Enhancing Crashworthiness in Origami Metastructures through Graded Stiffness Architectures

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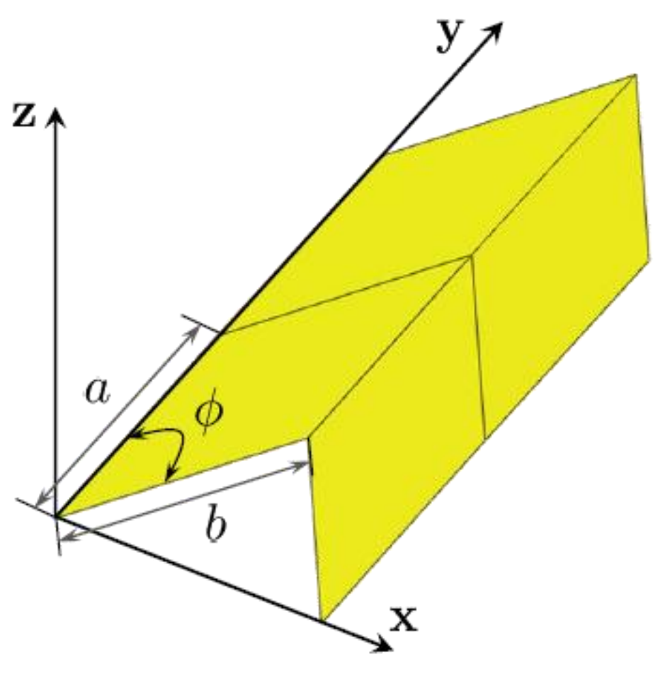
Abstract: *This study investigates the dynamic crushing behavior of multi-layered brass plates based on the Miura-Ori tessellation, focusing on the strategic implementation of graded stiffness to enhance Specific Energy Absorption (SEA). Using high-fidelity finite element analysis (Abaqus/Explicit) validated against experimental data, the research evaluates how varying sector angles (ϕ) across stacked layers influences deformation mechanisms under diverse loading rates. A comparative analysis between homogeneous and functionally graded configurations reveals that out-of-plane compression triggers a unique "self-locking" phenomenon in graded structures. Furthermore, the study explores the in-plane response, identifying a distinct auxetic behavior with negative Poisson's ratios (ν_{xy}) that persist under dynamic regimes. These findings suggest that origami-inspired gradations offer a programmable pathway for tailoring the impact response of next-generation aerospace and automotive components.*

1. Description of the Problem

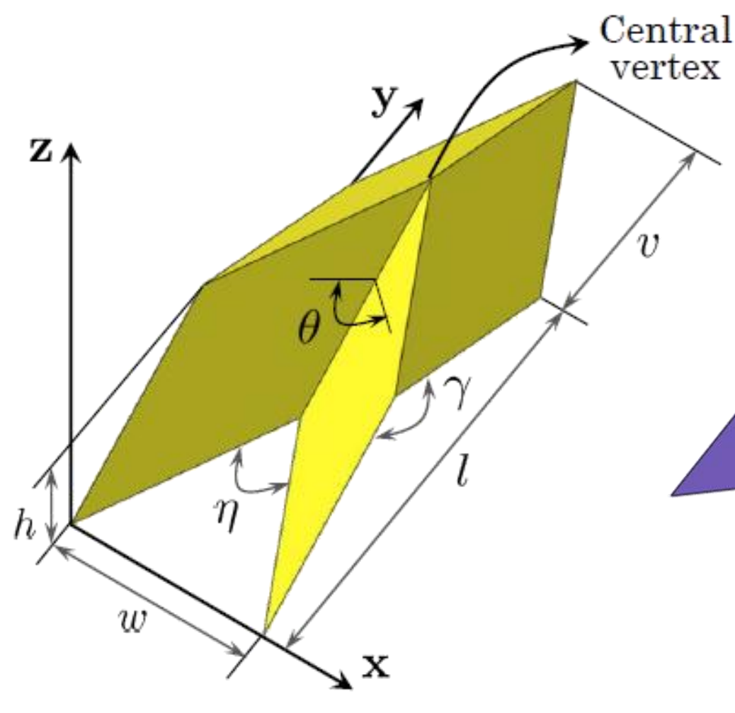
The problem analyzed consists on the uniaxial compression test of multi-layer Origami plates, in dynamic regime. The base geometry is the Miura-Ori unit cell, which can be defined using four independent geometrical parameters, which lead to six new geometrical entities defined by the following equations:

$$\cos\gamma = \frac{\sin^2\phi\cos^2(\theta/2) - \cos^2\phi}{\sin^2\phi\cos^2(\theta/2) + \cos^2\phi} \qquad \cos\eta = \sin^2\phi\cos\theta + \cos^2\phi \qquad w = 2b\cdot\sin(\eta/2) \qquad l = 2a\cdot\sin(\gamma/2) \qquad h = a\cdot\cos(\gamma/2) \qquad v = b\cdot\cos(\eta/2)$$

