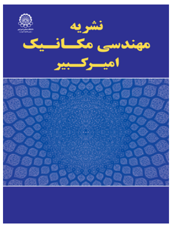

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Numerical and Experimental Study of Energy Absorption Amount of Functionally Graded Honeycomb with Negative Stiffness Property under Quasi-Static Load

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ABSTRACT: Functionally graded honeycomb with negative stiffness can be used extensively as an energy absorber because of having two features of negative stiffness and being functionally graded. In this research, the effect of using functionally graded honeycomb with negative stiffness in increasing energy absorption has been considered. In functionally graded honeycomb the thicknesses of structure change gradually in each layer, as a result, each layer has a different stiffness. Negative stiffness honeycomb is a type of energy absorbers that absorb energy by the transition from one buckled shape to another and show snap through- like behavior.In this research, at first quasi-static tests have been carried out on negative stiffness honeycombs with constant thickness. Then finite element model of negative stiffness honeycomb with constant thickness is simulated in ABAQUS software and the results of simulation are compared with experimental results and a good agreement between numerical and experimental results has been observed. Functionally graded honeycomb with negative stiffness then has been modeled numerically. Energy absorption per unit mass of the functionally graded negative stiffness honeycomb has been compared with conventional ones. Based on the results, energy absorption per unit mass in functionally graded honeycomb with negative stiffness increased by 1.57 times.

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1. Introduction

Mechanical systems often encounter vibrations and impact forces. A good suggestion to mitigate mechanical vibration or impact forces is honeycomb structures because they possess lightweight, high strength and energy absorption properties. However, they have a major disadvantage, they can not recover after the absorption of impact forces. The negative stiffness honeycombs have been devised to overcome this problem. They are designed by arraying negative stiffness elements in a honeycomb form [1]. Since 2010, many researchers have studied the behavior and construction of negative stiffness elements [2, 3]. Energy absorption of curved beam as a negative stiffness element has been studied by Fulcher et al. [2] and Klatt [3]. Correa et al. [1] continued the research on design and energy absorption characteristics of the negative stiffness honeycomb numerically and experimentally. In these investigations, they have shown that the negative stiffness honeycombs possess the energy absorption property like the conventional honeycomb and unlike the conventional ones, they can recover after the impact force is applied.

On the other hand, researches on functionally graded honeycombs have also been conducted [4-7]. Functionally graded honeycomb is a type of energy absorption structure that its cell size, shape, thickness or material properties vary functionally to change the relative density or other properties. Ajdari et al. [4] have shown that in functionally graded honeycomb when the relative density decreases in the impact direction, the energy absorption increases. A study by Galedari et al. [5] showed that functionally graded absorption reduces the rate of impact load on protective object. Also, the results of numerical research studied by Tau et al. [6] indicate that functionally graded honeycomb improves the specific energy absorption rate compared to the regular honeycomb approximately by 70%.

Based on the finding of the previous works on functionally graded honeycomb, which increases energy absorption and the duration of impact transmission, and negative stiffness honeycomb, recoverability after the impact, in this research, the functionally graded honeycombs with negative stiffness were investigated for the first time. In this article, energy absorption of negative stiffness honeycomb with constant thickness was studied numerically and experimentally. The quasi-static experiment is carried out on negative stiffness honeycomb, and then negative stiffness honeycomb with constant thickness is simulated in ABAQUS. Due to the good agreement between the experimental and numerical results, numerical modelling has been approved. Then, functionally graded honeycomb with negative stiffness is modeled in ABAQUS and quasi-static loading applied to the model. In this simulation the effect of being functionally on increasing energy absorption is studied.

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2. Experimental and Numerical Study

In this research, the amount of energy absorption by negative stiffness honeycomb with constant thickness is studied numerically and experimentally. The result of Finite Element (FE) simulation is validated with experimental results. The negative stiffness honeycomb has been manufactured using Nylon 11 material by a material jetting system (J750) from Stratasys in a multi-scale additive manufacturing lab at the university of Waterloo, Waterloo, Canada. Quasi-static loading has been applied to negative stiffness honeycomb by a universal testing machine. The test is performed at Odontology department at Mashhad university of medical science, Mashhad, Iran. The SANTAM universal testing machine with 50 kg load cell has been used. For experimental test, displacement of 33 mm was applied to the top of the honeycomb at a constant crosshead velocity of 5 mm/min and the force-displacement curve was recorded. Fig. 1 shows negative stiffness honeycomb with constant thickness under a quasi-static load.

