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Numerical analysis of recoverable Negative Stiffness Smart Structures for energy absorption in shock isolation

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ABSTRACT

The recently developed Negative Stiffness Honeycomb (NSH) structures have drawn tremendous interest in the field of energy absorption and shock isolation. The smart NSH structures have the advantage of being reused multiple times, where the conventional energy absorption techniques involve permanent deformation of the material via linear or nonlinear buckling or failure mode to absorb energy. In this study, the force-displacement characteristics of NSH structure with different materials has been investigated using Finite Element Method Based Software. A comprehensive investigation was undertaken to analyze the performance of the structure as energy absorbers in displacement-controlled loading condition. From the obtained results it was observed that the NSH structure shows good energy absorption without crushing. The energy absorption characteristics were analyzed for different flexible materials commonly used in additive manufacturing. Since the structure is recoverable after each unloading, with required specific energy absorption, these structures can be used for shock isolation in sensitive structures such as small containers, packaging, small shock absorbers etc.

Keywords: Negative Stiffness, Energy Absorption, Smart Structures, Honeycomb, Repeatability.

1. Introduction

Traditional energy absorbers absorb energy in the form of permanent deformations during impact or loading. Also, they absorb a large amount of energy in the course of crashing. For this they can't be used multiple times for usage and shock isolation or energy absorption where the required value is smaller. In this case, the recent invented Negative Stiffness Honeycomb (NSH) structure by D. Correa has drawn tremendous attention due to its repeatability [1]. NSH structures absorbs energy by buckling of material followed by elastic deformation similar to the way of regular hexagonal honeycombs. Very recently NSH structures showed a great attention to the researchers as it returns to its earlier configuration after the withdrawal of the loading. The NSH geometries are composed of negative stiffness beams which are shaped in a repetitive pattern. These negative stiffness beams show high initial stiffness and dissipates energy as they change buckling modes from one to another. Based on the work of Fulcher et al. [2], Kashdan et al. [3] and Klatt et al. [4] investigated the performance of single negative stiffness beam and showed that curved beams subjected to transverse loads shows negative stiffness behavior. Correa et al. compared the energy absorption characteristics with original hexagonal honeycomb structure which absorbs energy by permanent deformation [5]. He also modified the NS structure and achieved better energy absorption characteristics. From his study, it was obvious that a wide range of energy absorption can be achieved by modifying negative stiffness honeycomb structures.

Zakatayev et al. developed a methodology for the design of negative stiffness beams for predetermined sequence of buckling in NSH meso-structures [6]. Debeau et al. showed that NSH structures can be used for ideal shock isolation as long the mechanical energy of the system doesn't exceed the energy absorption capacity of the NSH structures [7]. Tan et al. investigated the shock absorption characteristics of Negative Stiffness beams for different geometrical parameters [8]. They analyzed the influence of the geometric parameters on energy absorption using an experimentally verified numerical model. Later, in another work, Tan et al. also showed the applicability of negative stiffness structure as cushion provider [9]. He also investigated the effect of structural parameters on the NS properties in that work. Chen et al. prepared a composite NSH model with two different elasticity properties materials by additive manufacturing and showed the characteristics of the composite structure [10]. At the same time, Ganilova et al. tried to investigate the opportunity of NSH structure in crumple zone of automotive car [11]. Goldsberry et al. analyzed the Negative stiffness honeycomb structure as tunable elastic metamaterials [12]. Researchers at Pennsylvania State University investigated the scope of using negative stiffness honeycomb structure as sensitive payload shock absorber [13]. They investigated the values and proposed for applying this structure in the tail section of Lockheed Martin's Desert Hawk III aircraft.

All these studies imply the scope of application of NSH structure in practical fields. More research on NSH of different materials and geometrical parameters should

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be conducted to attain a series of different energy absorption characteristics for finding the suitable model for different practical fields. Additive manufacturing has been the most popular manufacturing process now a days due to its ability of manufacturing complex model and ease of availability. Hence materials used in additive manufacturing are largely used in product industry. In this study, force-displacement and energy absorption characteristics of several flexible materials are used in additive manufacturing have been investigated.