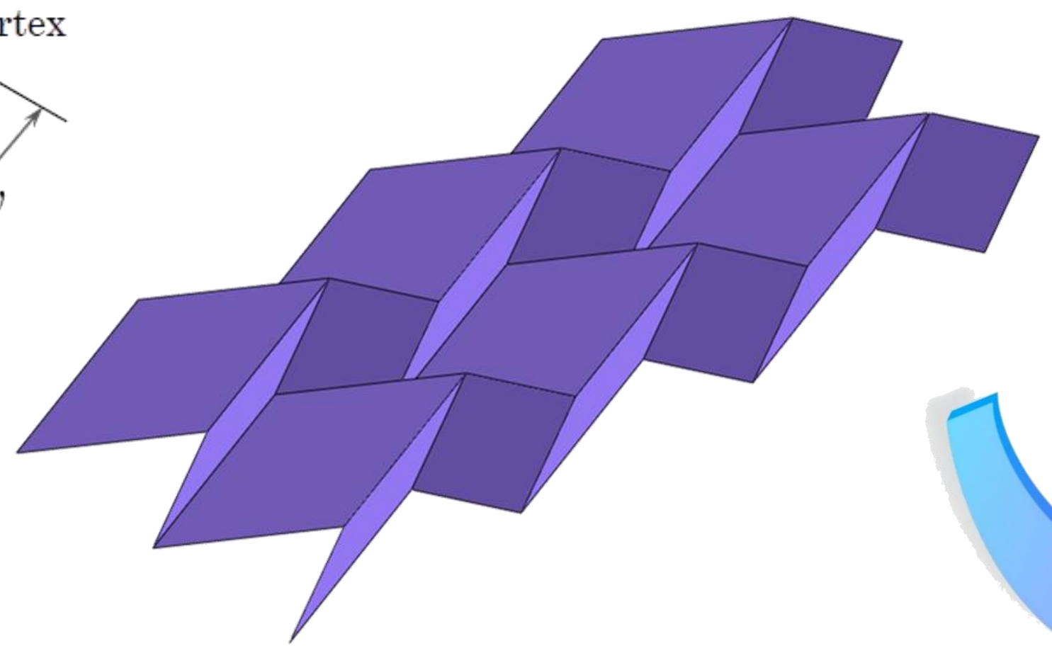
Geometrical parameters of the Miura-Ori unit cell



Unfolded Miura-Ori Unit Cell [1]



Folded Miura-Ori Unit Cell [1]



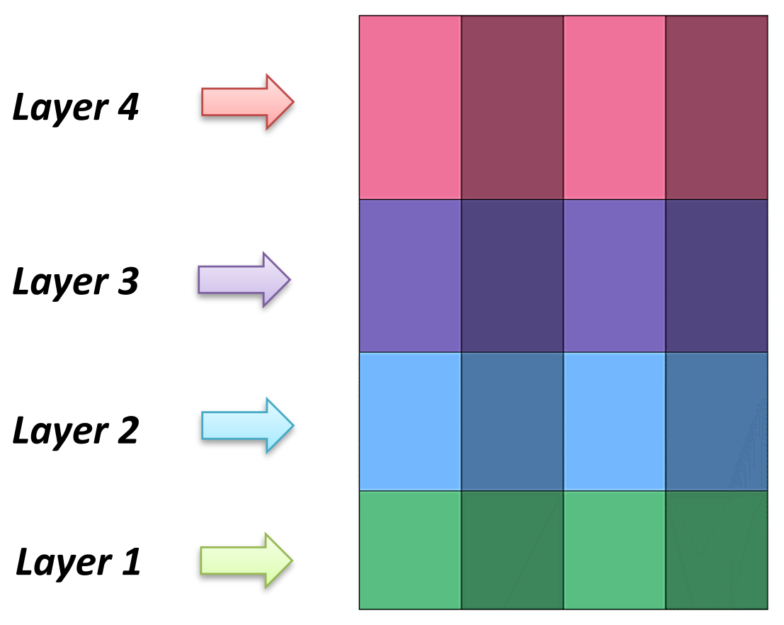
Single Layer

1.1. Configurations analyzed:

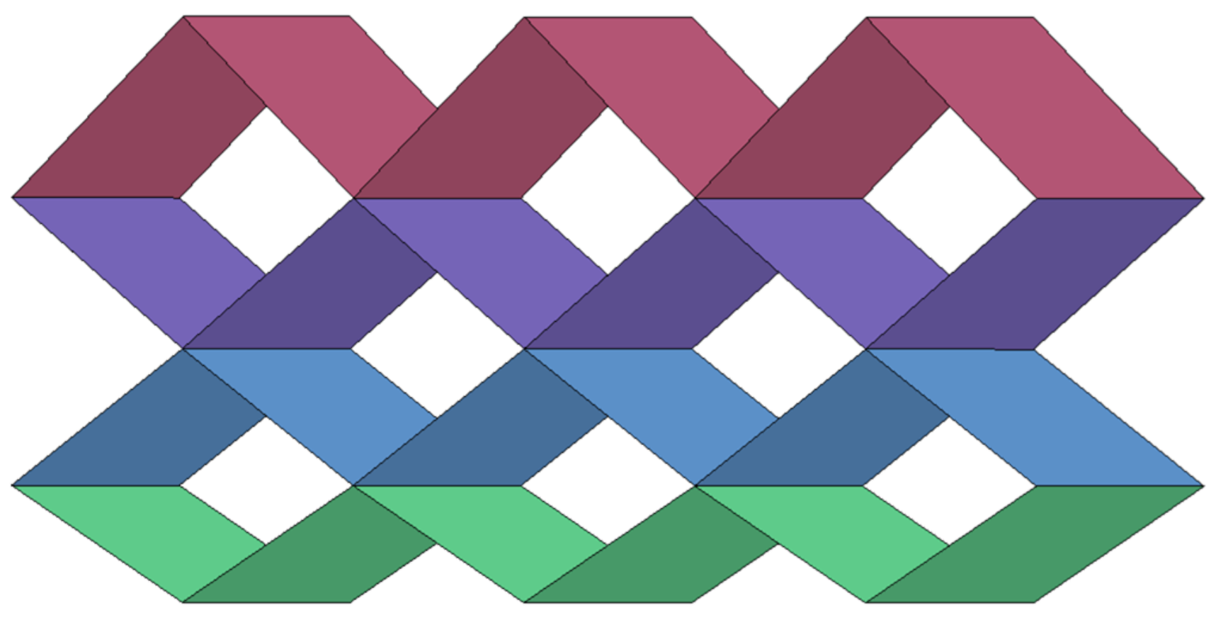
- Homogeneous structure: $\phi_1 = 48^\circ \ \phi_2 = 48^\circ \ \phi_3 = 48^\circ \ \phi_4 = 48^\circ$
- Graded structure: $\phi_1 = 39^\circ \ \phi_2 = 45^\circ \ \phi_3 = 51^\circ \ \phi_4 = 57^\circ$

