MECHANICAL PROPERTIES OF 3D PRINTED MIURA-ORI MECHANICAL METAMATERIALS

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ABSTRACT

In this research, kinds of gradient metacomposite structures are developed to achieve greater energy absorption than conventional non-gradient structures. By using the proposed gradient design pattern, larger stress plateau segments of the structure as well as continuous multiple negative-stiffness properties can be easily achieved. Various gradient structures are designed to evaluate their mechanical properties. The failure modes of the gradient structures are analysed with both theoretical and numerical investigations. Due to the introduction of gradients, the structures have higher stiffness and achieve larger average collision forces. Numerical and experimental validations are conducted. The structures are potentially applicable in energy absorption as well as energy mitigation devices.

1 INTRODUCTION

Energy dissipation in conventional materials and structures is often carried out through large deformations of the structure, and Miura-Ori origami structures have the general characteristics of energy absorbing structures [1]. However, at the same time, Miura-Ori is very different from conventional structural analysis in that it is able to withstand strong dynamic loads, and its deformation process involves large deformations, strain reinforcement effects, strain rate effects, and interactions between different deformation modes. Compared with conventional structures, Miura-Ori origami structures are not only lightweight and highly energy absorbing, but also can be accompanied by extraordinary mechanical phenomena such as negative Poisson's ratio [2,3] and negative stiffness [4-6], etc. The unconventional mechanical properties of Miura-Ori structures have gained much attention. However, it has been shown that the specific energy (SEA) absorption efficiency of gradient structures can be substantially improved compared to that of homogeneous structures. Although many researchers have investigated the origami structure extensively and have shown that Miura-Ori has good energy absorption [7-11]. However, little research on the energy absorption performance of gradient Miura-Ori metamaterials has been reported.

This work is based on a stacked origami structure with a gradient design to achieve greater energy absorption than conventional non-gradient structures. The proposed gradient metacomposite structures are developed to achieve greater energy absorption than conventional non-gradient structures. By using the proposed gradient design pattern, the stress plateaus of the structure can be easily realized, and continuous multiple negative-stiffness properties can be achieved. Various gradient structures are designed to evaluate their mechanical properties. The failure modes of the gradient structures are analysed using both theoretical and numerical investigations. Due to the introduction of gradients, the structures have higher stiffness and achieve larger average collision forces. Numerical and experimental validation has been conducted. The structures are potentially applicable in energy absorption as well as energy mitigation devices.

2 DESIGN AND RESULTS

2.1 Miura-Ori composite metastructure

The Miura-Ori structure is shown in Fig. 1. In Fig. 1(a), the folds of the structure in the initial paper state are shown, where the solid line indicates the mountain line and the dashed line indicates the valley line. It consists of multiple periodic unit cells, and the smallest unit that makes up the structure (see Fig.

1(b)) contains four identical parallelograms. The geometric configuration of the cell is defined in terms of two static fold lengths a, b and a static interior angle α. Its folding state is quantified by using the dihedral angle θ between the quadrilateral plane and the xy plane. The cell geometric configuration can be determined by the following equation

$$h = b\,sin\ \alpha\ \ sin\ \theta \tag{1}$$

$$L_x = a\frac{\tan\alpha\cos\theta}{\sqrt{1+\tan^2\alpha\cos^2\theta}} \tag{2}$$

$$L_y = b\sqrt{1-\sin^2\alpha\sin^2\theta} \tag{3}$$

$$L_s = \frac{a}{\sqrt{1+\tan^2\alpha\cos^2\theta}} \tag{4}$$

where h is the height of the structure along the z-direction, $2L_x$ is the length of the structure along the x-direction, and $2L_y+L_s$ is the length of the structure along the y-direction. The cells are arranged in eight pieces along the y-direction to splice into the Miura shell structure (see Fig. 1(c)).

