Low-velocity impact response of 3D-printed lattice sandwich panels

Sheng Wang¹, Yingjie Xu¹,²,* and Weihong Zhang¹,*

¹State IJR Center of Aerospace Design and Additive Manufacturing, Northwestern Polytechnical University, Xi’an, Shaanxi 710072, China
²Shaanxi Engineering Laboratory of Aerospace Structure Design and Application, Northwestern Polytechnical University, Xi’an, Shaanxi 710072, China

*Corresponding author (Yingjie Xu): xu.yingjie@nwpu.edu.cn
*Corresponding author (Weihong Zhang): zhangwh@nwpu.edu.cn

Abstract. This paper investigates the low velocity response of sandwich panels with four different lattice cores by conducting drop-weight impact tests. Sandwich panels are made of galvanized sheet and 3D-printed lattice cores in this study. Four different types of lattice, including body-centered cubic (BCC), z-reinforced body-centered-cubic (BCCz), gyroid lattice and Schwarz P lattice, are selected for the cores of sandwich panels respectively. Functional graded versions of these lattices are also examined, which features a density gradient along impact direction. Low-velocity impact response of a solid sandwich panel with the same quality is tested as a comparison. Experimental results show that lattice sandwich panels absorb more energy compared with solid sandwich panels. In addition, the graded lattice cores can further improve the energy absorption capacity of sandwich panels.

1. Introduction

Sandwich structures are widely used in aerospace applications such as fuselage, wing and other components. Compared with traditional foam and honeycomb sandwich structures, lattice sandwich structures have obvious advantages in light weight and multi-function [1-6]. In the past decades, the characterization and design of macroscopic mechanical behavior of lattice structures have been extensively studied experimentally, and theoretically. For example, macroscopic failures of octet-truss and Kagome truss (stretching-dominated truss) structures have been investigated by Deshpande et al. [7]. Luxner et al. [8] uses the finite element method to determine the elastic properties and the anisotropy level of four different lattice configurations, using beam elements for the core structure model and solid elements for the periodic unit-cell model. A heuristic optimization method is presented by Jason et al. [9] for efficiently synthesizing large mesoscale lattice structure on complex shaped parts that reduces the multivariate optimization problem to a problem of only two variables. A detailed review of the mechanical characterization and design of lattice structures can be found in [10].

With the development of Additive manufacturing technology, the geometric freedom of the lattice structures is greatly improved. A large amount of research on lattice structures manufactured by 3D printing technology has been carried out. Labeas et al. [11] studies the stress-strain relationship and failure mechanism of 3D printed body-centered cubic (BCC) lattice structure and its unidirectional...
reinforcement structure (BCCz lattice structure and F2FCC lattice structure) under quasi-static compression load. The influences of length-diameter ratio of internal rods and element size on the mechanical performance of lattice structure are investigated as well. Maskery et al. [12] investigates lattices based on triply periodic minimal surfaces produced by polymer additive manufacturing with a combination of experimental and computational methods. Smith et al. [13] establishes the finite element analysis model of selective laser melting built BCC lattice structure under compressive load. It is pointed out that the beam element model can analyse the structure with large number elements. This study focuses on the study of low velocity impact response of lattice sandwich panels manufactured by stereo lithography apparatus (SLA). It has been found that lattice structures are suited for absorbing energy due to a low density, cellular structure that deforms readily under load [14]. Various lattice structures are designed and manufactured. The drop-weight test is then conducted to test the impact responses of sandwich panels with different lattice cores.

2. Experiment

2.1. Specimen

The lattice cores of sandwich panels are designed with dimensions 150×100×17 mm³. The lattice cells are 5×5×5 mm³, which means the cores contains a 30×20×3 arrangement of cells. The solid plate at the bottom and top of the core is designed to be a better connection to the face sheets. For the uniform density lattice cores, all three layers are assigned relative densities of 0.19. For the graded density cores, each layer assigns a different relative density (0.09 for the top, 0.19 for the medium and 0.29 for the base). The average of these densities is 0.19, allowing the graded cores to have the same mass as the uniform cores. As for solid sandwich panel, the dimensions of the core are 150×100×4.14 mm³, in order to be compared with lattice sandwich panels on an equal mass basis. The details of the cores can be seen in figure 1. All the cores are manufactured by SLA on a SPS 350B machine from DSM Somos 14120. After solidification, they are post-cured in an ultraviolet oven for 15 mins. The SLA processing parameters suggested by experimental experts are adopted and are listed in table 1.