1.2. Geometry of the graded structure:

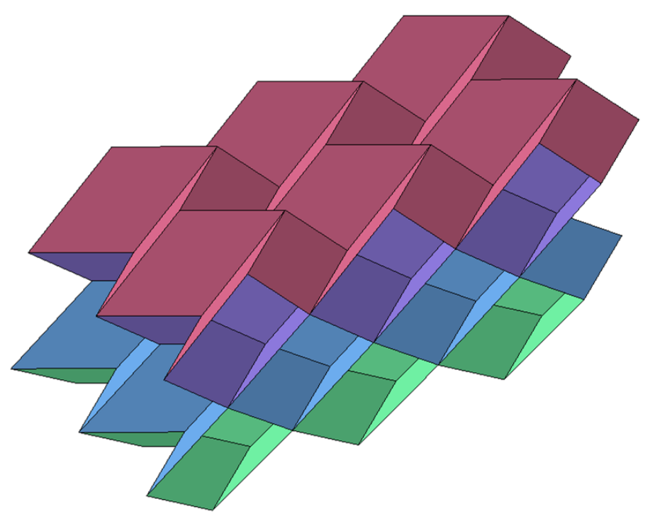
To create a 3D structure with geometric gradient, layers with different sector angles are stacked in the out-of-plane z direction. In this case, the geometrical parameters must fulfil some additional constraints



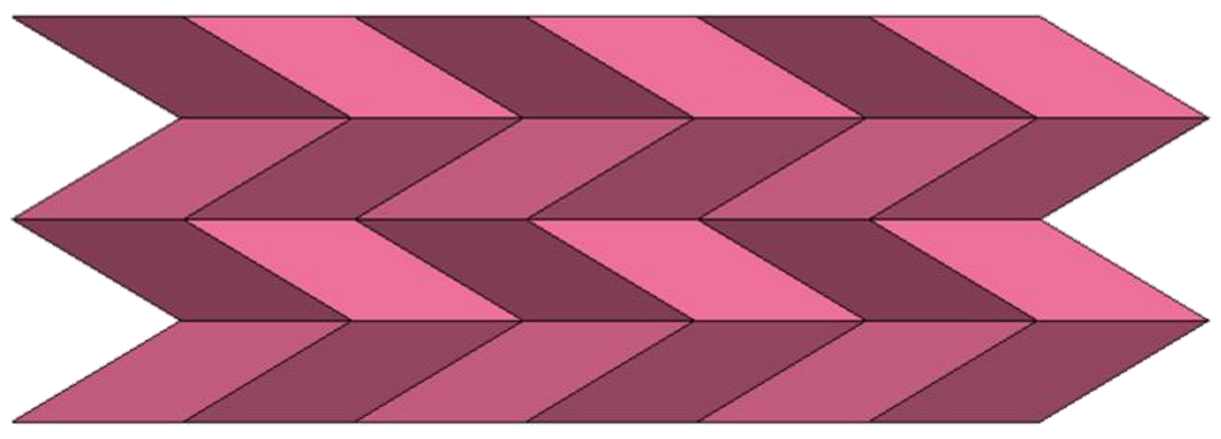
Side view



Front view



Multi-Layer



Top view

$$a_j = \frac{a_1\cos\phi_1}{\cos\phi_j} \qquad b_j = b_1 \qquad \theta_j = \cos^{-1}\left(1 - \frac{2\sin^2(\theta_1/2)\sin^2\phi_1}{\sin^2\phi_j}\right)$$

Geometrical constraints for the multi-layer structure

2. Material and Numerical Model

2.1. Material properties for Brass (CuZn40)

The material of the main structure has been considered has elastic-plastic with linear hardening equation [2].

Density	ρ = 8.33 g·cm^{-3}
Elastic Modulus	E = 111.1 GPa
Poisson coeficient	ν = 0.346
Yield stress	σ_y = 142 MPa
Tensile strength	σ_u = 424.9 MPa
Elongation	ε_u = 0.242

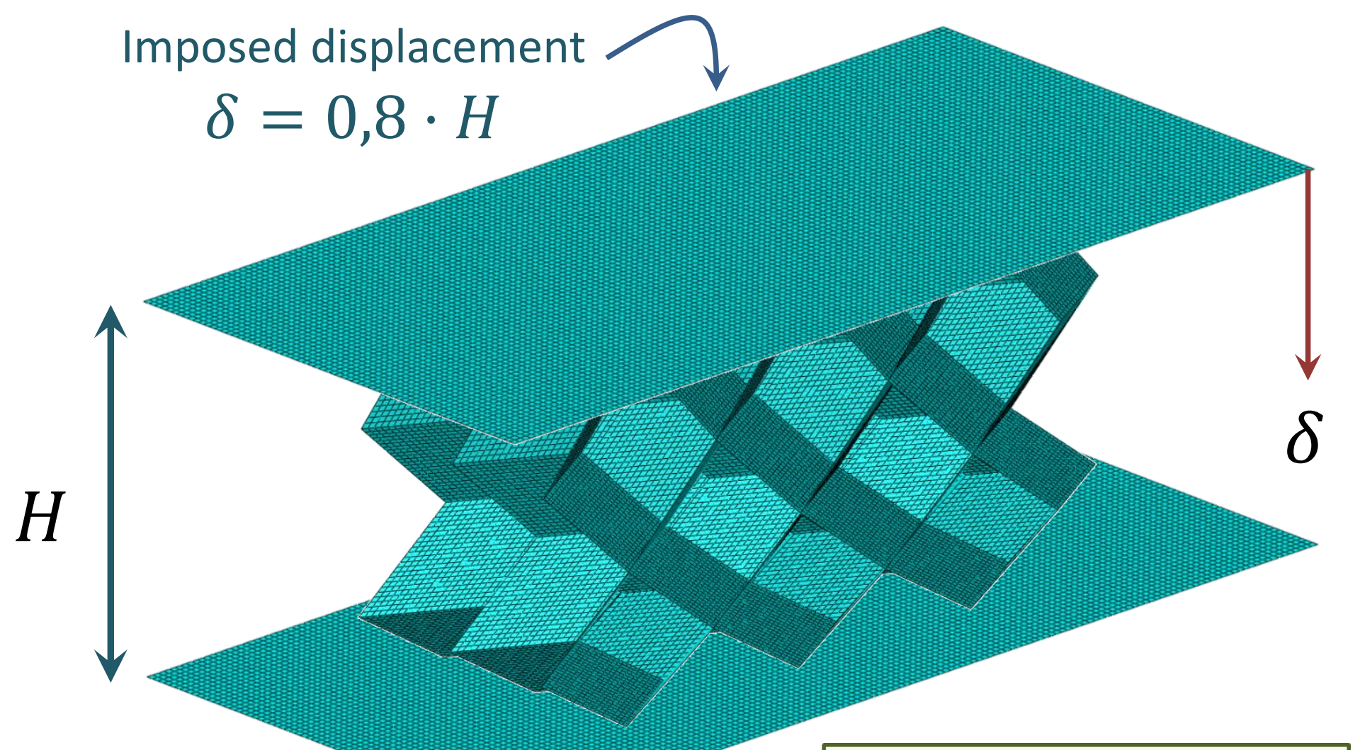
2.2. Material properties for steel:

