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Mechanical Response of Applying Different Parameters On Negative Stiffness Honeycomb Structure

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Abstract: It has become apparent that negative stiffness behavior may have potential applications in vibration isolation mechanisms, vibro-acoustic dampening materials, and mechanical switches. Unlike traditional honeycombs, due to these properties, a negative honeycomb can absorb substantial amounts of mechanical energy whilst maintaining a stable stress. The force threshold under displacement loading was investigated of three variables applied on different models of negative-stiffness honeycomb (NSH) structures. The three variables are material applied, honeycomb unit cell, and beam thickness of the negative honeycomb structure. Accordingly, nine models were developed, and the three varied materials were assigned repeatably to each model and then force threshold were studied after validating the model. The Finite element analysis (FEA) for formed model was validated and shows force value of 289 N with an error of 5% compared to the referenced model. In the 4- unit cell model, the highest force threshold of approximately 240 N was noticed during loading phase at the beam thickness of 19.05 mm for both nylon 11 and 12 material. Finally, the force threshold of 550 N during loading and unloading phases was observed for nylon 6/6 material at beam thickness of 19.05 mm. The results obtained confirm the negative stiffness behavior on the models and shows that the force threshold applied is reduced comparing to forces required in the conventional honeycombs models.

Keywords: Negative stiffness, negative honeycomb structure, Finite Element Modeling (FEM), LS-Dyna, Finite Element Analysis (FEA)

1. Introduction

Negative stiffness was originally noticed in structural engineering because of the phenomena of column instability, which was considered a failure mode since it lost its solidity through a quick rise in strain [1]. Negative stiffness innovation has proven an appealing choice for suppressing vibration at low recurrence excitations, providing linear isolators with load bearing capabilities [2,3]. Besides, Lakes et al. determined that combinations together with negative firmness incorporations in a visco-elastic lattice could be beneficial into actual circumstances in which the goal is to increase both solidity and damping. They discovered, however, that unstable manner of the innovation behavior occurs if there is no combination of positive stiffness portion [4]. Debeau et.al [5] studied the impact behavior of NSH structures. NSH has been demonstrated to absorb energy during collisions at a constant and low force threshold. This is due to the impact duration being extended in time and the peak acceleration being reduced during the impact. The force threshold is related to the number of negative stiffness cell columns in the NSH structure, whereas the energy absorption capability is proportional to the number of negative stiffness cell rows, as established by FEA and tests with aluminum and nylon NSHs. According to Qiu's theory [6], third mode buckling could replace second mode buckling if a double beam was rigidly clamped at the center. A prefabricated double beam with an elastic vertical connector at the

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center is shown in Fig. **1**.Because of the double beam construction, the beam snaps from one stable position to another while transitioning through a third mode shape, resulting in negative stiffness behavior.

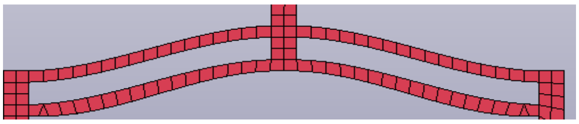


Fig. 1 - Prefabricated double beam with a central elastic connector

The use of negative stiffness beams in near-ideal shock absorption has been demonstrated in previous research. While these negative stiffness elements have been designed either as standalone structures or as components of shock isolation systems, they have not been widely assembled in a periodic honeycomb-like arrangement. Beams with negative stiffness allow energy dissipation when deforming from one shape with first modal buckling to another while exhibiting negative stiffness behavior. They tend to have high-level initial stiffness and provide near-ideal impact isolation at the designed force threshold. A performance evaluation of a single beam with negative stiffness was published by Klatt et al.[7], According to Fulcher et al., Kashdan et al. and Qiu et al. studies [6,8,9] Kratt et al. showed that a prefabricated curved beam as in Fig. 2 can be applied as a negative stiffness behavior like that typically exhibited by a straight beam that buckles from an axial load.