Fig. 1. Negative stiffness honeycomb with constant thickness under a quasi-static load

Then the quasi-static model of both conventional and functionally graded negative stiffness honeycomb is simulated in ABAQUS/standard version 2016. Since the model is under the large deformation and rotation, geometric nonlinearity has been used in the modelling. A total of 7374 C3D20H elements is employed.

3. Results and Discussion

The amount of energy absorbed by the negative stiffness honeycomb with constant thickness is calculated experimentally and numerically by calculating the area under the force-displacement diagram, in MATLAB software. The amount of energy absorbed by the negative stiffness honeycomb numerically and experimentally is respectively 4.6205 N.m and 5.1903 N.m. By comparing the experimental and FE results the acceptable agreement can be observed. The calculated relative error between numerically and experimentally results is 10.98%. In the present research, for the first time, a functionally graded honeycomb with negative stiffness has been employed for the energy absorption purpose. In this paper, the functionally graded negative stiffness honeycomb means the thickness of each layer of curved beam is varying. To studying the significance of functionally graded honeycomb in absorbing energy and the effect of varying the stiffness from one layer to another, the amount of energy absorbed by the functionally graded honeycomb with negative stiffness is compared with negative stiffness honeycomb with constant thickness. This comparison is simulated in the ABACUS software. In this numerical simulation, functionally graded honeycomb has thicknesses of 1.27, 1.48, 1.69 and 1.9 mm, respectively and the load has been applied to the thickest layer of honeycomb. The force-displacement results from the FE analysis for functionally graded negative stiffness honeycomb and negative stiffness honeycomb with constant thickness have been shown in Fig. 2.

As one can see in Fig. 2, by increasing the thickness of functionally graded negative stiffness honeycomb, the amount of peak load is increased. In order to study the effect of being functionally graded in the honeycomb structure on increasing the energy absorption, energy absorption per unit mass Specific Energy Absorption (SEA) of the functionally graded honeycomb with negative stiffness is calculated and compared with negative stiffness honeycomb with constant thickness. The amount of SEA for negative stiffness honeycomb with constant thickness and functionally graded honeycomb with negative stiffness is 102.65 J/kg and 161.25 J/kg, respectively. It is clear that the amount of SEA for functionally graded honeycomb with negative stiffness increased compared to negative stiffness honeycomb with constant thickness. For displacement of 33 mm, the relative increase is 57%, which indicates better performance of functionally graded honeycomb with negative stiffness.

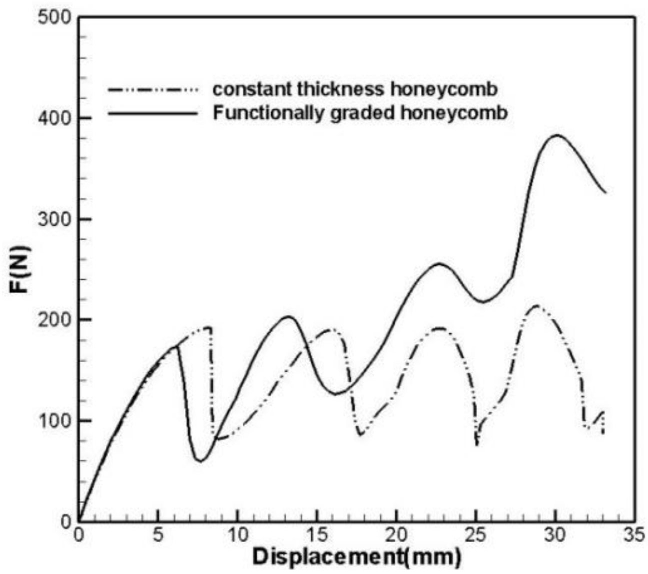

Fig. 2. Comparison between quasi-static force-displacement diagram for FE model of negative stiffness honeycomb with constant thickness and functionally graded negative stiffness honeycomb

4. Conclusions

In this research, the amount of energy absorption of functionally graded honeycomb with negative stiffness is compared with constant thickness negative stiffness honeycomb. To validate the FE simulation, the numerical and experimental results for constant thickness negative stiffness honeycomb have been compared. The results showed a good agreement between them so that the amount of energy absorption of experimental and numerical simulation has indicated 10.98% relative error. Then finite element model of functionally graded and constant thickness negative stiffness honeycomb is simulated in ABAQUS software and the results of the simulation are compared. The results of simulation show that energy absorption per unit mass in functionally graded negative stiffness honeycomb is 1.57 times higher than constant thickness one. In summary, it is observed that functionally graded negative stiffness honeycomb increases energy absorption. This feature along with recoverability of these structures is a unique feature for energy absorbers.

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