Title:
Research on the Design Method of Multi-material Heterogeneous Lattice Energy-absorbing Structures

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Introduction:
Due to the modern manufacturing industry's rapid development, 3D printing technology is widely used in a variety of fields, including the biomedical, aerospace, and construction industries [6]. However, the demands for multifunctional and multi-layered structures are now too great for the current traditional single-material 3D printing technology, and multi-material 3D printing technology can achieve integrated molding of heterogeneous structures as well as parallel design and manufacturing of part structure and function [7]. By contrasting multi-material structures with single-material designs, the superior benefits of multi-material structures in terms of performance and design freedom have been confirmed [4,5].

When compared to conventional single-material uniform lattice sandwich constructions, single-material gradient sandwich architectures perform better [1,2]. The choice of materials still limits single-material gradient sandwich structures despite their greater flexibility than single-material uniform lattice sandwich structures. This work addresses this difficulty by presenting a novel structure that is intended to satisfy intricate performance requirements. To address the shortcomings of the existing technology and advance multi-material 3D printing to meet a wider range of needs, we are introducing the integrated design of multi-material, gradient, and multi-type lattices.

Main Sections:
Design of a multi-material, heterogeneous sandwich structure that absorbs energy

There are many porous structures in nature. Two examples are grapefruit peels and turtle shells, which feature amazing multilayered gradient systems that serve a number of purposes in addition to providing supporting qualities. For instance, the hierarchical structure of a turtle shell, as illustrated in Fig. 1, is composed of cuticle, hard outer dense bone, soft fibrous closed-cell foam that is arranged randomly, and hard inner dense bone that runs from top to bottom. It is important to note that the fibrous closed-cell foam exhibits a gradient structure with a gradual thinning, making it possible to defend the body's interior tissues from external impacts more effectively. The gradient distribution of grapefruit skin, which is composed of three parts: exocarp, mesocarp, and endocarp, is likewise comparable. These gradient patterns in nature with several materials offer important insights. Similar multi-material gradient structures are used in the fabrication of helmets and other items in the current industries. Helmets, for instance, usually have three layers of material: an EPS inner shell, an ABS outer

shell, and a skin-friendly mesh. This work proposes a novel multi-material heterogeneous energy-absorbing sandwich construction that is inspired by these multi-material gradient structures.

More specifically, as Fig. 1 illustrates, we created a multi-material heterogeneous energy-absorbing structure. The initial layer of material in its composition is PLA, and the second, third, and fourth layers are made of TPU. The third layer's lattice core, which is made up of lattice1 with a gradient of rod sizes ranging from large to small, is of special interest. Fig. 2 displays the cellular unit of the lattice 1 and lattice 2. Consequently, this construction has a good energy absorption effect, a stiff exterior, and a flexible inside. It also offers a novel concept for the creation of a multi-material heterogeneous energy-absorbing sandwich structure.
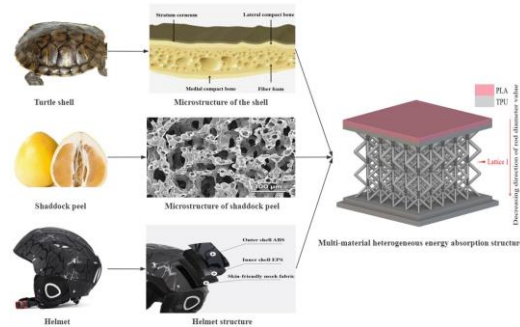
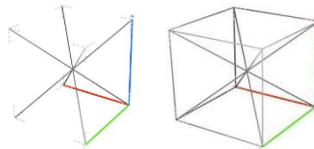Fig. 1: Design process of multi-material heterogeneous energy-absorbing sandwich structure.

Fig. 2: (a) Lattice 1 cell unit, (b) Lattice 2 cell unit.

How display dynamics affect the setup of a finite element model

The kinetic impact finite element model and the dynamic impact process are solved in this study using the ANSYS Workbench software. As demonstrated in Fig. 3, the simulation model of the impact established in this study, the energy-absorbing structure is subjected to a punch impact, kinetic impact collision and fall analysis, and glass is used as a protected part to analyze the equivalent force on the protected part as well as the specific energy absorption of the energy-absorbing structure.
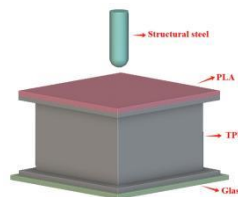
Fig. 3: Impact simulation model.

The dynamic impact test is conducted using bound contact as the contact mode and 22℃ as the impact simulation's ambient temperature. The punch's form and shape are used in the impact energy absorption test. According to Fig. 3, impact energy absorption studies utilizing a punch with a height

of 20 mm and a radius of 4 mm are defined as a projectile. At this point, the equivalent force transmitted to the protected components should not exceed 60 MPa. The projectile model in the energy-absorbing structure above 10 mm is only permitted to move in the impact direction at an initial speed of 15 m/s. This allows the projectile mass to be weighted at 6 kg by utilizing the increased equivalent density. Simulation affects experiment material parameter settings, as Table 1 illustrates.

Materials	Density	Young's Modulus	Poisson's Ratio
PLA	1260kg/m³	1820MPa	0.33
TPU	1200kg/m³	26MPa	0.33
Projectile Rigid Material	5.27×10⁶kg/m³	200GPa	0.3
Glass	2500kg/m³	80GPa	0.3

Tab. 1: Parameter settings of materials for simulated impact experiments.