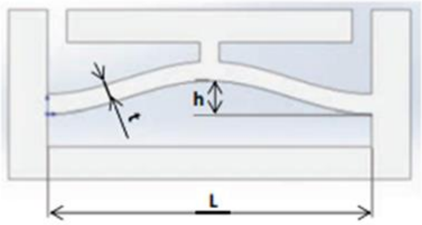


Fig. 2 - Negative stiffness beam in Klatt's study [7]

As shown in Fig. 3 (a), Correa et al. [10] have developed honeycomb structures with negative stiffness composed of prefabricated buckled beams arranged in multiple rows and columns. Selective laser sintering was used for manufacturing the two honeycomb prototypes. NSH structures recovered their initial profiles with minimal plastic deformation when compared with regular honeycomb structures. An estimated 65% of the energy input was dissipated through the system. The NSH structure is formed by snapping units arranged in a regular pattern, which Rafsanjani [11] investigated under tension loading. Fig. 3 (b) illustrates how NSH structures behave under tension loading. Based on the results, different nonlinear mechanical responses could be generated by tuned NSH structures.

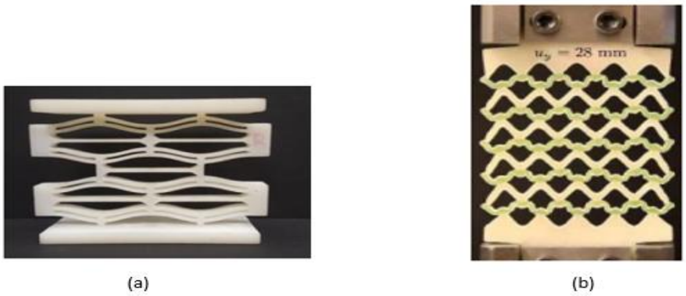


Fig. 3 - (a) Negative stiffness honeycomb structure [10] and; (b) different meta-material honeycomb structure under tension [11]

Tan et al. [12] examined the structure of a cylinder honeycomb occupied by projecting beams. The results revealed that cylindrical arrays can dissipate energy under displacement loads, but the force thresholds were same as honeycombs with negative stiffness. The composite system comprised of pre-buckled beams with polymer material matrix was experimentally examined by Cortes et al. [13] during uniaxial compression, the strength of the material is measured, as well as its energy dissipation. To increase stiffness and energy absorption of the system due to negative stiffness (pre-buckled beams), matrix construction is used. Highest strain experienced by the beam before buckling was referenced for a design. Using a negative stiffness matrix, we found that stiffness and energy dissipation were improved by ensuring that the beam stiffness was precisely matched to the matrix stiffness before buckling.

A metamaterial structure with negative Poisson's ratio and stiffness behavior was proposed by Hewage et al. [14] in a study that linked two unnatural properties. An experimental evaluation and analytical modeling of the proposed system were conducted using a negative Poisson's ratio assembly that stabilized negative stiffness elements. To demonstrate how three changes for metamaterial elements with negative stiffness design show how composite structures based on its stiffness and Poisson’s ratio exhibit direction reversal simultaneously in both axial and lateral dimensions, evaluated in the specified range of strain under displacement loading on the host assembly value. Such composite systems have demonstrated capacity to improve properties like vibration damping for transportation, defense, operational applications, and applications in the space field.

While there has been a lot of past research on negative stiffness beams and their uses, negative stiffness honeycombs are not widely used. To be able to design structures that are appropriate for the situation, it is important to comprehend the necessity of NSHs and recoverable buckled beam. In this study, FEA is used to investigate how negative stiffness structures behave when different parameters (Material type, unit cell of structure, and beam thickness) on the structures are applied. Additionally, the force threshold behavior of negative stiffness honeycombs un-der various quasi- static loading scenarios is evaluated.

