LOW VELOCITY IMPACT OF A RECOVERABLE MULTISTABLE MECHANICAL METAMATERIAL WITH NEGATIVE STIFFNESS ELEMENTS

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Materials and structures absorbing shock energy are crucial for diverse engineering applications. Conventional materials or structures absorb energy through material destruction or viscoelastic effect, resulting in systems that can be used only once or strongly rate-dependent. Very recently, mechanical metamaterials have been designed in novel geometries to achieve recoverable energy absorption in elastic systems, opening new avenue for mechanical dissipation of energy. However, numerical modeling of impact response of this mechanical materials is really scarce. Here we build a finite element method (FEM) model of a mechanical metamaterial with negative stiffness elements to simulate the quasi-static and low velocity impact behavior. Quasi-static simulation results agree well with experimental results reported in literature, and low velocity impact results indicate this mechanical metamaterial with multistable negative stiffness elements is ideal for impact energy absorption. The methods and results are helpful for analyzing, designing, and manufacturing of mechanical metamaterials for energy absorption.

Keywords: low velocity impact, multistable, negative-stiffness, energy absorption

1. Introduction

Mechanical metamaterial is a cutting-edge frontier from both academic and engineering perspectives\(^1\). Mechanical metamaterials are man-made materials whose behaviors are dictated and regulated by deformation, motion, stress and strain, and vibration or wave \(^2-6\). Mechanical metamaterials have been explored to develop vibration isolators, impact protectors, seismic shielders, noise cancellations, morphing and deployable structures as well as soft robotics \(^7-13\).
In terms of impact protection, mechanical metamaterials can absorb energy by using their own large deformation, and the deformation is recoverable. Researchers have used the characteristic of the mechanical metamaterials to study and design a variety of reusable devices. Shan \cite{14} studied the multistable architected materials for trapping elastic strain energy, which is actually tilted beam that may snap between two different stable configurations, and the elastic strain energy can be absorbed or released during the transformation process between various steady-states. A kind of impact protection device was designed by this principle, and the effectiveness of protection was verified by experiments. Frenzel \cite{15} designed a lightweight impact energy absorber with recoverable deformation using the buckling instability characteristics of the pre-stressed beam under compressive load, and studied the energy absorption characteristics of the device. Correa \cite{16} experimentally studied the compression process of a honeycomb sandwich structure with negative stiffness elements, and mechanical instability phenomena were observed during the compression process because of buckling elements. In the literature, numerical simulation analysis was processed with Comsol software, however, there are large deviations between the experimental result and numerical result.

Although significant progress has been made in impact protection design, the research on the application of mechanical metamaterials in impact protection is in the beginning stage, and theoretical analysis, numerical simulation methods, experimental verification deserve further in-depth research. Based on the above research, especially following Correa's work, we research the static behavior of negative stiffness honeycomb sandwich structure by a commercial software, ABAQUS, the numerical simulation results are in good agreement with the experimental results \cite{16}. Based on the static analysis, the low-velocity impact process of negative stiffness honeycomb sandwich structure is simulated numerically, and the mechanism of impact protection is explained in the perspective of energy. The result shows that the negative stiffness honeycomb sandwich structure can be used to design shock-recoverable impact energy absorbing device.

2. Static behavior analysis

2.1 Finite element model

The honeycomb sandwich structure studied in this paper is shown in Fig. 1, which is composed of basic structural units arranged in a certain way. The square area with blue line in the center of Fig. 1 is the basic structural unit of the honeycomb sandwich structure. The main dimensions of the unit cell are exactly the same with the literature \cite{16}. The upper and lower parts of the honeycomb sandwich structure are set with 10 mm thick panels, which are named as the upper panel and the lower panel respectively. The out-of-plane thickness of the honeycomb sandwich structure is 12.7 mm.

![Figure 1: The honeycomb sandwich structure.](image)
The material of the honeycomb sandwich structure is nylon11. According to the experimental results\cite{16}, it can be approximated as a linear elastic material with the elastic modulus $E=1.582\text{GPa}$, Poisson's ratio $\mu=0.33$, and density $\rho=1040\text{kg/m}^3$. Two-dimensional model of the honeycomb sandwich structure shown in Fig. 1 is established, and the element type is reduced integral 4-node quadrilateral plane strain element CPE4R. In order to improve the accuracy of the calculation results, the sandwich structure is cut into regular regions, and each region is separately divided with quadrilateral mesh. Self-contact is set to model the contact between adjacent surfaces inside the honeycomb sandwich structure during the compression process.

