POLITECNICO MILANO 1863
SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

Development of an effective reusable crash absorber based on an improved Negative Stiffness Honeycomb approach

TESI MAGISTRALE IN AERONAUTICAL ENGINEERING – INGEGNERIA AERONAUTICA

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1. Introduction

Crash absorbers are structural devices used in automotive and aerospace field to reduce the severity of an impact through storage and redirecting of the initial kinetic energy of the moving body.
Conventional crash absorbers dissipate the kinetic energy through plastic irreversible deformation. This method has the advantage of being effective and safe, reducing the potential harming of the surrounding environment in the event of a crash; however, after the collision the structure needs to be massively serviced and replaced in order to regain functionality, highly increasing cost and inconvenience of the system, especially in applications involving repeated impacts or when substitution results complex for environmental and economic factors.
The aim of this thesis work was to design, manufacture and test an effective reusable crash absorber, able to withstand consequent collisions recovering the deformation.
The selected design was the Negative Stiffness Honeycomb, a metamaterial composed of several curved beams, which are designed to snap to a second equilibrium position curved in the opposite direction as a response to a transversal load in the middle. This deformation results in a region of negative slope in the force-displacement plot, creating an oscillatory response. However, tailoring the characteristics dimensions of the cells it is possible to achieve this type of deformation (addressed as *snap-through* behaviour) with elastic or partially elastic buckling, being able to recover several times before failure.
Currently the amount of energy absorbed by structures exploiting Negative Stiffness Honeycomb approach in literature is generally negligible with respect to conventional crash absorbers, and the proposed structures are tested in static compression tests or not suitable for a reliable working in a dynamic compression environment. Therefore, we investigated if improving the functionality of this design was a feasible way to reach our objectives.
In the first section of the work are presented the analytical and numerical computation methods

which constitute the theoretical premises to the design and manufacturing of three prototypes, with a brief description of the characteristic dimensions and main features.
In the second section are reported the results of the static and dynamic compression tests conducted on the three iteration models, compared to numerical simulations and to previous literature studies.

2. Methodology

2.1 Theoretical computations

One great advantage of the negative stiffness honeycomb concept consists in the flexibility of the design: the characteristic dimensions of the cells can be tailored to adapt to every type of material, because the recoverability depends mainly on the geometrical parameters of the cell, represented in Figure 1. In fact, the maximum value of deformation can be computed with eq. (1) approximating a linear constitutive relation of the material, [1]

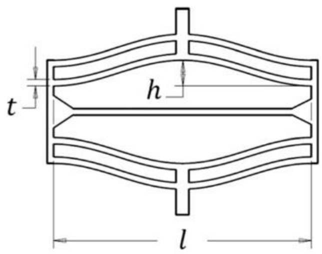

Figure 1: Drawing of a negative stiffness honeycomb cell with characteristic dimensions[2]

$$\epsilon_{max} = \frac{\pi^2 th}{l^2}\left(2 + \frac{4t}{3h}\right) \qquad (1)$$

Parametric analyses were performed on the base of the formula for the evolution of the force with respect to the vertical displacement of the apex of the beam, already developed by *Qiu et al.*[1] and *Mehreganian et al.* [3]. It was observed that the main independent geometric variables influencing the performance parameters were the thickness of the beams t and the bistability ratio Q, intended as the ratio between the apex height h and the thickness of the beams.

2.2 Numerical simulations

Numerical simulations were conducted on the nonlinear finite elements software LS-Dyna by ANSYS ® in order to explore different technical solutions and to predict the results of the experimental tests, with the possibility of extending the results to conditions difficult to achieve in experimental test, upon validation.