2. Methodology

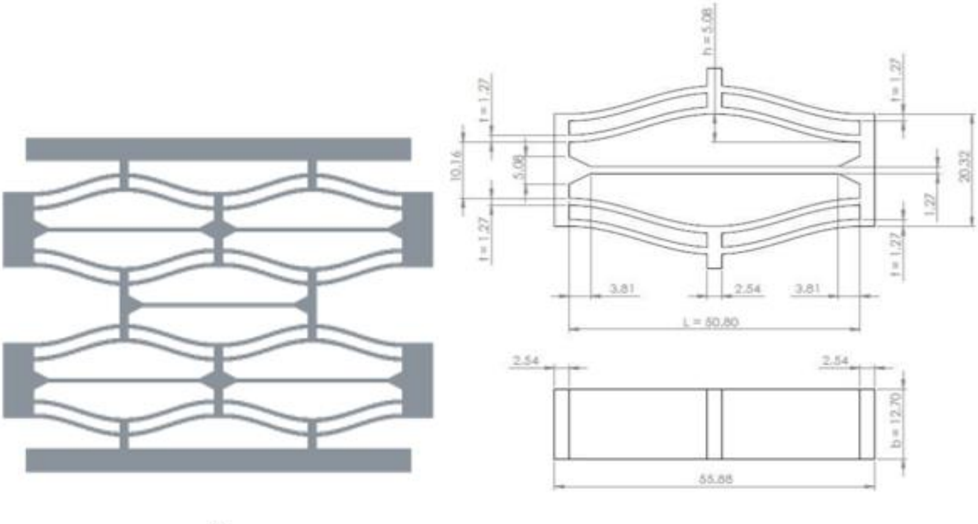
Negative stiffness beams are arranged in various combinations to explore their effects using FEA. This is accomplished by analysing negative stiffness model studied by correa et.al [10] in FEA under quasi-static displacement loading and validating it with the modelled honeycomb structure in this study. Accordingly, the referenced model is used further in the study to examine the mechanical performance of the negative honeycomb structure behaviour in various models. Then the effects of applying different variables (material, beam thickness, and unit cell) in a honeycomb-like configuration are evaluated.

2.1 Finite Element Modeling

A model was imported from SolidWorks software and used in finite element modelling software (LS-Dyna). In LS DYNA, the finite model of the negative stiffness honeycomb (NSH) structure evaluated by correa was validated by applying exact dimensions and properties analysed in Correa et al. model [10]. Various models were developed after the FEM was validated, to investigate the effect of different NSH parameters, including the structure thickness, multiple honeycomb units as well as different material types of negative- honeycomb structures.

2.1.1 Geometry of The Model

Honeycomb structure designed for negative stiffness, as shown in Fig. 4(a), 5-unit cell of double buckled beams, was formed with SolidWorks, and then imported to LS-DYNA. To prevent second mode beam buckling, a vertical line links in between of each double buckled beams when it shifts from one position to another according to Correa study, thereby ensuring beam instability. Based on the model done by correa et. al [10], the unit cell dimension illustrated in Fig. 4 (b).



(a) (b)

Fig. 4 - (a) Modeled negative stiffness honeycomb structure, and; (b) geometry of unit cell negative stiffness honeycomb structure[14]

In Fig. 5, the model shaped in LS-Dyna represents the negative stiffness honeycomb structure was formed with the same dimension of referenced paper and was used in validation. To make the model constructable, a uniform vertical link in the middle of each unit cell was added to achieve the third mode buckling (negative behavior). The quasi-static analysis was simulated by applying two steel plates as support on the model, one plate was used as fixed support, while the second plater was used as displacement load receiver.

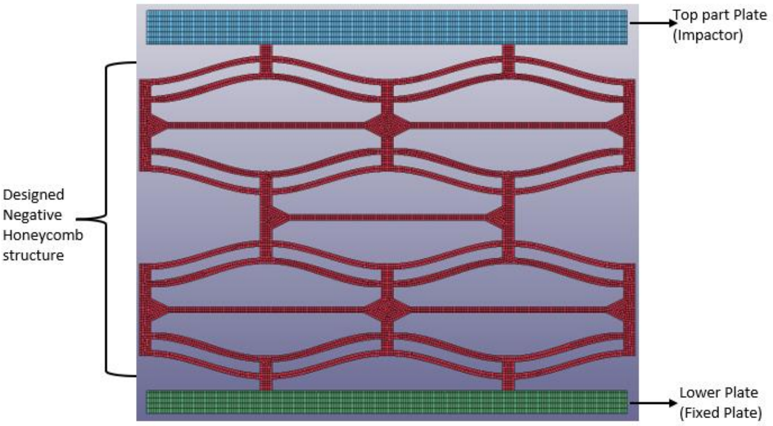


Fig. 5 - Modeled FE model of NSH structure

2.1.2 Material Modeling

The applied material for the modelled NSH in LS-DYNA is Nylon 11. The Nylon 11 is widely used in normal honeycomb structure and recently been used for negative stiffness honeycomb structure as it has higher strength, better heat resistance, lower impact on environment and during production it utilizes fewer renewable resources. Steel plates were modelled as upper loading plates and lower base plates. As shown in **Error! Reference source not found.**, input values of yield stress, Poisson's ratio, density, and young's modulus were applied for the Nylon11 and steel material model. Material properties of selected material were listed in Table 2. Based on referenced paper [10] simulation nylon11 was used, and nylon 6/6 with nylon12 were applied as other two materials since there are widely used after nylon 11 to investigate the effect of applying change in material on the model.

