 2.54     | 1.51|
| 120–2| 38.69    | 1.803    | 154.80 | 4.00      | 0.61| 3.10     | 1.72|
| 120–3| 38.69    | 1.826    | 131.43 | 3.40      | 0.61| 2.63     | 1.44|

Figure 11. (a) Initial peak force, (b) mean crushing force, (c) specific energy absorption and (d) crushing force efficiency of BILMs.
larger than 1.0. On the whole, BILMs with central angle of 60° have excellent performance with maximum SEA and the CFE is close to 1.0. On the other hand, BILMs with central angle of 120° have excellent performance with maximum MCF and EA and the CFE is close to 1.56.

5 Analyses

5.1 IPF prediction

To predict the IPF of BILM, the Shanley model [40,41] is applied to predict the load of the curved wall, as shown in Figure 12, in which the middle section of curved wall is simplified as two short elastic-plastic bars connected by a hinge. And these two short elastic-plastic bars have the same cross-sectional area.

When the element considered is short enough, the whole bar can be approximately regarded as a bar composed of numerous hinges in series. Therefore, there is only axial force on the upper and lower boundary of the element under axial load. The inner section bears compressive stress and the outer section bears tensile stress. When the stress produced by the axial force exceeds the strength of the elastic-plastic bar, the elastic-plastic bar will be destroyed, resulting in structural buckling.

The spacing is $t$ and the area is $A$. The eccentric distance is $e$. The bearing load is $P$. Based on the balances of forces and torques, the equilibrium equations are given by

$$P_1 - P_2 = P$$

(5)
and

\[(P_1 + P_2)t = 2Pe\]  

(6)

with

\[e = \frac{L}{2 \sin(a/2)} [1 - \cos(a/2)]\]  

(7)

The force is given by \(P_1\)

\[P_1 = P \left(\frac{1}{2} + \frac{e}{t}\right)\]  

(8)

The plastic stress, \(\sigma\), of the PLA is given by \(\sigma_0\)

\[\sigma_0 = \frac{1}{\varepsilon_u} \int_{\varepsilon_0}^{\varepsilon_u} \sigma d\varepsilon\]  

(9)

In this research the plastic stress is 31.72 MPa. To predict the IPF, let

\[P_1 \leq \frac{1}{2} \sigma_0 t T\]  

(10)

\[P_{\text{max}} = 6\sigma_0 t T \left(1 + \frac{L}{t} \frac{1 - \cos(a/2)}{\sin(a/2)}\right)^{-1}\]  

(11)

As shown in Figure 13, the predicted IPFs are consistent with the experimental data. In Eq. (11), replacing with will reduce of the prediction error of the BILM, so that using to predict the IPF is more reasonable. \(\sigma_0 \sigma_y \sigma_y\)

Figure 13. Prediction of IPF changing with central angle.
5.2 Strut fracture judgment

Only considering the flexural deformation in crushing, the maximum strain of the strut, \( \varepsilon \), is predicted by:

\[
\varepsilon = \left( \frac{1}{\rho} - \frac{1}{\rho_0} \right) \frac{t}{2}
\]

where \( \rho \), \( \rho_0 \) and \( t \) represent the curvature radius, the initial curvature radius and the thickness of the honeycomb wall, respectively. The distance between the node shortened by the flexure, \( \delta \), can be predicted by:

\[
\delta = \rho_0 \sin \left( \frac{s}{\rho_0} \right) - \left( \frac{2\varepsilon}{t} + \frac{1}{\rho_0} \right)^{-1} \sin \left( \frac{2\varepsilon}{t} + \frac{1}{\rho_0} \right) s
\]

where \( s \) is the length of the strut. The critical value of at the fracture of the strut, \( \delta_c \), is given by:

\[
\delta_c = \rho_0 \sin \left( \frac{s}{\rho_0} \right) - \left( \frac{2\varepsilon_f}{t} + \frac{1}{\rho_0} \right)^{-1} \sin \left( \frac{2\varepsilon_f}{t} + \frac{1}{\rho_0} \right) s
\]

where \( \varepsilon_f \) is the fracture strain of the strut material. In this research, \( \varepsilon \) is predicted by:

\[
\varepsilon = \varepsilon_t = 0.104\varepsilon_f
\]

and

\[
\delta_c = \varepsilon s
\]

The distance between horizontal struts is \( d \). If \( \delta_c < d \), the strut will be broken directly and the crushing of the lattice is brittle. If \( \delta_c > d \), the struts will contact with each other before the occurrence of the beam fracture and the crushing is ductile. \( d \) is smaller than the strut distance, \( d \). When the central angle is 0°, 30° and 45°, the value of is smaller than the strut distance, \( d \). Accordingly, the crushing of BILMs with central angle of 0°, 30° and 45° is dominated by strut fracture, while the crushing of BILMs with central angle of 60°, 90° and 120° is dominated by strut bending.