Material considered for the compressive plates.

Density	ρ = 7.85 g·cm^{-3}
Elastic Modulus	E = 210.0 GPa

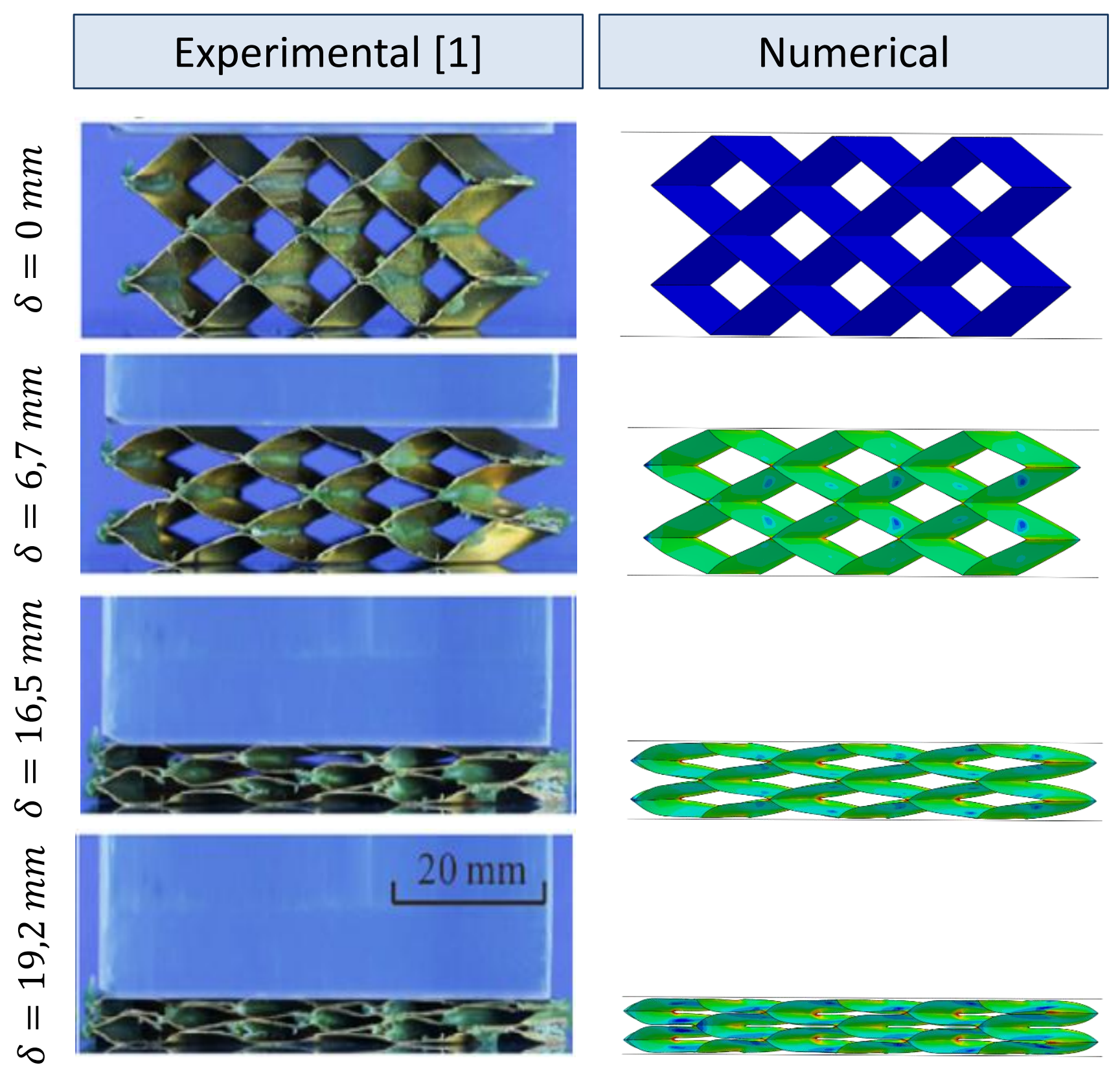
2.3. Numerical model

All the components, the two plates and the multi-layer origami structure, are defined as shell geometries