Table 1 - Material properties of applied materials on the model

Property	Steel	Nylon 11 (PA 11)
Density (D) kg/m^3	7830	1040
Poisson's Ratio (PR)	0.30	0.33
Young's Modulus (E) MPa	2e+05	1582
Yield Strength (SIGY) MPa	320	250

Table 2 - Properties of the selected materials

Property	Nylon 6/6	Nylon 11	Nylon 12	Steel
Density (D) kg/m^3	1140	1040	930	7830
Poisson's Ratio (PR)	0.33	0.33	0.33	0.30
Young's Modulus (E) MPa	1900	1582	1650	2e+05
Yield Strength (SIGY) MPa	250	250	250	320

2.1.3 Validation of The Negative Stiffness Honeycomb Model

To validate the model, a model in Fig. 5 was developed with the same dimension of referenced model as sketched in Fig. **4**, the beam thickness of 12.70 mm and full model height of 76 mm was used as per referenced. Then, applying boundary condition and lower plate was fixed (constrained), honeycomb structure was assigned as constraint and only movement in the negative y-direction was selected. A roller constraint applied on the side honeycomb model to allow it to rotate in the y-direction only as the study is using quasi-static (displacement) analysis in one direction only. Finally, the displacement load was distributed equally on the upper part (impactor) of the model with a displacement loading of 25 mm and the model simulation was running through LS-Dyna run.

2.1.4 Material Type Effect

To examine the effect of material type on the negative stiffness honeycomb, the validated model in Fig. 5 was used. Three commonly used materials for honeycomb structures are Nylon 11, Nylon 6/6, and Nylon 12 which were used in this study. From LS-DYNA, three different model with the desired materials were created and material properties corresponding to each material (Nylon 6/6 ,11 and 12) were applied in accordance with values reported in Table 2. The loading was idealized by applying fixed support for the bottom plate, displacement loads on the top plate and roller supports on the side corners were assigned to simulate the model in negative stiffness mode. Young modulus of 1582 MPa and Poisson's ratio of 0.33 were assigned in the three different FEA models. The displacement loading of 10 mm were applied for this simulation to study the force threshold behaviour by changing material of the validated model of negative stiffness honeycomb.

2.1.5 Beam Thickness Effect

It is important to note that the beam thicknesssignificantly influences the negative stiffness of buckled beam structure. Based on the findings of Qiu et al., beam thicknesshas a significant effect on stability, which influences negative stiffness behavior. Consequently, three different models of the negative stiffness honeycomb structure were generated to study the effect of changing the beam thickness. As illustrated in Fig. 6, the beam thickness of 6.35 mm, 12.7 mm and 19.05 mm and was modeled in LS-DYNA.

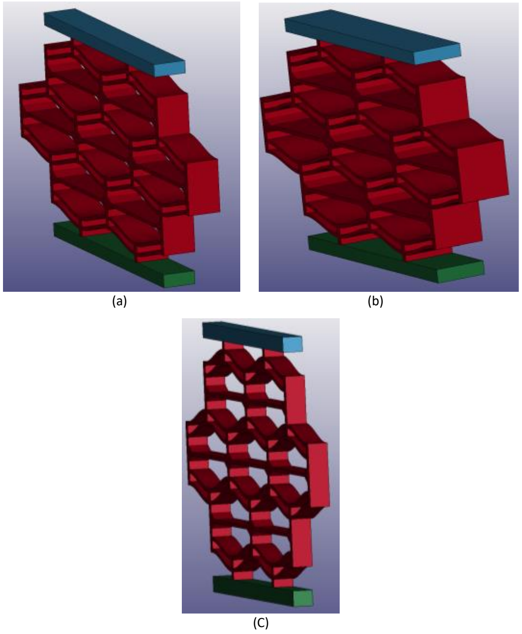


Fig. 6 - Beam thickness (a) thickness of 12.7 mm; (b) thickness of 19.05 mm; (c) thickness of 6.35 mm

2.1.6 Unit-Cell Honeycomb Effect

The geometry of the buckled beams, configuration of the beams, and the material of the honeycomb are various approaches for increasing the force threshold. To achieve higher force thresholds, it may also be feasible to use multiple honeycomb structures or a honeycomb structure with multiple buckled beams. A finite elementof the modeled honeycomb was developed by applying a different arrangement of unit cells with the same dimensions after model validation to examine the force threshold behavior of using multiple unit cell of honeycomb models. The unit cell of honeycomb is placed juxtaposed in arrangements to achieve the 4-, 5- and 7-unit cell shape respectively as shown in pervious chapter. All cells were simulated under displacement loading of 10 mm to study the effect of applying various arrangement and unit cell of honeycomb structure.