2. Methodology

To characterize the energy absorption capacity of several materials, the NS honeycomb under a vertically oriented compressive load is numerically analyze using FEA software ABAQUS. In static general module, displacement-controlled loading was applied in the model to analyze the energy absorption characteristics. The energy absorbing characteristics of any system is described by various crash parameters such as Energy Absorbed (EA), Specific Energy Absorption (SEA), Crash Load Efficiency (CLE) and the mean crushing force (MCF). From the force displacement diagram, the energy absorbed (EA) can be calculated.
Specific energy absorption (SEA) is defined as the ratio of energy absorbed & the mass of the model. Mathematically, SEA is given by [14],

$$SEA = \frac{EA}{m} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where EA represents the total energy absorbed and m is the mass of the deforming structure.

2.1 Geometry Modeling

The Negative Stiffness Honeycomb structure was modeled in 3D modeling software Solidworks. Four different material specifications were considered for the study named as Model A, Model B, Model C and Model D. All the models have same geometrical parameters but different materials properties. The geometry of the NSH unit cell with dimensions in orthographic view is shown in Fig. 1. Fig. 2 depicts the 3D Negative Stiffness Honeycomb structure model developed using Solidworks.

2.2 Material Specifications

For the repeatability of the model, four flexible materials that are used in additive manufacturing were selected. In this study, the Polyamide (PA) 11, Nylon 645, Taulman Plasticized Copolyamide TPE (PCTPE) and NinjaFlex (TPU) are named as Material A, Material B, Material C and Material D respectively.

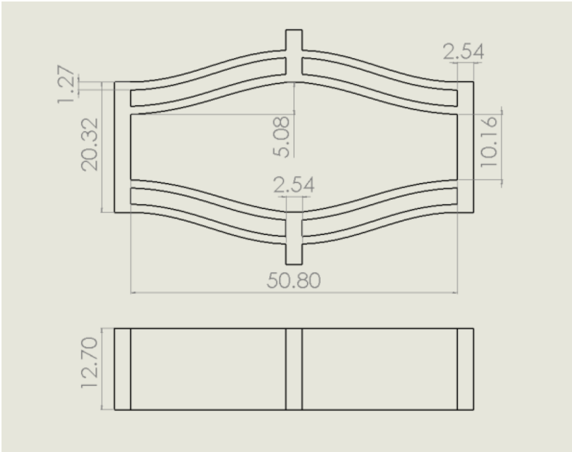

Fig. 1 Dimensions of the NSH structure unit cell (mm).

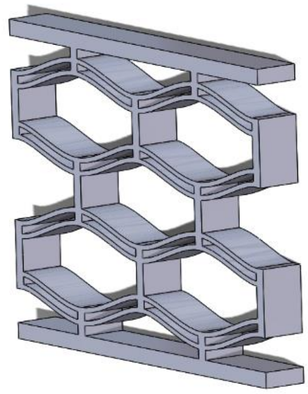

Fig. 2 3D Negative Stiffness Honeycomb structure model.

These materials are widely used for commercial 3D printing area for fabricating flexible models [15]. These materials possess wide range of elastic properties. Hence, these materials are selected to investigate how the energy absorption results varies with different elastic properties for the NSH structure. The respective mechanical properties of the materials are tabulated in Table 1.

2.3 Boundary Conditions

A displacement-controlled loading of 5mm was applied in the negative Y direction on the upper surface of all models. The baseline surface was assigned as ENCASTRE condition (fixed boundary condition). The X directional motion of the side faces of the structures were restrained by putting displacement value in X direction as 0. Fig. 3 shows the detailed boundary condition of NSH structure.

Table 1: Mechanical properties of materials [16-19].