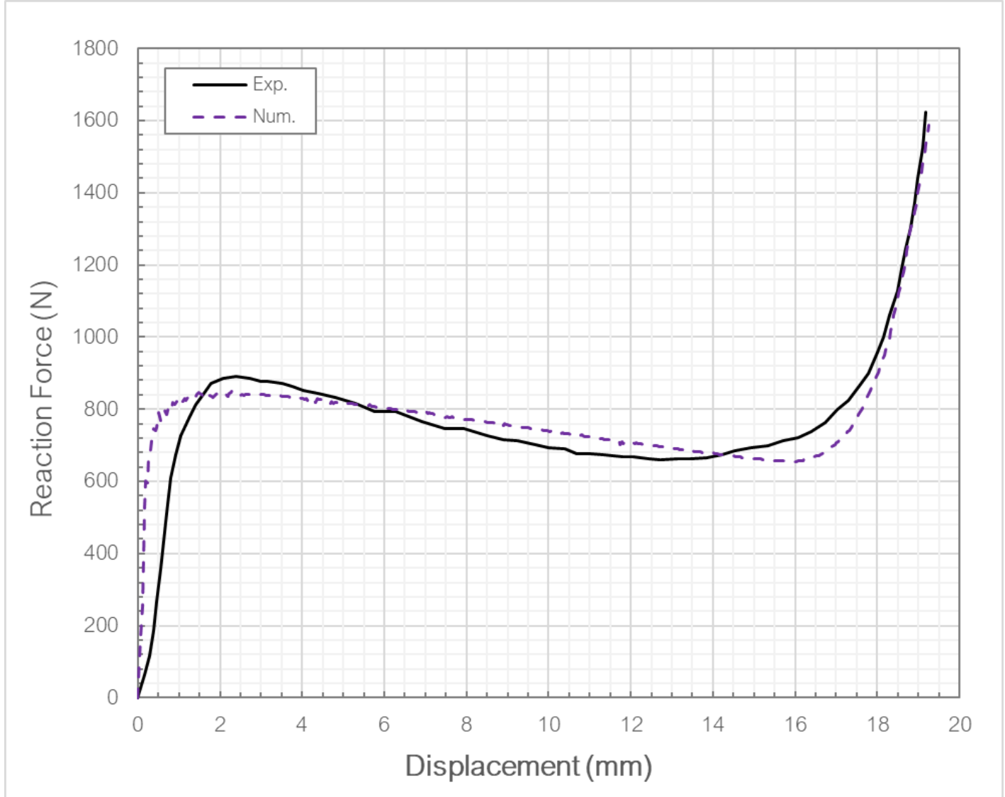


Model Information	
Number of elements	*45600*
Element type	*S4R*

3. Validation



The relative error in terms of absorbed energy is **3.28 %**



MODEL VALIDATED

4. Results

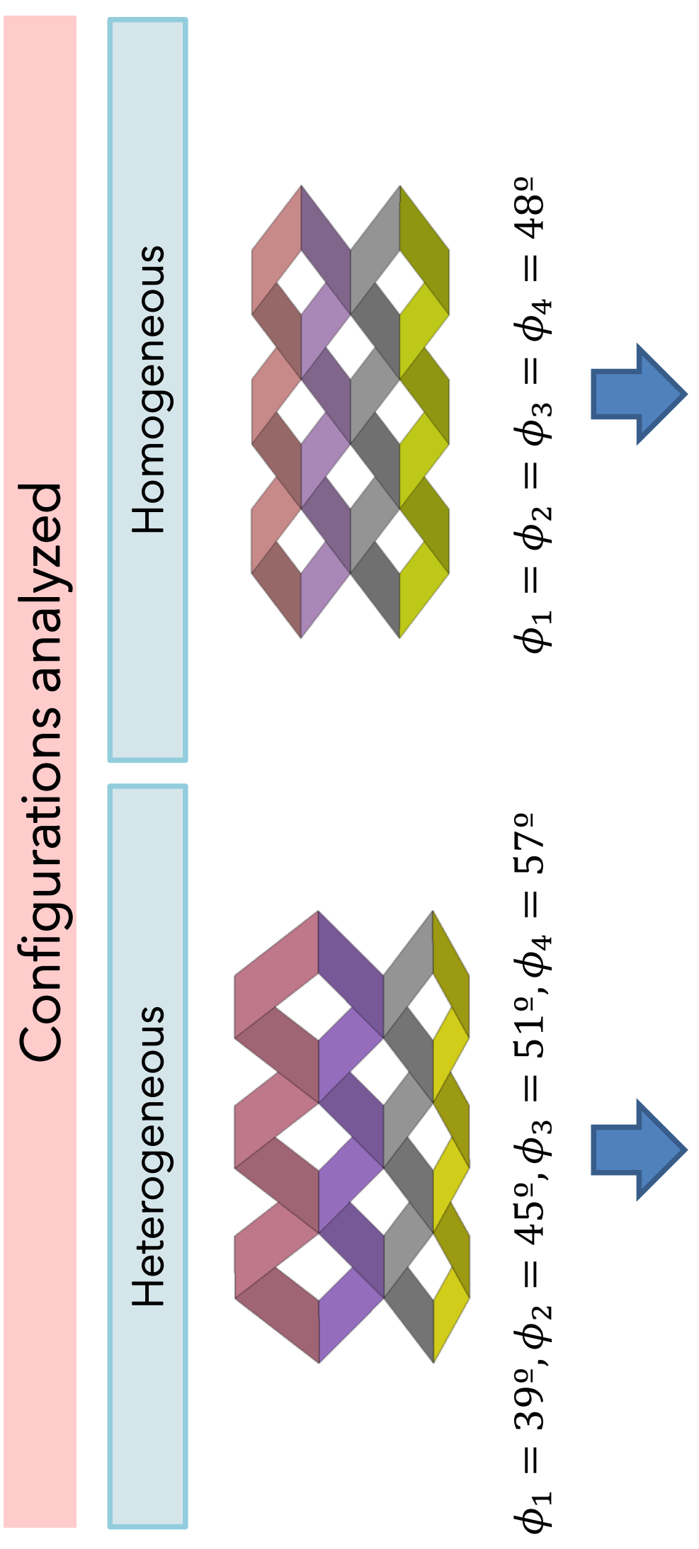
4.1. Effect of stacked sequence

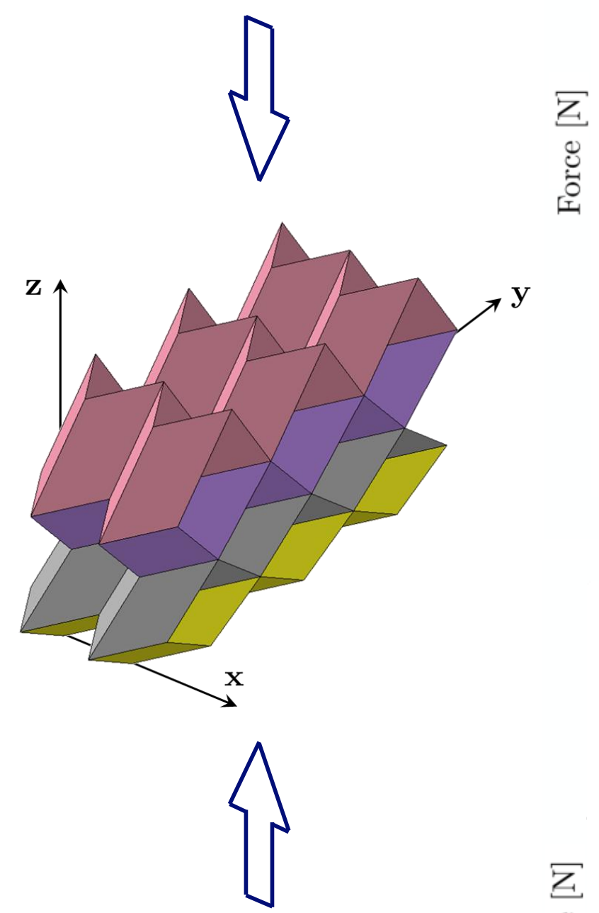
Two deformation mechanisms occur: **unfolding** and **crushing** (associated