3. Results Analysis

3.1 Validation of The Model

Using LS-DYNA, the modelled negative honeycomb was simulated for validation. To idealize the analysis, roller supports for each of the vertical side cell walls was applied on the model, the bottom part (lower plate) was used as fixed support and the upper plat (impactor) was used as displacement loading on it in the y-direction.A quasi-static displacement load of 25 mm was applied on the impactor of honeycomb as the main purpose of this study to investigate the first peak force threshold of the honeycomb structure. In addition, the double beam connecters were assigned as roller support as well to simulate the third bulking mode to achieve the negative stiffness honeycomb perspective in FEM. The material properties were applied according to the referenced values in the referenced model as shown in **Error! Reference source not found.**. For the honeycomb structure model as referenced model to be nylon 11, bottom fixed plate and top plate (impactor) to be steel. Each negative stiffness region is caused by a row of curved beams transitioning from one first mode buckled to another, then, the layers buckle consecutively. The referenced and predicted force-displacement curve from FEA reveals continuous negative stiffness regions as noticed from Fig. **7**and the force threshold is approximately 289 N before buckling occur while the force is 275 N as per referenced paper which shows strong correlation between the two models with an error of almost 5%. The slight difference in values obtained between two model might be due to material properties of the Nylon 11 as the values which was considered in the validation as listed in **Error! Reference source not found.** as per referenced paper are young modulus's, density and yield stress, while properties such as Strain rate parameter and tangent modulus were ignored in the study. These values would change the results obtained to match with the desired value of the force threshold.

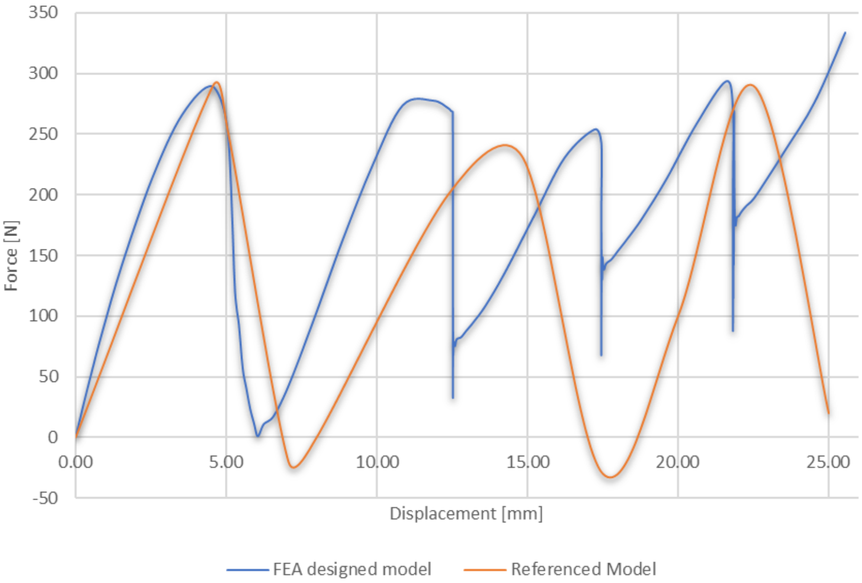


Fig. 7 - Force-displacement curve of the modelled and referenced honeycomb structure.