The quasi-static compression deformation process of honeycomb sandwich structure is studied by explicit dynamics simulation. The boundary condition is as follows, the bottom surface of the lower panel is fixed, and under displacement-control, the top surface of the upper panel is applied with a uniform downward compression load by the smooth amplitude curve method. The analysis step duration is set as 1. In order to suppress the numerical oscillation during the calculation, a very small viscous surface load is uniformly applied to the outer surface of the honeycomb sandwich structure, which is $3\times10^{-7}\text{MPa}$. In the quasi-static compression analysis, the kinetic energy and internal energy of the system are always monitored. The percentage of kinetic energy of the structure is always below 1%, which meets the requirements of quasi-static analysis.

### 2.2 Results and discussion

The calculation result of the quasi-static compression process of the honeycomb sandwich structure is shown in Fig. 2. State A in Fig. 2(a) is the free state of the honeycomb sandwich structure without external load. State F is the final deformation state after compression. State B~State E are the intermediate states in the process of compression. The relationship between the compression load and the displacement is shown in Fig. 2(b), in which, the horizontal axis is the displacement and the vertical axis is the compression load. The solid line with black square mark in the Fig. 2(b) is the experimental result from the literature\cite{16}, the dotted line with red circle mark is the numerical calculation result from the literature\cite{16}, and the other solid line is the numerical result of this paper. There are six triangular marks on this solid line, which correspond to the State A~State F in Fig. 2(a).

It can be seen from Fig. 2(b) that the numerical results obtained by Abaqus in this paper are closer to the experimental results\cite{16} than the numerical results from the literature\cite{16}. During the compression process of the honeycomb sandwich structure, four peaks appear in the compression load curve, and there is a negative stiffness stage after the compression load crosses each peak, in which the compression load gradually decreases as the displacement increases. The compression process of the honeycomb structure exhibits negative stiffness characteristics, which is similar to the tilted beam in the literature\cite{14}.

The honeycomb sandwich structure can be regarded as consisting of four layers of tilted beams. Because of the slight differences among four layers of tilted beams, during the compression process, when the compressive load reaches critical value, the tilted beams in a certain layer always firstly enter the negative stiffness state because of buckling instability, and the displacement of the honeycomb sandwich structure rapidly increases while the compression load decreases because of the buckling deformation of the certain layer of tilted beams. The deformation state of the honeycomb sandwich structure will be readjusted in the process. When the deformation of this layer of tilted beams occurring buckling instability is large enough, the compression load will gradually increase as the deformation increase further. Next, another layer of tilted beams will enter negative stiffness stage because of buckling instability when the compressive load reaches critical value, and forming another peak in the force-displacement curve. This process is repeated until the whole four-layer tilted beams fulfill buckling deformation entirely. There are four layer of beams, and each layer of beams corresponds to a peak and a negative stiffness stage, therefore, there are four peaks and four negative stiffness stages on the force-displacement curve.
The finite element calculation results are not exactly the same as the experimental results. This may be related to the dispersion of the material performance parameters, perhaps the material properties of the honeycomb sandwich structure may change continuously during the compression process. In addition, the polymer materials used in the literature have a certain viscoelasticity, which is ignored in the calculation.

(a) Deformation process of the honeycomb sandwich structure under compression.

(b) Displacement-load curve of the honeycomb sandwich structure [16].

Figure 2: The deformation result of the honeycomb sandwich structure under compression.