2.3 Materials

The first two prototypes, which will be illustrated in the next section, were produced with the technology of 3D printing by Fused Deposition Modeling (FDM), addressing the possibility of rapid prototyping to achieve a functional and reliable design. The material chosen was a spool of Nylon Novamid ID1030 ®, due to its high value of yield and failure strain which were suitable to design a durable model, able to withstand and recover high levels of deformation several times before failure.
Once the suitable configuration was achieved, the last iteration model was produced using laser cut stainless steel AISI 304 to explore the real potentiality of Negative Stiffness Honeycomb maximizing the absolute performance in terms of peak force and energy absorption.

2.4 Testing

Two types of test were conducted on the models produced in this thesis work.
Static compression tests were performed at low constant speed $\left(20\frac{mm}{min}\right)$, with the Testing machine *MTS ® 370.10* equipped with load cell *MTS ® 661*.
Dynamic compression tests were performed on the vertical sled and the acceleration data were measured with *EGCS-S425-250* sensor by *Mesurement specialties ®*, rated for a sensitivity of $0.503\,\frac{mV}{g}$.

3. Models

Three different prototypes were developed in series following a multi-step experimental approach based on the critical evaluation of the testing results of each prototype, with the goal to improve their functionality maximizing their performance.

3.1 First iteration model

The first model consisted in a simple bidimensional design, with Negative Stiffness Honeycomb cells arranged in a 2x2 configuration (two rows of two adjacent cells), 3D printed in Nylon by FDM. Two different iterations of the same design, but with different characteristic dimensions, denominated *L65 2D* and *L55 2D* (Figure 2: Picture of the two bidimensionl prototypes of the first iteration model) were produced and tested in loading-unloading cycles of static compressions with the purpose of proving the reusability of Negative Stiffness Honeycomb approach.

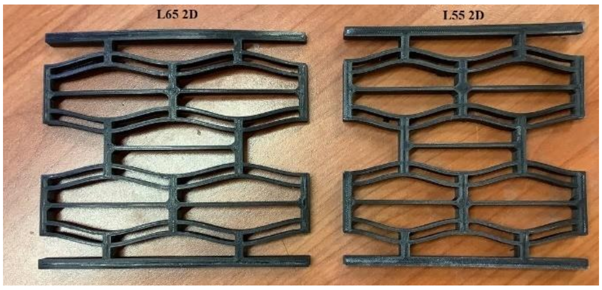

Figure 2: Picture of the two bidimensionl prototypes of the first iteration model

3.2 Second iteration model

The second model, denominated *Modular L80* (Figure 3), was intended to solve the lack of stability and performance, observed in the testing of the first iteration model, by proposing a three-dimensional modular design made of cells, individually manufactured with the same technique of the first model, stacked and perpendicularly interlocked with planar and cross-shaped inserts, and bolted connections. With respect to other solutions proposed in literature (like brazing process and increased width of the bidimensional model), this technique resulted in an easier manufacturing and assembly of a product with a reliable behaviour in dynamic collision events. The design opens the possibility to add multiple modules to achieve higher performance requirements.
Moreover, the bistability ratio of the cells was also increased to enhance the negative stiffness behaviour.

Figure 3: Picture of the assembled prototype of the second iteration model

3.3 Third iteration model

The purpose of the third iteration model, denominated *Steel L130* (Figure 4), was to explore the full potentiality of the Negative Stiffness Honeycomb concept, by using the same three-dimensional modular design of the second model, exploiting the superior mechanical properties of steel. The characteristic dimensions of the cell were tailored to achieve a lower level of deformation, following eq. (1) , compatible with the lower values of yield and failure strain of the metal with respect to thermoplastics.

Figure 4: Picture of the assembled prototype of the third iteration model

4. Results

4.1 First iteration model

The first iteration bidimensional model succeeded in proving the reusability of the Negative Stiffness Honeycomb approach in cyclic loading-unloading static compression cycles. In fact, as can be seen in Figure 5, the curves of consequent tests conducted on the same specimens resulted almost superimposable, with an instant full recovery of the deformation. Moreover, it is observed a hysteresis cycle between the loading and unloading phase, which is desirable in the context of energy absorbing devices. However, the distinctive negative stiffness portion in the loading curve results much attenuated by the geometrical dimensions of the cell (low value of bistability ratio) and the poor mechanical properties of the material.