![Figure 1. CAD models of cores for sandwich panels: lattice core (a) and solid core (b).](image)

The sandwich panels are fabricated by bonding the 3D printed cores to the galvanized sheets of 1mm thickness on the top and bottom with Ergo 1309 adhesive, a methyl methacrylate structural adhesive. All the manufactured samples can be seen in figure 2.
2.2. Experimental setup and design
The drop weight impact test of the sandwich panels is carried out using an Instron Ceast 9340 drop tower Impact System according to ASTM D7136. The diameter of the hemispherical impactor is 20 mm. The total mass of the impactor carrier is 3.23kg. All the specimens are tested at a drop height of 315 mm, which makes a total impact energy of 10 J. The impact energy corresponds to impactor velocity of 2.487 m/s respectively. Sample measurements during all impact tests are obtained from a force transducer mounted on the impactor, each sampled at a rate of 1000 kHz. When the impact test is completed, the specimen is cut along the midpoint of the long side of the specimen with a numerical control machine tool, in order to observe the internal damage better.

Table 1. SLA parameters used in the production of the cores.

| SLA processing parameters          |          |
|-----------------------------------|----------|
| Laser power                       | 210 mW   |
| Laser scanning speed              | 8 m/s    |
| Operating environment temperature | 32 °C    |
| Printing accuracy                 | 0.1 mm   |
| Processing layer thickness        | 0.05 mm  |

Figure 2. Manufactured solid sandwich panel and lattice sandwich panels.

2.3. Data processing and analysis
A typical example of the force data from the data acquisition system (DAS) of Instron Ceast 9340 is shown in figure 3. The impact region considered in this study is from point A to Point C. Point A corresponds to the impact start point, which is the moment when the impactor contacts the specimen. Point B is the maximum force acting on the structure during the test. After point B, the force between the impactor and the specimen starts to decrease. Point C is the ending of this impact test, which occurs at completely separation between impactor and specimen. The duration of the impact is around 0.00439 s in this particular example.
To find energy absorption, the force-time curve is converted to an energy-time curve by the supporting software of the Instron Ceast 9340 according to the following steps.

![Figure 3. An example force-time curve obtained from DAS.](image)

![Figure 4. Absorbed energy calculated by the supporting software.](image)

The first step calculates the initial velocity ($V_0$) of the impactor at point A by equation (1) assuming a free-fall condition.

$$V_0 = \sqrt{2gh}$$  (1)
The initial velocity is 2.487 m/s given the height of 315 mm and \( g = 9.81 \text{ m/s}^2 \). Second, the velocity up to point \( i \) (point number obtained by DAS) can be calculated according to the formula:

\[
V_i = V_{i-1} - t_{\text{sampling}} \frac{F_i + F_{i-1} - gM_{\text{total}}}{2M_{\text{total}}}
\]

(2)

\[
t_{\text{sampling}} = t_i - t_{i-1}
\]

(3)

Where \( t_{\text{sampling}} \) is the sampling time of DAS, \( F \) is the impact force and \( M_{\text{total}} \) is the total impact mass. The third step analyses the displacement (specimen deformation) \( \epsilon \) up to point \( i \) using equation (4).

\[
\epsilon_i = \sum_{i=0}^{i-1} \epsilon_i + t_{\text{sampling}} \frac{V_i + V_{i-1}}{2}
\]

(4)

Lastly the absorbed energy \( E \) can be calculated as:

\[
E_i = \sum_{i=0}^{i-1} E_i + t_{\text{sampling}} \frac{F_iV_i + F_{i-1}V_{i-1}}{2}
\]

(5)

The absorbed energy-time curve of figure 3 is shown in figure 4. Point D is the maximum displacement, where the whole impact energy is transferred to the specimen. After point D, the impactor starts to rebound, and part of the energy is retransferred to the impactor. The absorbed energy decreases until point C, which is the moment when the impactor leaves specimen. The energy value shown at point C is the energy absorbed by the specimen during the impact process.