3. Low-velocity impact behavior analysis

Based on the numerical simulation of the quasi-static compression process, the low-velocity impact dynamic response of the honeycomb structure is further studied, in which a cylindrical weight falls onto the upper panel of honeycomb sandwich structure. In order to illustrate the impact protection effect of the honeycomb sandwich structure by comparison, the same cylindrical weight will fall onto the solid panel with the equivalent thickness. The material properties, geometric width, and the mass of the solid panel are the same as the honeycomb sandwich structure, and the thickness of the solid panel is equivalent to 37.08 mm. The radius of the cylindrical weight is $R=30\text{mm}$, and material is made of steel with density $\rho=7800\text{kg/m}^3$. The element types of the cylindrical weight, solid panel and honeycomb sandwich structure are all the same, which is reduced integral 4-node quadrilateral plane strain element CPE4R. The dynamic process is simulated by Dynamic/Explicit method in Abaqus.
The cylindrical weight respectively impacts the honeycomb sandwich structure and the solid panel at the same velocity of 5 m/s. The acceleration response at the centre of the cylindrical weight during the impact is shown in Fig. 3, the red dotted line is the acceleration curve impacting solid panel, and the black solid line is the acceleration curve impacting honeycomb sandwich structure. It can be seen from Fig. 3 that the acceleration response of the cylindrical weight is up to about $3.5 \times 10^4$ m/s$^2$ when the cylindrical weight impacts the solid panel, while the acceleration response is only about $5 \times 10^3$ m/s$^2$ when the cylindrical weight impacts the honeycomb sandwich structure, the acceleration peak drops by about an order of magnitude. The comparative analysis shows that the honeycomb structure with negative stiffness unit has really good protection effect, more importantly, after impacting, the honeycomb structure will recover without damage, which means this kind of impact protection structure is recoverable and reusable.

In order to further reveal the low-velocity impact protection mechanism of the mechanical metamaterial sandwich structure, Fig. 4 shows the energy change of the whole system during the impact process. The honeycomb sandwich structure is shown in Fig. 4(a), in which the internal energy in honeycombs refers only to the multi-layer tilted beams in the sandwich structure, excluding the upper and lower panels. The solid panel is shown in Fig. 4(b).

It can be seen from Fig. 4 that during impact, the kinetic energy of the cylindrical weight gradually decreases, and the internal energy of the solid panel and the honeycomb sandwich structure gradually increases. As for the honeycomb sandwich structure, when being impacted, the multi-layer tilted beams
undergo large deformation, and most of the kinetic energy of the cylindrical weight is transformed into the internal energy of the honeycomb structure and stored, only a little part is transformed into the internal energy of the upper and lower panels. Therefore, after the cylindrical weight rebounds, the kinetic energy of the cylindrical weight is greatly reduced. For the solid panel, after the impact, the kinetic energy of the cylindrical weight is almost transformed into the internal energy of the solid panel, but when the cylindrical weight rebounds, the internal energy of the solid panel almost completely transformed into the kinetic energy of the cylindrical weight again with almost no energy stored. Therefore, the solid panel is almost invalid in impact protection, and the honeycomb sandwich structure is available to absorb impact energy.

The reason why the honeycomb sandwich structure can produce much smaller acceleration response may be as follows. When the cylindrical weight is in contact with the honeycomb sandwich structure, on the one hand, during the downward movement of the cylindrical weight, the honeycomb sandwich structure is compressed and deformed, and the kinetic energy of the cylindrical weight is gradually transformed into the internal energy, thereby effectively reducing the energy transformed into the upper panel by the collision. On the other hand, benefiting from the compression deformation of the honeycomb sandwich structure, the release of kinetic energy is a much slower process. When the cylindrical weight hits the solid panel, the transformation of the kinetic energy needs about $2.5 \times 10^{-4}$s, which is very short time. As for the honeycomb sandwich structure, it takes about $1.5 \times 10^{-2}$s, which is much longer, about 60 times of the former. This means the kinetic energy will be released in a longer period of time, thereby effectively alleviating the impact effect of the cylindrical weight on the upper panel.

4. Conclusion

Mechanical metamaterials are artificial materials whose unique mechanical properties depend on their structure and arrangement of the unit cells rather than the chemical composition. Mechanical metamaterials have attracted a large number of researchers because of the designability of mechanical properties and more broad application prospects in vibration isolation, energy absorption, noise cancellation, et al. Among these, impact protection is an important research hotspot of mechanical metamaterials. Here we study the application of mechanical metamaterial sandwich structure with negative stiffness elements in low-velocity impact protection. We build a finite element method (FEM) model of the sandwich structure to simulate the quasi-static and low velocity impact behaviour, and the quasi-static simulation results agree well with experimental results reported in literature. The low velocity impact behaviour shows that this material will effectively absorb impact energy by its multi-stable properties and dramatically reduce acceleration response during impact, and most importantly, the deformation of this material is recoverable and can be reused. The mechanical metamaterials with multi-stable negative stiffness elements is ideal for impact energy absorption, and the methods and results are helpful for analyzing, designing, and manufacturing of mechanical metamaterials for energy absorption.

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