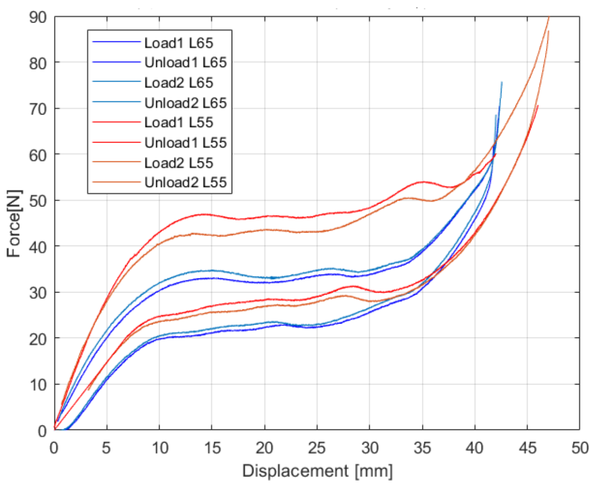

Figure 5: Comparison of experimental data of the two prototypes of the first iteration model in subsequent static compression tests

4.2 Second iteration model

The second iteration model showed substantial improvement in performance during static compression tests with respect to the first iteration model (+195 % considering maximum peak force and +247 % in Energy absorbed). Four distinct peaks are clearly visible in the load-displacement curve (Figure 6), corresponding to the snap-through events of the 4 rows of double curved beams.

Moreover, it can be observed in Figure 6 that the numerical simulations are validated in the case of the static compression test, but only considering the loading cycle, with a maximum scatter of 18 % in approximating the local maximum points.

The unloading curve is not captured due to the highly complex nonlinear hysteresis behaviour of thermoplastics under cyclic loading [4].

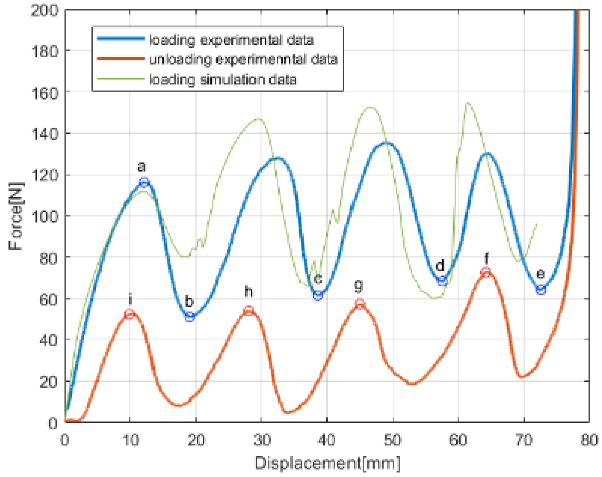

Figure 6: Comparison of experimental and numerical data of static compression test on second iteration model

The prototype was also tested in two consequent dynamic compression tests with a mass of 32.5 kg falling from 65 and 80 mm. In both cases the prototype successfully recovered the deformation without apparent major damage.

The most interesting aspect about this experiment consisted in the recovery phase of the device, which was not immediate after the unloading of the mass, as observed in static compression tests, but the deformation was recovered in 60 seconds with a slow sequence of autonomous snap-back events. This behaviour is considered convenient for a crash-absorbing device since the kinetic energy of the impact is not fully transmitted back to the moving body reducing potential harming to the surrounding environment. The reasons of this behaviour were found in the increased bistability ratio of the geometry of the cells, which delayed the recovery of the deformation, as well as the presence of a component of viscous damping in the mechanical response of the Nylon material 3D printed.

4.3 Third iteration model

The prototype of the third iteration model was evaluated in dynamic compression tests with a mass of 32.5 kg falling from 605 mm.