with buckling phenomena in the panels). The occurrence of one or the other is governed by the **self-locking phenomenon**.

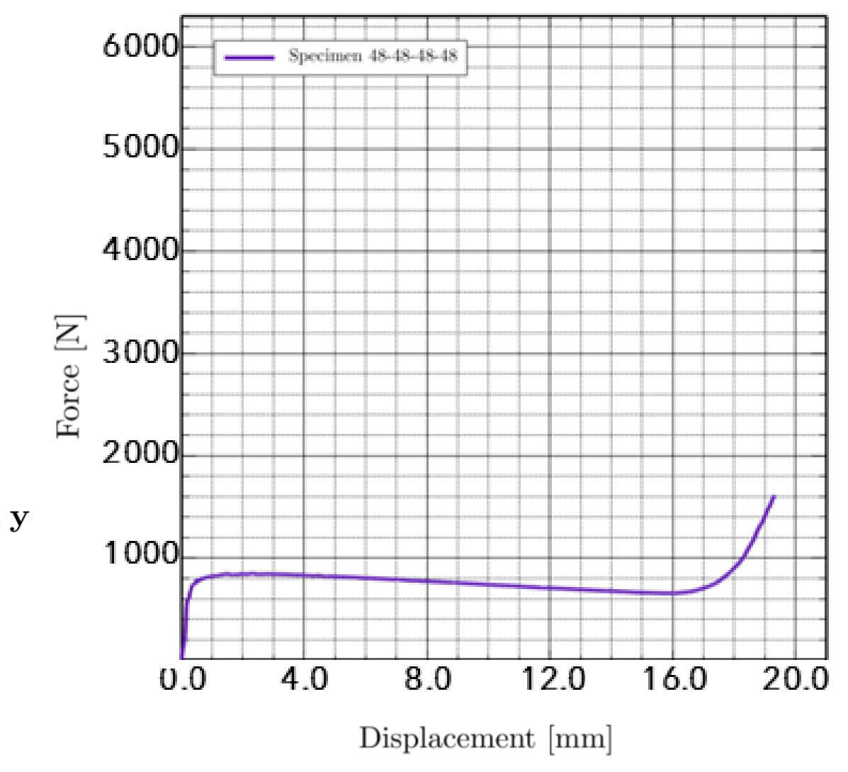
Applying compression perpendicular to the stacking direction results in **auxetic behavior** of the structure (negative Poisson's ratio). In this case, **there is hardly any difference between a homogeneous and a heterogeneous structure**.