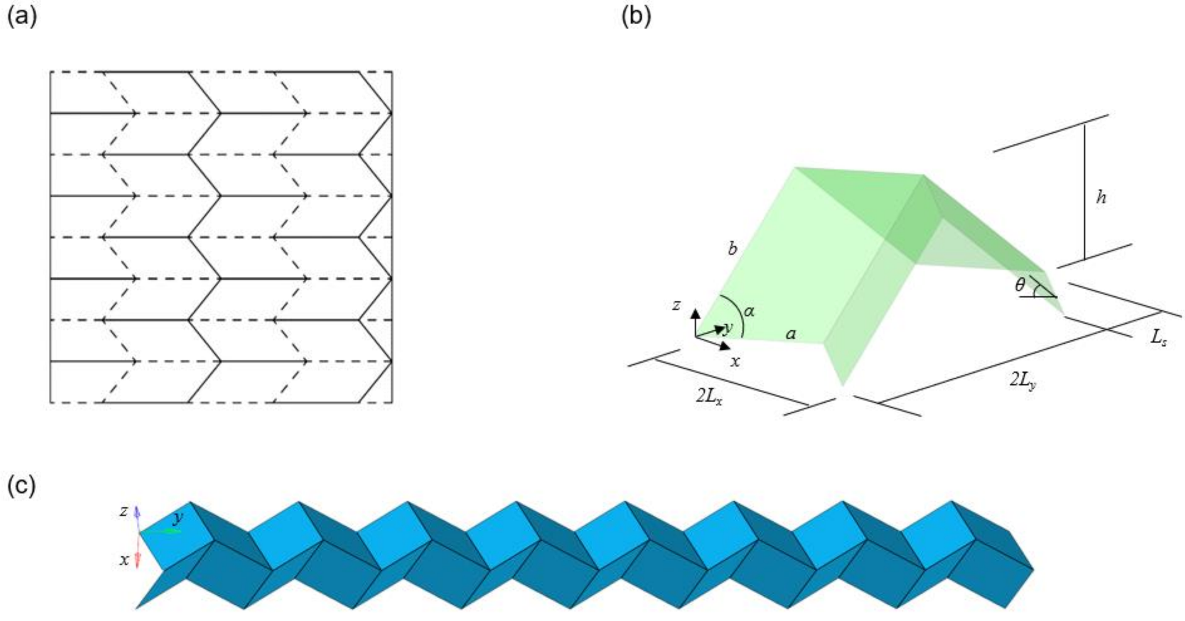

Figure 1: Schematic of the (a) Miura crease, (b) Miura-Ori unit cell, (c) single layer metastructure.

2.2 Gradient design

Considering the geometric configuration of the basic unit of Miura origami, it is found that the coupling of the cell expansion in both x and y directions depends only on the angle between the edge length a and the y axis. Therefore, Miura structures with different heights h can be stacked together and glued along the folding line. The stacked triplet structures are obtained by rotating one layer of triplet structures and gluing them along the fold line (as in Fig. 2(a)). Now the gradient design is introduced and the height h of the cytosol is changed, then the obtained gradientized origami stacked structure is shown in Fig. 2(b).

In order to investigate the effect of different gradient patterns of height h on the mechanical properties of Miura-Ori metamaterials, four different gradient metamaterials with height h are set up in this paper, and the relative density of these four gradient metamaterials remains basically the same as that of the homogeneous metamaterials. The normalized height $h/(2L_y)$ of the origami metastructures with four different height h gradients are shown in Fig. 3(a). As the structure transitions from Model-0 to Model-3, it can be seen that the gradient property of the structure becomes more and more obvious. From the fourth single cell in the y-direction, it can be seen that the height h of this single cell decreases gradually from Model-0 to Model-3.

The material properties used in this research are listed in Table 1.

Material	Aluminum
Density (kg/m^3)	2700
Young's modulus (GPa)	70
Poisson's ratio	0.3
Yield stress (MPa)	180

Table 1: Material properties used in the continuum model.

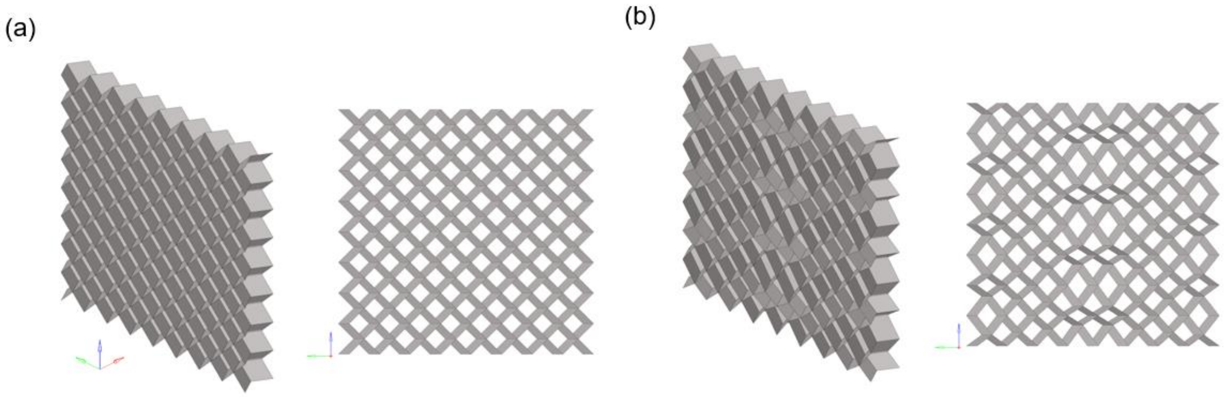

Figure 2: Origami structure (a) without gradient, (b) with gradient.