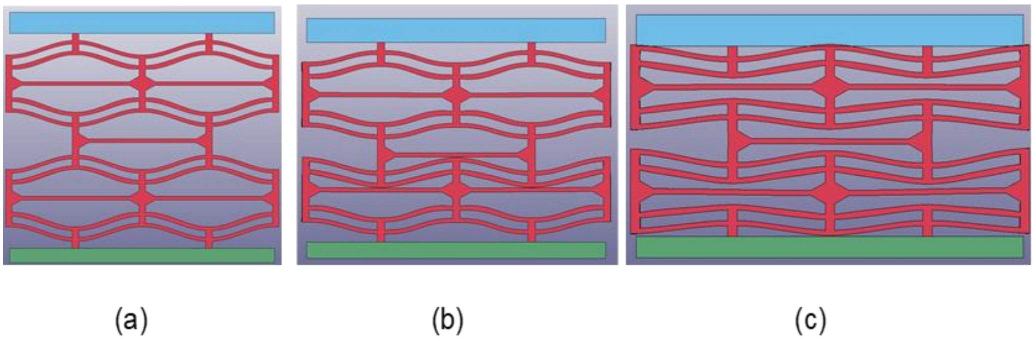


Fig. 8 - Deformed model in LS-DYNA simulation

Fig. 8 illustrate the model deformation during simulation applied in LS-DYNA. As a result of the validation of the model, the main characteristics of negative stiffness honeycombs were captured. Hence, various structures of the negative honeycomb will be investigated using different parameters which include material type applied in the model, the beam thickness of the negative stiffness model and unit cell number of the model that matching with the referenced geometry.

3.2 Effect of Material Type

Fig. 9 shows force versus displacement curve of nylon 6/6,11 and 12 materials. The referenced material used in validation was nylon11 as stated in Correa study [10], which was applied in the simulation to address the effect of various type of material on the negative honeycomb structure. The force threshold was approximately 400 N in nylon

6/6, which is higher than nylon 11 and 12 values (around 320 N) at the first peak. However, in the second peak the values of both nylon 6/6 and nylon 12 (650 N and 730 N respectively) were higher than nylon 11 (200 N).

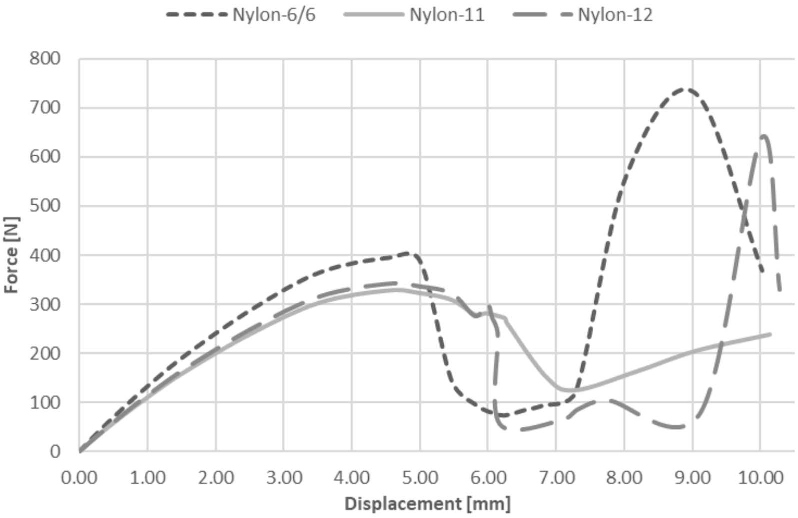


Fig. 9 - Force-displacement response of three different materials

3.3 Effect of Beam Thickness

The force threshold of almost 500 N represent the buckled beam rows force in beam thickness of 19.05 mm as shown in Fig. 10 The force value was almost 300 N for beam thickness which is almost half of the force threshold (150 N) of beam thickness of 6.35 mm.