For each drop test, the impact properties, including maximum force, maximum displacement, and energy absorption can be extracted from the supporting software.

3. Results and discussion

Results obtained from the impact test by DAS are shown in figure 5 and figure 6, which represent, respectively, the data collected for uniform lattice sandwich panels and graded lattice sandwich panels compared with solid sandwich panel.

![Figure 5.](image)
The force-time curve of solid sandwich has more obvious fluctuations, meaning that the vibration during impact test is relatively large. At about 0.0003s, the force value has a sudden drop, because the inner solid core is obviously damaged and the structural stiffness decreases.

Analyzing the force-time curves of uniform lattice sandwich panels in figure 5, it conveys that the load histories are quite similar for different lattice cores. Compared with solid sandwich panel, it takes a little longer for the lattice sandwich panels to reach the maximum impact force, which indicates that the lattice sandwich panels have a better cushioning effect on the impactor.

![Figure 6. The impact load histories of graded lattice sandwich panels compared with solid sandwich panel.](image)

As for graded lattice sandwich panels presented in figure 6, there are obvious difference among different cores. For the same lattice cell, the cushioning capacity of graded structure is better than that of uniform structure. BCC and BCCz have the most obvious improvements, followed by gyroid, and schwarz P is the worst.

The comparison between the solid sandwich panel and lattice sandwich panels in terms of maximum force, maximum displacement and absorbed energy is shown in table 2.

|                  | Max force (N) | Max displacement (mm) | Absorbed energy (J) |
|------------------|--------------|----------------------|---------------------|
| Solid            | 6012.371     | 2.990                | 5.209               |
| BCC              | 4746.609     | 3.800                | 6.229               |
| Graded BCC       | 3802.938     | 4.590                | 6.323               |
| BCCz             | 4650.547     | 3.905                | 6.734               |
| Graded BCCz      | 4125.029     | 4.061                | 6.962               |
| Gyroid           | 4902.004     | 3.950                | 5.830               |
| Graded BCCz      | 4286.075     | 4.368                | 6.746               |
| Schwarz P        | 4899.178     | 3.613                | 6.535               |
| Graded schwarz P | 4639.245     | 3.668                | 6.883               |
Comparing the maximum force recorded from the instrumentation during the impact for both solid sandwich panel and lattice sandwich panels, it is obvious that the values for maximum force are shifted to lower values for lattice sandwich panels, especially for graded lattice sandwich panels. This result suggests that lattice sandwich panels have a significant damping effect, which can greatly reduce the impact force. The maximum force of graded BCC sandwich panel decreases the most, 36% less than that of solid sandwich panel.

The maximum displacement of the impactor for lattice sandwich panels have a large increase compared to solid sandwich panel. The reason for this phenomenon is that lattice structures have a much higher structural deflection than the solid structure. For the same lattice cell, graded lattice sandwich panels have higher maximum displacement than uniform lattice sandwich panels, particularly for BCC and gyroid.

Regarding the absorbed energy, the phenomenon presented is somewhat similar to the maximum displacement. Graded lattice sandwich panels have the strongest ability to absorb impact energy, followed by uniform sandwich panels, and the ability of solid sandwich panel is the worst. Graded BCCz sandwich panel absorbs the most energy, 34% more than solid sandwich panel.

![Visual inspection of impacted samples](image)

Figure 7. Visual inspection of impacted samples: solid sandwich panel (a), uniform BCC sandwich panel (b) and graded BCC sandwich panel (c).