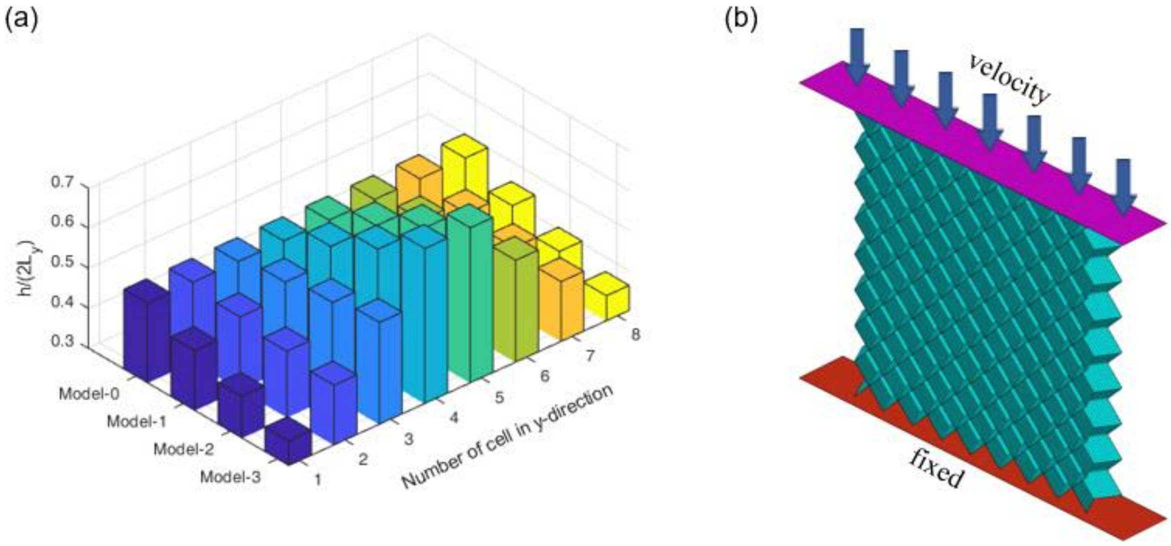

Figure 3: (a) Gradient change diagram, (b) FEM model and boundary condition settings.

2.3 Mechanical properties

Finite element simulations were simulated for the above four Miura-Ori metamaterials with different height gradients. The simulations were carried out by the LS-DYNA software. The boundary conditions of the FEM model are shown in Fig. 3(b), where the Miura-Ori metamaterial is placed between two rigid plates with the lower panel rigid body completely fixed, meaning that all its degrees of freedom are constrained. Meanwhile, the upper panel rigid body retains only the degree of freedom of translation in *z*-direction and the velocity of the upper panel is 1m/s.

The out-of-plane compression process of origami metastructure involves non-linear phenomena such as large deformation and buckling, while the process has a complex contact problem. In this case, there are problems that the general static solver solution is not easy to converge and the numerical simulation time is long, so this paper adopts dynamic analysis to simulate the static problem. The mechanical property curve of the compression process of the metastructure is shown in Fig. 4.

The process of deformation of the origami superstructure under load can be divided into the following three stages: as the initial action of the compression load, the structure deformation in the elastic stage; with further action of the load, the plastic depression deformation of the unit wall occurs and enters the plastic buckling stage; the final action of compression, the wall of the structure is compacted and produces contact, and the mutual force makes the load rise sharply, which is the densification stage.

The force-displacement curves show that the elastic stage of the gradientized origami structure is almost the same, but it is able to have higher load-bearing performance in the platform stage. Meanwhile, the origami structure exhibits significant negative stiffness as well as multi-stability characteristics as the gradient increases in the plateau stage.