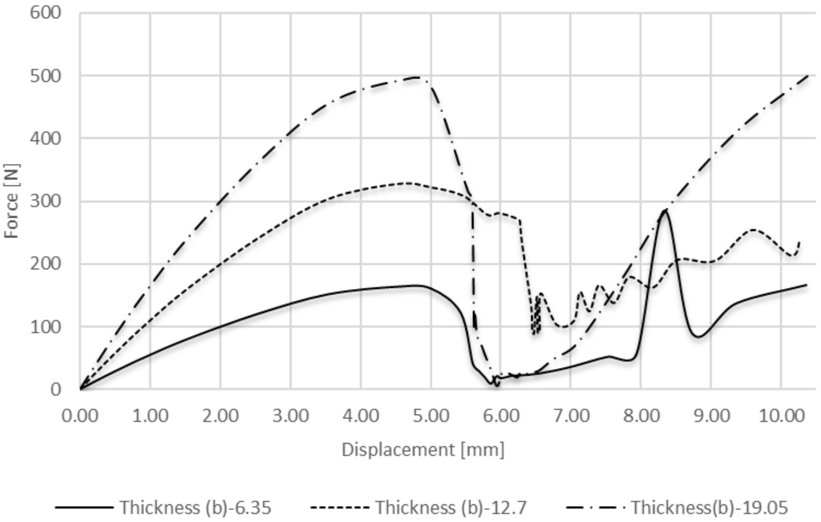


Fig. 10 - Force-displacement response of different beam thickness

3.4 Effect of Multiple Honeycomb Unit-Cell Structure

Fig. **11** shows the force-displacement relationship of the multiple unit cell honeycomb model and reference model [10]. During the loading phase of the honeycomb, the force threshold was the same in the 7-unit cells and 5-unit cells arrangement of honeycomb and was almost half (150 N) for the 4-unit cell model. However, the model showed a higher threshold at which beams started rebounding during unloading in 5- and 7-unit cell model than the 4-unit cell model. As a result, multiple honeycomb units with fixed dimensions, a magnification of the force threshold will occur, depending on their properties.

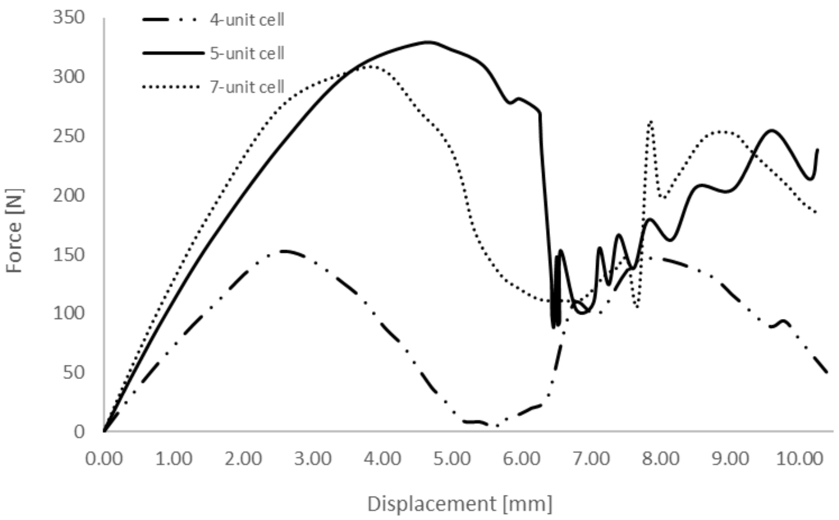


Fig. 11 - Force-displacement relationship of applying different unit cell of honeycomb structure

4. Conclusions

The paper meticulously studied the mechanical performance of multiple models of honeycomb structure with applying negative stiffness behavior on the models by using FEA runs in LS-DYNA, the quasi-static displacement loading was applied and the force threshold of the each NSH structures were explored. The model of NSH structure was developed and simulated in FEA for validation with the NSH structure. The force threshold during loading and unloading phase in validation part for the model was 289 N, while the referenced paper force values was 275 N which indicates an error of 5 %. After the model was validated, it was used to investigate the effect of changing three different parameters on the honeycomb structure performance. First, the effect of material change was studied by applying nylon 11, nylon 12 and nylon 6/6 as different material and evaluate the force threshold at beam thickness of 12.70 mm and 5-unit cell model of honeycomb structure and the result shows that the nylon 11 material is the best option compared to other studied material as the force threshold was the lowest with value of 328 N while the nylon 12 and 6/6 were 342 N and 394 N. Accordingly, the nylon 11 used as material for honeycomb structure since it shows good contribution in decreasing the force threshold due to its materials properties to maintain the stability of the model and helps regain its original shape which confirms the achievement of negative stiffness behavior on the model. Then, three different beam thickness of 6.35 mm, 12.70 mm and 19.05 mm was modeled and three runs were simulated in LS-Dyna for each beam thickness considering nylon 11 as material. The force threshold value of 492 N was required for the beam thickness of 19.05 mm during the first loading and unloading phase. And force 164 N was noticed for the beam thickness of 6.35 mm. Results indicate that force threshold capacities of the models increase with increasing thickness values intervals. Finally, the force threshold was investigated for applying multiple numbers of unit cell on the honeycomb structure. Four-, five- and seven-unit cell numbers were modeled in this study in LS-Dyna to investigate their effect on the force threshold. For 4-unit cell number model, the force obtained was 152 N at displacement of 2.54 mm, force values of 241 N and 274 N for 5- and 7- unit cell arrangement were observed respectively at 2.54 mm of displacement loading. Results concludes that the unit cell numbers with its arrangement have a significant role in determining the compressive force characteristics of NSH structures.