We set up a total of 7 simulation experimental structures in this research because we need to investigate the impacts of material type, lattice type, and rod diameter gradient on energy absorption, respectively. As seen in Fig. 4, seven simulation experimental structure finite element models, referred to as S1–S7, are produced by importing the geometric model of the experimental structure into ANSYS Workbench software for pre-processing. The simulation impact experimental framework is configured as Table 2 illustrates. Among them, S5 is borrowed from Cheng Shuliang [3] et al. who used the drop hammer impact test to study the local impact dynamic characteristics of X-type dot-matrix sandwich structure and analyzed the effect of different parameters on its impact performance. The results show that the dot matrix sandwich structure composed of a single aluminum alloy material absorbs energy well.
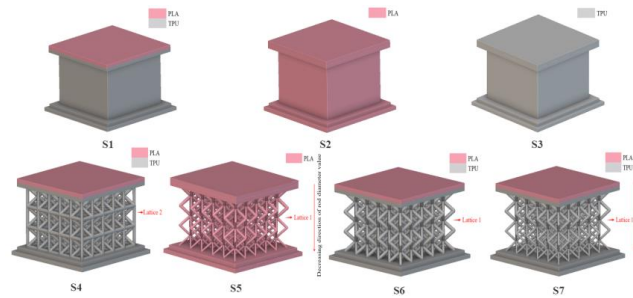

Fig. 4: Simulated experimental structure finite element model.

Name of structure \ Structural parameters	Material type	Lattice type	Gradient of rod diameter
S1	PLA+TPU	No	No
S2	PLA	No	No
S3	TPU	No	No
S4	PLA+TPU	Lattice 2	No
S5	PLA	Lattice 1	Rod diameter decreases from top to bottom
S6	PLA+TPU	Lattice 1	No
S7	PLA+TPU	Lattice 1	Rod diameter decreases from top to bottom

Tab. 2: Structure of the simulated impact experiment.

Simulation of impact experiment results analysis
The mass-specific energy absorption of the seven groups of structures and the stress on the protected portions are taken as the assessment indexes in order to study and evaluate the energy-absorbing impact of the structures, as demonstrated in Fig. 5, shown in Table 3 S1-S7 group of structural simulation results data.
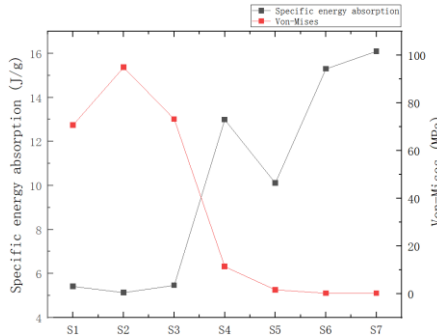

Fig. 5: Comparison of the absorbed energy and stress on the protected parts in the simulated impact experiments of group S1-S7 structures.

Name of structure	Specific energy absorption/$J \cdot g^{-1}$	Von-Mises on the protected object/MPa
S1	5.41	70.76
S2	5.13	94.92
S3	5.46	73.21
S4	12.99	11.34
S5	10.11	1.6
S6	15.3	0.19
S7	16.1	0.16

Tab. 3: S1-S7 group structure simulation result data.

Comparing and analyzing the results of simulation compression experiments in Fig. 6 and Table 3, the following conclusions can be drawn:

(1) We thoroughly compared S1, S2, and S3 in the first set of comparative experiments. With a specific absorption energy of 5.41 $J \cdot g^{-1}$, S1 produced an equivalent force of 70.76 MPa on the protected parts; S2 produced an equivalent force of 94.92 MPa with a specific absorption energy of 5.13 $J \cdot g^{-1}$; and S3 produced an equivalent force of 73.21 MPa with a specific absorption energy of 5.46 $J \cdot g^{-1}$ on the protected parts. It is clear that S1 absorbs energy more efficiently than S2, and even though S1 and S3 have nearly identical specific absorption energies, S1's protected areas are under less stress than S3's.

(2) In the second set of comparative experiments, we analyzed S1, S4 and S6: the specific absorption energy of S1 was 5.41 $J \cdot g^{-1}$, resulting in an equivalent force of 70.76 MPa on the protected part; the specific absorption energy of S4 was 12.99 $J \cdot g^{-1}$, resulting in an equivalent force of 11.34 MPa; and the specific absorption energy of S6 was 15.3 $J \cdot g^{-1}$, resulting in an equivalent force of only 0.19 MPa. It is evident that S4 and S6 have the same specific absorption energy as S1, and that S6 has a greater energy absorption impact than S4.

(3) We conducted a thorough comparison between S5, S6 and S7 in the third set of comparative studies. S5 has a specific absorption energy of 10.11 $J \cdot g^{-1}$, and the protected part's equivalent stress is

1.6 MPa. S6 has a specific absorption energy of 15.3 J·g^{-1}, and the protected part's equivalent stress is 0.19 MPa. S7 has a specific absorption energy of 16.1 J·g^{-1}, which means that the shielded component would experience an equivalent stress of 0.16 MPa. S7's energy absorption effect is generally noticeably superior to S5's and S6's.

When considering all of the materials combined, the multi-material solid structure performs better in terms of energy absorption than the single-material solid structure. Further observation suggests that the multi-material uniform lattice sandwich construction is superior than the multi-material solid structure in energy absorption. In the meantime, the multi-material gradient lattice structure performs better in terms of energy absorption than the multi-material uniform lattice sandwich construction.

Conclusions:
In this work, we have effectively created a novel, multi-material, heterogeneous sandwich construction that absorbs energy, modeled after structures like turtle shells. Multiple materials and gradient variations are used in the building. The printing procedure of the multi-material heterogeneous energy-absorbing sandwich structure is more complex than that of the already existing energy-absorbing structures because it necessitates varying the rod diameter gradient and selecting a dot matrix type. Consequently, more research is required to determine the best choice of dot matrix units and to enhance the process of printing multi-material heterogeneous energy-absorbing sandwich structures.

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