Material	A	B	C	D
Commercial Name	Polyamide (PA)	Nylon 645	Taulman (PCTPE)	Ninjaflex (TPU)
Density (Kg/m^3)	1040	1250	1250	1190
Young's Modulus (MPa)	1582	212	73	12
Poisson's Ratio	0.33	0.42	0.48	0.34

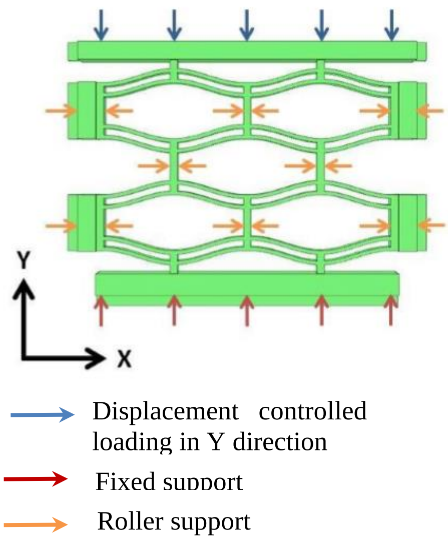

Fig. 3 Numerical model of NSH structure with loading and boundary conditions.

2.4 Mesh Independence Test

This analysis was performed numerically by the general-purpose finite element program, ABAQUS v16.14. Hexagonal shaped C3D8R element type meshing was used which is an 8-node linear brick and reduced integration element. Fig. 4 shows the NSH structure specimen with hexagonal mesh. To obtain independent mesh for the further analysis a result is compared for different meshing combination. In this case force threshold is calculated for specific loading and boundary condition as shown in Fig. 5. Finite element models with an average element size of 0.4 mm, 0.5 mm, 0.8 mm, and 1.5 mm were constructed and analyzed, respectively. The number of elements varies with respect to element size. The variation of force threshold with respect to number of elements for these models were presented in Fig. 5. It is observed that at first force threshold changes rapidly but later the change in force threshold is very few or negligible. That indicates independence of the model. Finally, a model with average mesh size was selected as 0.5 mm. At this element sizing, there was 338260 nodes and 265500 elements. For the lower values of mesh size

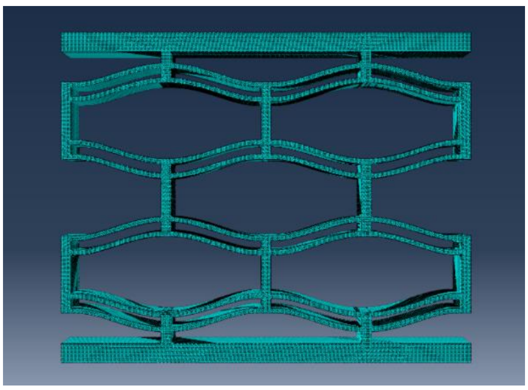

Fig. 4 3D model of specimen with structured mesh.

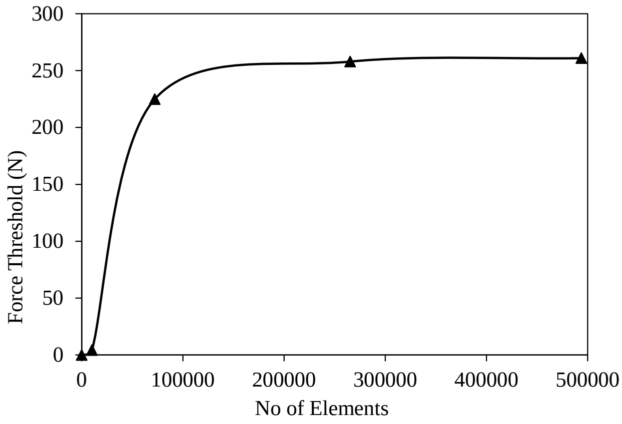

Fig. 5 Comparison of force threshold obtained for different number of elements.

of 0.5 mm, there was very little change of peak reaction force of the model. Moreover, at smaller values of mesh size, the number of elements increases significantly which limits the computational limitation of the available system. Hence, the mesh size of 0.5 mm (265500 elements) was chosen for the analysis.

3. Computational Result and Discussion

3.1 Validation of Analysis

The effectiveness of the present numerical analysis is demonstrated by comparing the obtained numerical result with the results in the literature. For same material, dimension and boundary conditions the numerical analysis was validated with the study of D. Correa et al. [5] and Ganilova et al. [11]. Using the data collected from the model, a Force-Displacement curve was plotted and then compared with the results in the literature as shown in Fig. 6. It is observed that the present study maintains very good agreement with the reference results. But The portion of the graph after the 5 mm displacement was neglected because of the limitation of static general solver in which the buckling of the structure can't be considered. Regardless this small difference the results shows that the model is valid for further evaluation.