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References

[1] Batou, A., & Adhikari, S. (2019). Optimal parameters of viscoelastic tuned-mass dampers. Journal of Sound and Vibration, 445. https://doi.org/10.1016/j.jsv.2019.01.010

[2] Bazant, Z. P., Cedolin, L., &Tabbara, M. R. (1991). New method of analysis for slender columns. ACI Structural Journal, 88(4). https://doi.org/10.14359/2679

[3] Correa, D. M., Klatt, T., Cortes, S., Haberman, M., Kovar, D., &Seepersad, C. (2015). Negative stiffness honeycombs for recoverable shock isolation. Rapid Prototyping Journal, 21(2). https://doi.org/10.1108/RPJ-12-2014-0182

[4] Correa, D. M., Klatt, T. D., Cortes, S. A., Haberman, M. R., Kovar, D., &Seepersad, C. C. (2014). Negative stiffness honeycombs for recoverable shock isolation. 25th Annual International Solid Freeform Fabrication Symposium &#65533; An Additive Manufacturing Conference, SFF 2014.

[5] Cortes, S., Allison, J., Morris, C., Haberman, M. R., Seepersad, C. C., & Kovar, D. (2017). Design, Manufacture, and Quasi-Static Testing of Metallic Negative Stiffness Structures within a Polymer Matrix. Experimental Mechanics, 57(8), 1183–1191. https://doi.org/10.1007/s11340-017-0290-2

[6] Debeau, D. A., Seepersad, C. C., & Haberman, M. R. (2018). Impact behavior of negative stiffness honeycomb materials. Journal of Materials Research, 33(3), 290–299. https://doi.org/10.1557/jmr.2018.7

[7] Fulcher, B. A., Shahan, D. W., Haberman, M. R., Seepersad, C. C., & Wilson, P. S. (2014). Analytical and experimental investigation of buckled beams as negative stiffness elements for passive vibration and shock isolation systems. Journal of Vibration and Acoustics, Transactions of the ASME, 136(3), 1–12. https://doi.org/10.1115/1.4026888

[8] Hewage, T. A. M., Alderson, K. L., Alderson, A., & Scarpa, F. (2016). Double-Negative Mechanical Metamaterials Displaying Simultaneous Negative Stiffness and Negative Poisson’s Ratio Properties. Advanced Materials, 28(46), 10323–10332. https://doi.org/10.1002/adma.201603959

[9] Kashdan, L., Seepersad, C. C., Haberman, M., & Wilson, P. S. (2012). Design, fabrication, and evaluation of negative stiffness elements using SLS. Rapid Prototyping Journal, 18(3), 194–200. https://doi.org/10.1108/13552541211218108

[10] Klatt, T., Haberman, M., &Seepersad, C. C. (2013). Selective laser sintering of negative stiffness mesostructures for recoverable, nearly-ideal shock isolation. 24th International SFF Symposium - An Additive Manufacturing Conference, SFF 2013.

[11] Pietrosanti, D., de Angelis, M., &Basili, M. (2020). A generalized 2-DOF model for optimal design of MDOF structures controlled by Tuned Mass Damper Inerter (TMDI). International Journal of Mechanical Sciences, 185. https://doi.org/10.1016/j.ijmecsci.2020.105849

[12] Qiu, J., Lang, J. H., & Slocum, A. H. (2004). A curved-beam bistable mechanism. Journal of Microelectromechanical Systems, 13(2), 137–146. https://doi.org/10.1109/JMEMS.2004.825308

[13] Rafsanjani, A., Akbarzadeh, A., &Pasini, D. (2015). Snapping Mechanical Metamaterials under Tension. Advanced Materials, 27(39), 5931–5935. https://doi.org/10.1002/adma.201502809

[14] Tan, X., Wang, B., Chen, S., Zhu, S., & Sun, Y. (2019). A novel cylindrical negative stiffness structure for shock isolation. Composite Structures, 214, 397–405. https://doi.org/10.1016/j.compstruct.2019.02.030

[15] Wang, X., He, T., Shen, Y., Shan, Y., & Liu, X. (2019). Parameters optimization and performance evaluation for the novel inerter-based dynamic vibration absorbers with negative stiffness. Journal of Sound and Vibration, 463. https://doi.org/10.1016/j.jsv.2019.114941