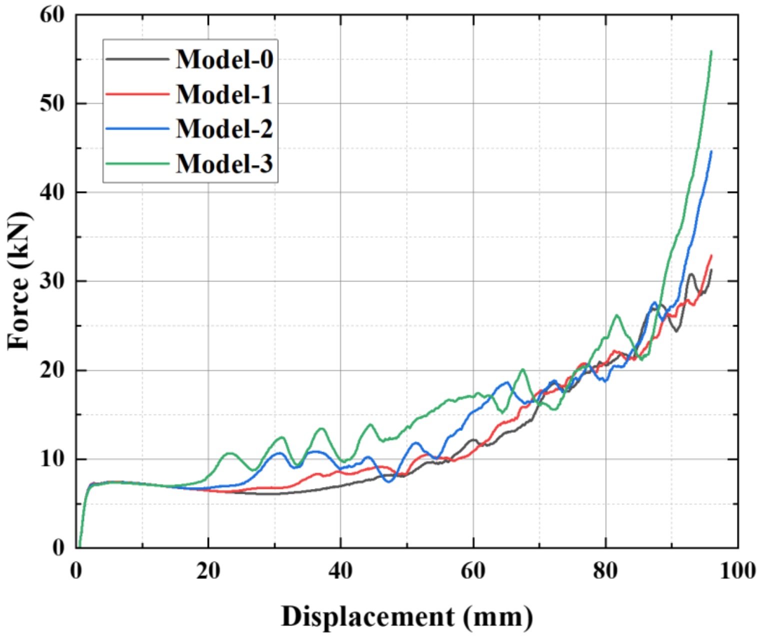

Figure 4: Force-displacement curves for metamaterials with different gradients.

2.4 Energy absorption properties

In order to investigate the effect of gradient patterns on the mechanical properties of Miura-Ori metamaterials, the specific energy absorption (SEA) and the mean collision force (MCF) are used to evaluate the energy absorption capacity of the structure. The specific energy absorption SEA is defined as the energy absorbed per unit mass, and the higher the specific energy absorption, the higher the energy absorption efficiency and the higher the material utilization, which is defined as

$$SEA = \frac{E}{m} \tag{5}$$

where E is the total absorbed energy; m is the total mass of the origami superstructure.

The mean collision force MCF represents the energy dissipated per unit compression of the overall model and is an overall response to the energy absorption performance of the structure. In general, a larger MCF value represents the higher energy dissipation capability of the structure:

$$MCF = \frac{E}{x} \tag{6}$$

where x denotes the real-time displacement of the structure.

Summaries of the SEA and MCF corresponding to the four gradient origami structures at the same compression displacement are shown in Fig. 5. The results clearly show that the gradientized origami structures possess higher SEA and MCF than the non-gradientized structures. Furthermore, the SEA and MCF increase as the gradient increases.

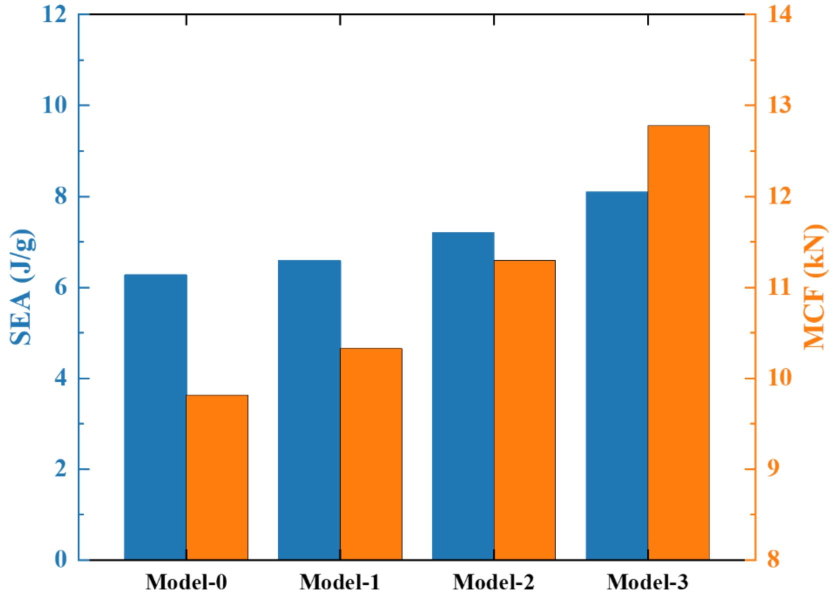

Figure 5: Comparison of SEA and MCF for different gradient metamaterials.

3 CONCLUSIONS

In this research, various origami metastructures with gradients are proposed. Through analytical studies, numerical simulations and experimental validation, the following conclusions can be drawn:

(1) Based on the proposed gradient superstructure, higher specific absorption energy and mean collision force are achieved than those of the non-gradient structure. And with the increase of the gradient effect, the higher the specific absorption energy and the mean collision force of the structure.

(2) Numerical validation was conducted by using the finite element model. The numerical results are in good agreement with the analytical results.

(3) Further experimental validation was performed for the metamaterial. The experimental results also show that the gradientized structure has better energy absorption performance.

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