| Table 3 Theoretical calculation results of BILM. |
| Central angle (°) | \( \rho_0 \) (mm) | \( \rho \) (mm) | \( \delta_c \) (mm) | \( d \) (mm) |
|-------------------|-----------------|----------------|-----------------|----------------|
| 30                | -30.910         | -7.334         | 1.4569555       | 1411.894       |
| 45                | 20.905          | 6.586          | 10.803          | 10.817         |
| 60                | 16.000          | 6.006          | 11.786          | 9.713          |
| 90                | 11.314          | 5.198          | 12.737          | 7.373          |
| 120               | 9.238           | 4.711          | 11.873          | 4.762          |

From Table 3 and Figure 14, when the central angle is 0°, 30° and 45°, the value of is smaller than the strut distance, \( d \). When the central angle is 60°, 90° and 120°, the value of is larger than the strut distance, \( d \). Accordingly, the crushing of BILMs with central angle of 0°, 30° and 45° is dominated by strut fracture, while the crushing of BILMs with central angle of 60°, 90° and 120° is dominated by strut bending.
There are three energy absorbing mechanisms, as shown in Figure 15. The first is the energy absorbed by the compression deformation of the vertical walls, as shown in Figure 15(a). The second is the energy absorbed by the plastic bending of the vertical walls, as shown in Figure 15(b). And the last is energy absorbed by the flattening of all the curved walls, as shown in Figure 15(c). The straight-walled lattice only has the first mechanism. The BILM with small central angle has the first and the third mechanisms. The BILM with great central angle has all these three mechanisms.

According to energy conservation, the MCF for the energy absorbed by the compression deformation, \( \Phi_m \), can be predicted by
\[ P_{m1} = \frac{6\sigma_0 T \varepsilon_u H}{H - 16t} \] (18)

With \( \sigma_0 = 31.72\) MPa, \( \varepsilon_u = 0.11275 \) and \( P_{m1} = 1.11 \) kN. For the curved column, it can be equivalent to a vertical column of the same height to calculate the compression energy absorption. The MCF, for the energy absorbed by the plastic bending moment, is given by \( P_{m2} M_p \)

\[ P_{m2} = \frac{30M_p (\pi - \alpha)}{H - 16t} \] (19)

with

\[ M_p = \frac{\sigma_0 T t^2}{4} \] (20)

With \( M_p = 0.50752 \) N \cdot m

\[ P_{m2} = \frac{30M_p (\pi - \alpha)}{H - 16t} = 0.305 (\pi - \alpha) \] (21)

The MCF, for the energy absorbed by the flattening is given by \( P_{m3} \)

\[ P_{m3} = \frac{50}{H - 16t} \int_0^{t/2} 2\sigma_0 T d\tau = \frac{12.5\alpha \sigma_0 T t^2}{H - 16t} = 0.508\alpha \] (22)

The MCF is given by

\[ P_m = 1.11 + 0.508\alpha \] (23)

for lattices with none or small central angle, where the bending energy is not included as the fracture of the struts is brittle, and

\[ P_m = 1.11 + 0.508\alpha + 0.305(\pi - \alpha) \] (24)

for BILMs with great central angle, where the bending energy is included. In this research, the critical central angle is 45°, as shown in Figure 3.

The predictions are consistent with the experiments. The gray area indicates the contribution from the flattening of the curved wall, while the blue area indicates the contribution from the bending of the curved wall.

6 Conclusions

In order to reduce the IPF of lattice structures but increase the CFE and the SEA, a new type of auxetic BILM was designed, printed, tested and analyzed. According to the experiments, the crushing pattern and the EA performance of the BILMs made of buckled walls with different central angles were revealed.
The buckling inspired meta-topology endows the BILM negative Poisson’s ratio, obviously decreases the flexural strain and resists the brittle fracture of the struts. The meta-topology induces strut contacts and results in plastic deformation mechanisms.

The auxetic BILM has three typical crushing patterns, including layer-by-layer fracture pattern of BILMs with central angle of 0° and 30°, hybrid crushing pattern of BILM with central angle of 45°, and stable plastic crushing pattern of BILMs with central angle of 60°, 90° and 120°. The first pattern is brittle and has bad EA. The last pattern is ductile and has excellent EA performance. Structural evolution from curved-walled square lattice to curved-walled triangular lattice and Poisson’s ratio transformation from negative to positive greatly improve the EA of the BILM.

The buckling inspired meta-topology can change the brittle crushing to aductile crushing. With the increase of the central angle, the overall ductility of the BILM increases continuously with fewer fracture points produced during the crushing. Flattening mechanism of curved walls greatly increase the EA of the BILM.

With the increase of the central angle, the IPF and the ECD of the BILM continues to decrease, while the CFE continues to rise. In terms of the MCF, the EA and the SEA, they are basically on the rise. When the central angle is 120°, the BILM has the best performances in MCF and EA. When the central angle is 60°, the BILM has the best performance in SEA.

Through the research, it is concluded that introducing buckling meta-topology into ordinary lattice structures can obviously improve the EA performance through reducing the IPA but increasing the EA, the SEA and the CFE. Buckling meta-topology is an efficient way to construct absorbers with excellent EA.

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