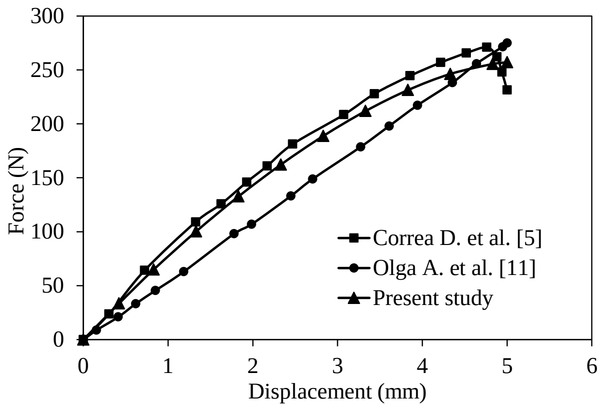

Fig. 6 Validation of present study with results in the literature.

3.2 Stress Analysis

The stress formation in the NSH structures after 5mm compression for different materials are shown in Fig. 7-10. From these figures it is observed that almost same deformation patterns were seen for all the materials. The output stress distribution data shows how the applied forces spread throughout each component of that structure, resulting in stresses, strains and the deflections of the entire structure. All components that are designed with NSH geometry must obviously be designed to have a capacity greater than what is expected to develop during the structure's use to obviate failure. Also, for a fixed material criterion, if the compressive stress exceeds the yield strength limit, the geometry should be modified to meet the required factor of safety.

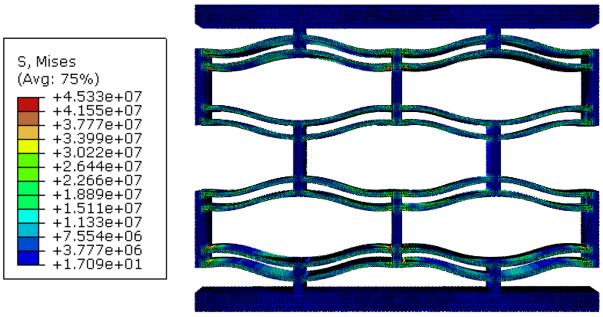

Fig. 7 Stress distribution after 5 mm compression (Material A).

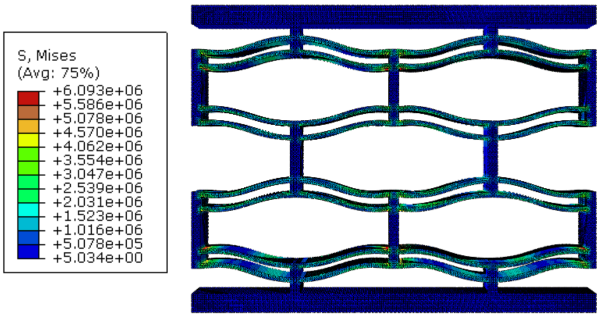

Fig. 8 Stress distribution after 5 mm compression (Material B).

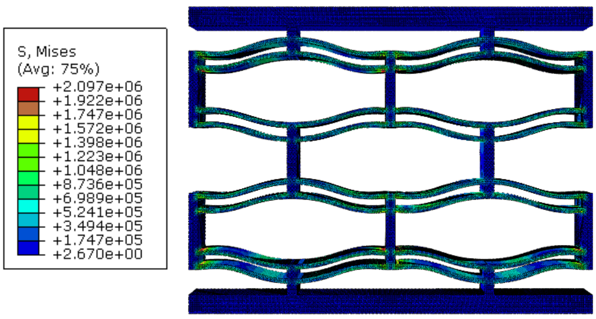

Fig. 9 Stress distribution after 5 mm compression (Material C).