After two consequent tests no sign of fracture was observed (Figure 7).
Due to the inevitable onset of plastic deformation the recovery of the initial configuration was not autonomous but was forced with the application of a traction force in tensile testing machine, which allowed to recovery the original shape of all the cells, as well as 85 % of the initial stroke

Figure 7 : Picture of the third iteration model in the deformed state after the second dynamic compression test

The increased mechanical performance of the steel model allowed to achieve a substantial increase in energy absorption performance with respect to Nylon 3D printed models, with a value of Peak Force of 4500 N and 170 J of energy absorbed on the first compression event.

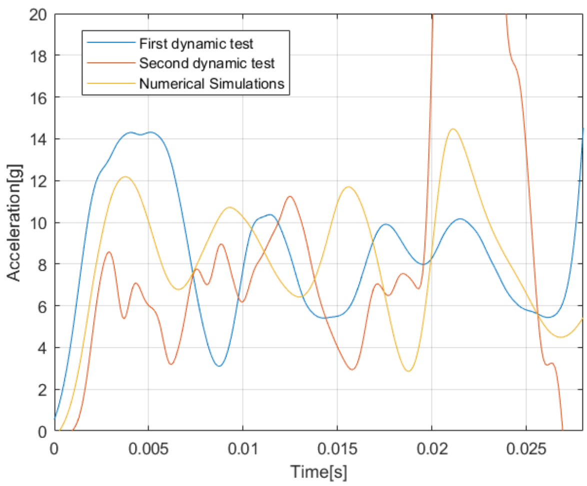

Figure 8: Comparison of experimental and numerical data on third iteration model during dynamic compression test

As can be seen in Figure 8 , during the second compression test the model showed a reliable response with a decrease in performance of 18 % in peak force and 35 % in energy absorbed with respect to the first test, mainly caused by minor damaging of the material and the reduction of the stroke

In this case the numerical simulations are validated by the experimental data of the first compression test: it is registered a difference in the average value local maximum and minimum points in the acceleration plots (Figure 8) of 4%.

5. Comparison with previous literature studies

The thesis work satisfied the aim of the study in creating an effective and functional reusable crash absorber based on the concept of Negative Stiffness Honeycomb.

The performance of the second and third model proposed in this thesis work were compared to previous literature studies showing a massive improvement in absolute values of peak force and energy absorbed (Table 1).
Moreover, the three-dimensional modular design effectively increased the functionality of the device by ensuring high repeatability in dynamic compression tests and decreasing the complexity of the assembly and manufacturing processes.

	Peak Force [N]	**Energy absorbed [J]**	**Specific energy $\left[\frac{J}{Kg}\right]$**
Chen, 2021 [5]	100	1.9	20.3
Chen, 2022 [6]	320	5.6	690
Debeau, 2017 [7]	434	4.4	[-]
Zhang, 2021 [8]	45	4	[-]
Tan, 2018 [9]	1200	28.8	[-]
Modular L80	130	7.56	43.6
Steel L130	4500	170	64.6

Table 1: Comparison between performance parameters of second and third iteration models with previous literature studies

6. Conclusions

In conclusion, this thesis work provided evidence for the potential use of Negative Stiffness Honeycomb as an effective and functional reusable crash absorber. The original concept was improved with a modular three-dimensional configuration which led to an increase in the performance, as well as a simpler and cheaper manufacturing and assembly process, with respect to previous studies. Further developments are proposed in terms of structural optimization of the geometrical parameters of the cell, more accurate modeling of the damage of the material and development of lattice structure following the same concepts. If these aspects are addressed, this work negative stiffness honeycomb could become a viable alternative in those contexts where conventional crash absorbers are not convenient for practical applications involving repeated impacts or when substitution of the device is made complex by environmental and economic factors, with the final result of reducing cost, time and work associated to the replacement of the deformed safety device after the collision.

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