For the explanation of lattice sandwich panels having better energy absorption ability, the cross-section of impacted BCC lattice sandwich panels compared to solid sandwich panel are presented as a typical example in figure 7. As can be seen from figure 7a, the weak energy absorption ability of solid plate is due to the small deformation provided by the solid core. And it can be seen that the whole solid core printed by polymer has been damaged to varying degrees. For uniform BCC lattice sandwich panel, the deformation area caused by impact is larger. The failure and fracture of the struts further improve the energy absorption capacity. The graded BCC sandwich panel has the best energy absorption ability because it not only enlarges the deformation area further, but also increases the damage thickness in the direction of impact. The Other lattice sandwich panels are basically similar.
4. Conclusion
This paper presents the impact properties of lattice sandwich panels compared with solid sandwich panel at a low impact velocity of 2.487 m/s. Four different lattice cells are selected to form the cores of sandwich panels by the means of 3D printing. The experimental results show that lattice sandwich panels have a good improvement of energy absorption than solid sandwich panel. Under impact loading, lattice structures can produce greater deformation to absorb more energy. This study shows that good design of lattice sandwich panels can greatly improve energy absorption capacity, which has great benefits in applications requiring high impact energy absorption. For example, in personal protective equipment, the maximum deceleration of the human body must be minimized in order to prevent injury.

Acknowledgments
This work is supported by National Key Research and Development Program of China (2017YFB1102800), National Natural Science Foundation of China (11872310, 5171101743) and Key Research and Development Program of Shaanxi Province (2017KJXX-31).

References
[1] Gibson L J and Ashby M F 1999 Cellular solids: structure and properties (Cambridge university press)
[2] Evans A G, Hutchinson J W, Fleck N A, Ashby M F and Wadley H N G 2001 The topological design of multifunctional cellular metals Prog. Mater. Sci 46 309-27
[3] Xue Z and Hutchinson J W 2004 A comparative study of impulse-resistant metal sandwich plates Int. J. Impact Eng 30 1283-305
[4] Kim T, Hodson H P and Lu T J 2004 Fluid-flow and endwall heat-transfer characteristics of an ultralight lattice-frame material Int. J. Heat. Mass. Tran 47 1129-40
[5] Wang J, Lu T J, Woodhouse J, Langley R S, and Evans J 2005 Sound transmission through lightweight double-leaf partitions: theoretical modelling J. Sound. Vib 286 817-47
[6] Liu T, Deng Z C and Lu T J 2007 Bi-functional optimization of actively cooled, pressurized hollow sandwich cylinders with prismatic cores J. Mech. Phys. Solids 55 2565-602
[7] Deshpande V S, Fleck N A and Ashby M F 2001 Effective properties of the octet-truss lattice material J. Mech. Phys. Solids 49 1747-69
[8] Luxner M H, Stampfl J and Pettermann H E 2005 Finite element modeling concepts and linear analyses of 3D regular open cell structures J. Mater. Sci 40 5859-66
[9] Nguyen J, Park S I and Rosen D 2013 Heuristic optimization method for cellular structure design of light weight components Int. J. Precis. Eng. Man 14 1071-8
[10] Mahmoud D and Elbestawi M 2017 Lattice structures and functionally graded materials applications in additive manufacturing of orthopedic implants: a review J. Manuf. Mater. Process 1 13
[11] Labeas G N and Sunaric M M 2010 Investigation on the static response and failure process of metallic open lattice cellular structures Strain 46 195-204
[12] Maskery I, Sturm L, Aremu A O, Panesar A, Williams C B, Tuck C J, Wildman R D, Ashcroft I A and Hague R J 2018 Insights into the mechanical properties of several triply periodic minimal surface lattice structures made by polymer additive manufacturing Polymer 152 62-71
[13] Smith M, Guan Z and Cantwell W J 2013 Finite element modelling of the compressive response of lattice structures manufactured using the selective laser melting technique Int. J. Mech. Sci 67 28-41
[14] Tancogne-Dejean T, Spierings A B and Mohr D 2016 Additively-manufactured metallic micro-lattice materials for high specific energy absorption under static and dynamic loading Acta. Mater 116 14-28