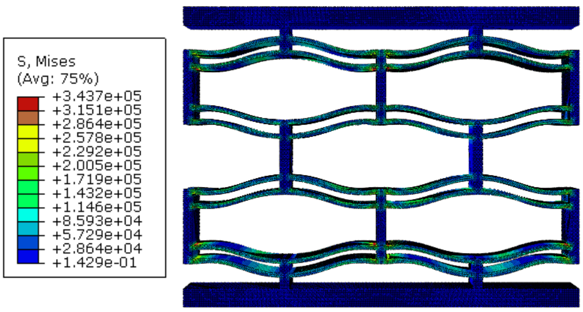

Fig. 10 Stress distribution after 5 mm compression (Material D).

3.3 Energy Absorption Characteristics

For the same amount of displacement, the initial peak threshold force and mass has been observed from the computational analysis and plotted here as shown in Fig. 11. It can be seen that there is a sharp rise in peak force for Material A, whereas Model B, C and D has less initial peak threshold force. Hence, model A possess high initial stiffness and can be used for handling larger loads. At the same time lesser mass is required for material A. Followed by material A, material B shows higher force threshold, but higher material is required than others. Whereas Material C and D had lower range initial peak

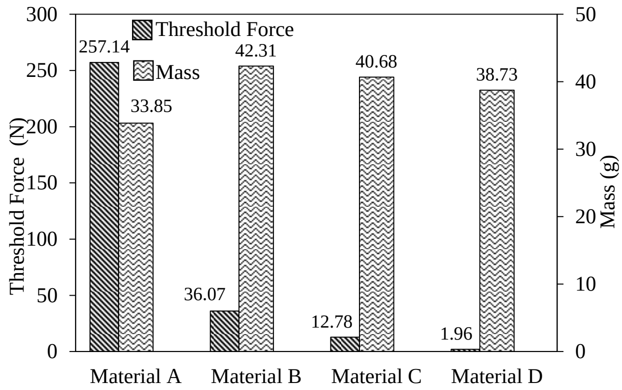

Fig. 11 Threshold force and mass of NSH structure made with different materials.

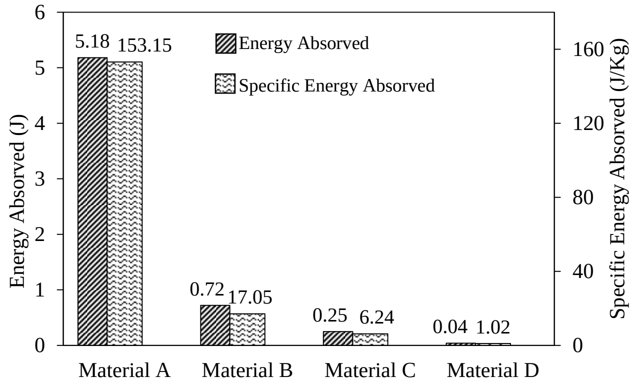

Fig. 12 Energy absorption of different negative stiffness honeycombs.

threshold force. Fig. 12 depicts the energy absorption characteristics of negative stiffness honeycomb structures in compression incident. The Material A showed the largest energy absorption, whereas Material D showed least energy absorption. Material B and C has shown mid-range EA values. Same pattern has been obtained for the case of specific energy absorption.

4. Conclusion

A comprehensive investigation on energy absorption and force-displacement characteristics as well as compressive stress corresponding to the mass of the negative stiffness honeycomb structures in compression for different materials are presented in this study. The analysis results indicate that the cellular NSH structure has the subsequent advantages such as the materials used in this study all are flexible materials that can be easily manufactured via additive manufacturing process where needed and the structure is highly repetitive. Material A named as PA 11 showed the SEA and initial reaction force value which suggests this structure as highly stiff. Material B and C named as Nylon 645 and PCTPE showed middle range energy absorption values in comparison with others and can be used for small energy absorption equipment. Material D named as Ninjaflex TPU showed very low stiffness and the least energy absorption among the four materials and can be usable for vibration damping devices. The numerical results found in this study can be used to design equipment for different applications by considering the required factor of safety, stiffness and energy absorption. Future work will focus on the effect of geometrical modification with a combination of different materials to achieve a series of models that can provide required energy absorption values for different applications, for example.