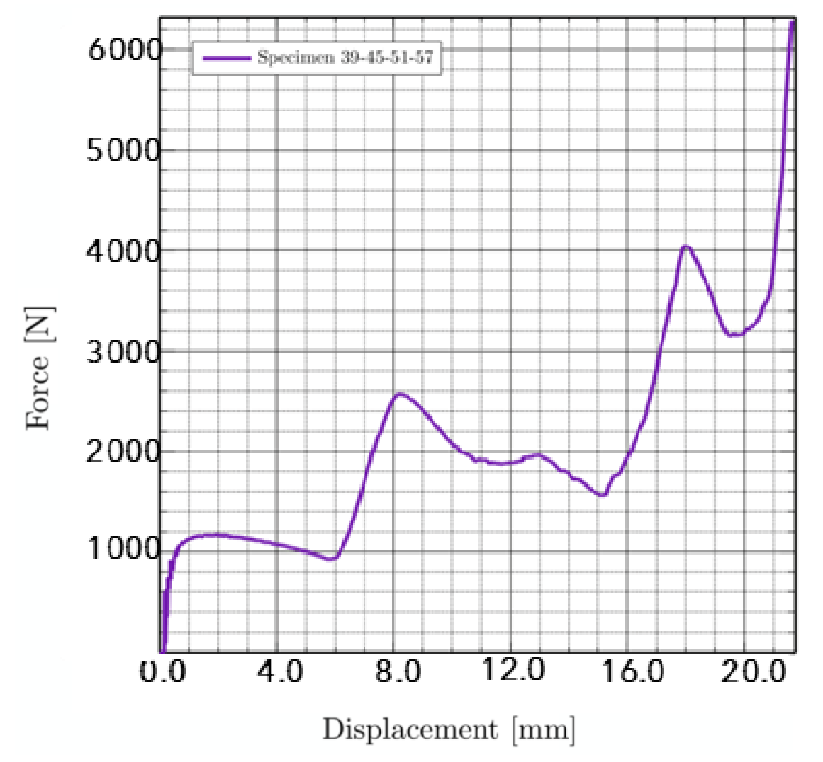
Graded Stiffness

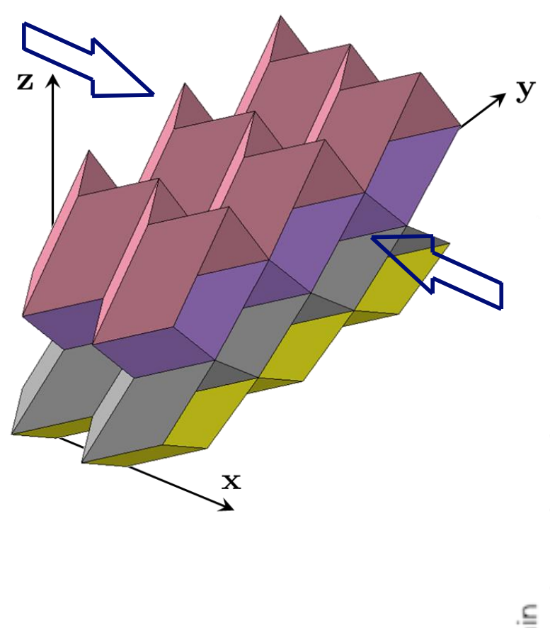
Graded Stiffness

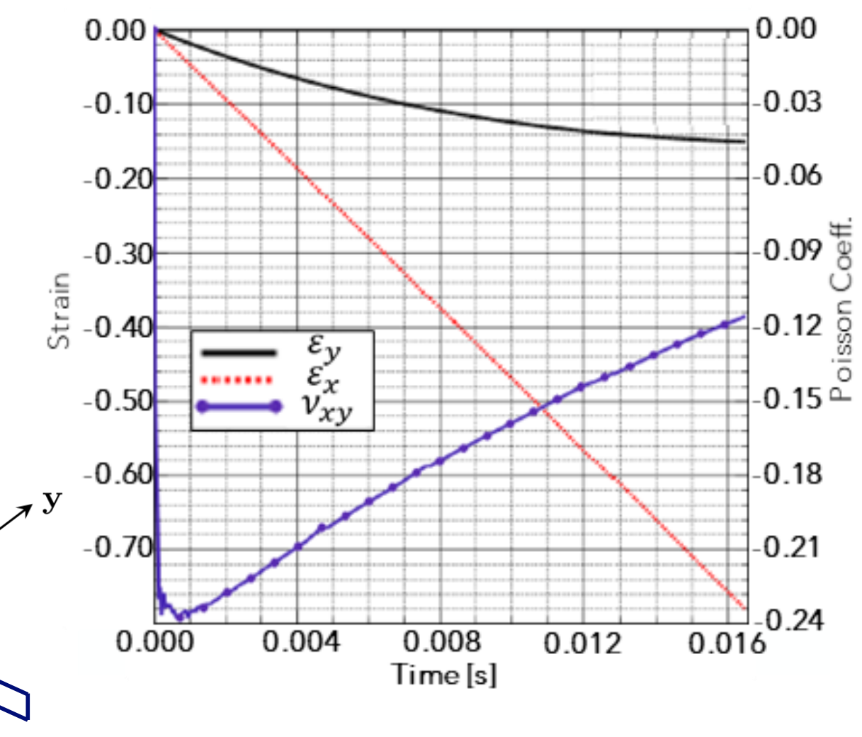


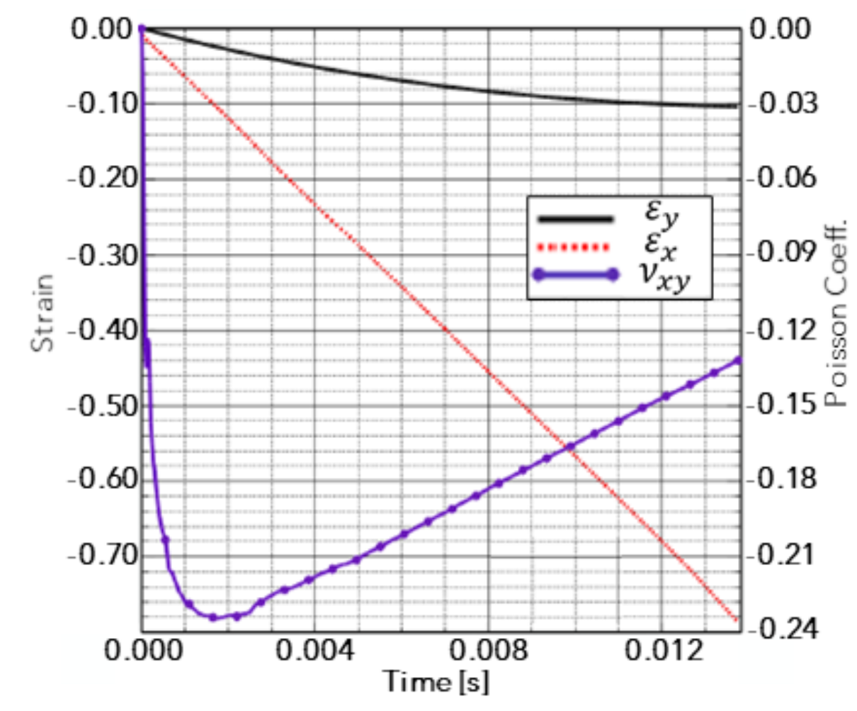




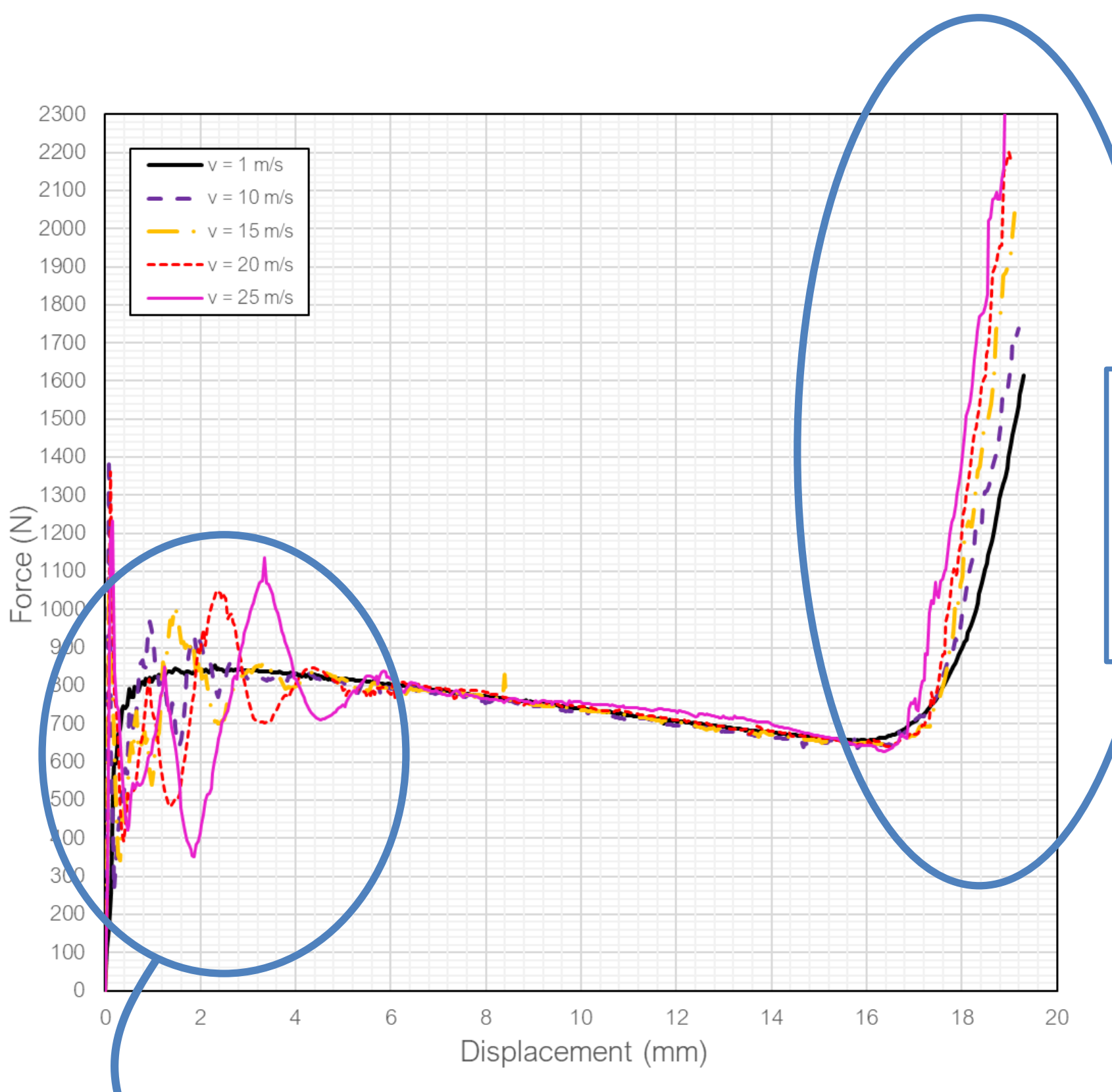






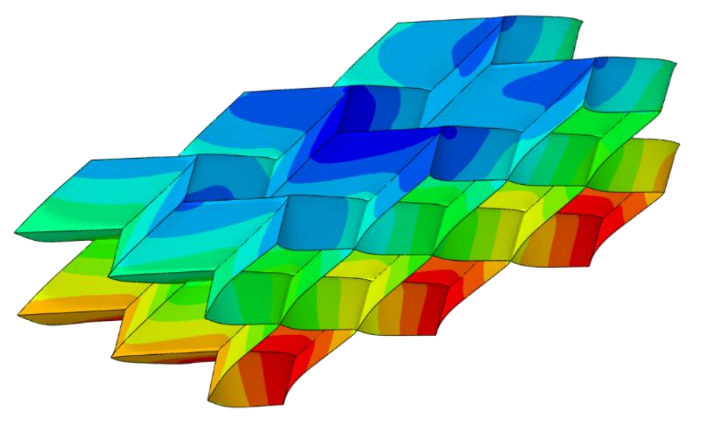


4.2. Influence of the compression velocity



The slope of the densification area is higher as the compression velocity increases.

The apparition of waves due to dynamic effects is more pronounced for higher velocities



5. Concluding Remarks

- ○ Using the Finite Element Method, a full 3-D numerical model of the compression tests in multi-layer metamaterial plate, has been implemented.
- ○ The **numerical model has been validated** with results published in the literature, leading to a **relative error of about 3 %.**
- ○ The morphological evolution of the structure during the compression process reproduce accurately the experimental observations.
- ○ The **self-locking phenomenon** that occurs in heterogeneous metastructures determines the predominant deformation mechanism: **unfolding or crushing**.
- ○ **Energy absorption capacity** increases significantly in **heterogeneous structures**.
- ○ Applying compression perpendicular to the stacking direction of the individual layers results in **auxetic behavior of the metastructure**. This behavior is not affected by the type of structure (homogeneous or heterogeneous).
- ○ The slope of the densification area in the Force-Displacement curve is higher as the compression velocity increases.

References

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[4] Mousanezhad D., Haghpanah B., Ghosh R., Hamouda A.S., Nayeb-Hashemi H., Vaziri A. Elastic properties of chiral, anti-chiral, and hierarchical honeycombs: a simple energy-based approach. Theoretical and Applied Mechanics Letters 2016; 6:81-96.

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