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5. References

[1] Correa D. M., Seepersad C. C., M. R., Haberman M. R., Mechanical design of negative stiffness honeycomb materials, *Integrating Materials and Manufacturing Innovation*, vol. 4, no. 1, pp. 10, Jul 2015.

[2] Fulcher, B.A., Shahan D.W., M.R. Haberman, Seepersad C.C., Wilson P.S., "Analytical and Experimental Investigation of Buckled Beams as Negative Stiffness Elements for Passive Vibration and Shock Isolation," *Journal of Vibration and Acoustics*, Vol. 136, No. 3, pp.031009 (1-12), 2014.

[3] Kashdan, L., Seepersad C.C., Haberman M., Wilson P., Design, Fabrication, and Evaluation of Negative Stiffness Elements Using Selective Laser Sintering, *Rapid Prototyping Journal*, Vol. 18, No. 3, pp. 194-200, 2012.

[4] Klatt, T., Haberman M., Seepersad C.C., Selective Laser Sintering of Negative Stiffness Mesostructures for Recoverable, Nearly Ideal Shock Isolation, *Solid Freeform Fabrication Symposium*, 2013.

[5] Correa D. M., Klatt T., Cortes S., Haberman M., Kovar D., Seepersad C., Negative stiffness honeycombs for recoverable shock isolation, *Rapid Prototyping Journal*, vol.21, pp.193-200, 2015.

[6] Zhakatayev A., Kappassov Z., Varol H. V., Analytical modeling & design of negative stiffness honeycombs, *Smart Materials and Structures*, vol. 29, no. 4, pp. 1-22, 2020.

[7] Debeau, D. A., Seepersad, C. C., Haberman M. R., Impact behavior of negative stiffness honeycomb materials. *Journal of Material Research* Vol. 33, pp.290-299, 2018.

[8] Tan, X., Chen S., Zhu S., Wang B., Xu P., Yao K., Sun Y., Reusable metamaterial via inelastic instability for energy absorption. *International Journal of Mechanical Sciences*, Vol. 155, pp. 509-517, 2019.

[9] Tan, X., Wang, B., Chen, S., Zhu, S., Sun, Y., A novel cylindrical negative stiffness structure for shock isolation. *Composite Structure*, Vol. 214, pp. 397-405, 2019.

[10] Chen S., Wang B., Zhu S., Tan X., Hu J., Lian X., Wang L. Wu L., A novel composite negative stiffness structure for recoverable trapping energy, *Composites Part A: Applied Science and Manufacturing*, Vol. 29, 2020.

[11] Ganilova, O. A., Low, J. J., Application of smart honeycomb structures for automotive passive safety. *Proceedings of the Institution of Mechanical Engineers, Part D-Journal of Automobile Engineering*, vol. 232, pp. 797-811, 2018.

[12] Goldsberry, B. M. & Haberman, M. R. Elastic wave dispersion in pre-strained negative stiffness honeycombs. *Acoustical Society of America Journal*, vol. 140, pp. 3104-3104, 2016.

[13] Bonner D., Pellegrini S., Rudolph M., Hilbere M., Sensitive Payload Shock Absorber, Research report, The Pennsylvania State University, 2016.

[14] Priem C., Othman R., Rozycki P., Guillon D., Experimental investigation of the crash energy absorption of 2.5D-braided thermoplastic composite tubes, *Composite Structures*, vol. 116, pp.814-826, 2014.

[15] https://io3dprint.com/types-of-flexible-3d-printing-filament/ (8 March 2020).

[16] D. M. Correa, C. C. Seepersad and M. R. Haberman, "Mechanical design of negative stiffness honeycomb materials", *Integrating Materials and Manufacturing Innovation*, vol. 4, pp.165-175, 2015.

[17] https://taulman3d.com/nylon-645-spec.html, (10 March 2020).

[18] https://taulman3d.com/pctpe-spec.html, (10 March, 2020).

[19] https://ninjatek.com/wp-content/uploads/2019/10/NinjaFlex-TDS.pdf, (10 March 2020).