

A Modeling Study of Elastic Properties of Structured Fabrics under Vacuum Pressure

Emiliano Rustighi, Davide Raffaele, Paolo Gardonio, Ciro Malacarne, Matteo Perini

Abstract. Structured fabrics are compliant, engineered textile materials that can be designed using interlinked truss-like grain elements. Examples include traditional knitted sheets and chainmail armours, which are characterised by negligible bending stiffness in their unconfined state. Recent research, however, has shown that when subjected to confinement pressure, these structures exhibit increased stiffness, transforming them into cohesive structural materials and structures. This unique behaviour enables the development of lightweight, tuneable, and adaptive fabrics for a range of advanced applications, including wearable exoskeletons, haptic systems, and devices for passive and semi-active vibration and noise control, such as tuneable vibration absorbers. In this study, we present a homogenized physical model that describes the variation in elastic properties of in-vacuo structured fabrics with confinement pressure. Inspired by models for granular media, the proposed improved approach incorporates the effects of grain geometry. The model is then applied to predict the resonant response of finite beam structures. Predictions are validated through experimental results, demonstrating the model's capability to capture the mechanical adaption of the in-vacuo structured fabrics with confinement pressure.

Key words: In-vacuo structured fabrics, homogenized elastic properties

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1 INTRODUCTION

Traditional knitted fabrics are made from continuous flexible materials, such as fibres or wires which are interlaced to form two- or three-dimensional fabrics [1]. While 3D woven fabrics offer enhanced structural integrity, they still present a large compliance and they are not yet usable for engineering applications. Recent digital fabrication techniques, such as 3D printing and computational modelling, have enabled the creation of complex textile geometries with tailored mechanical responses [2, 3]. In particular, structured fabrics are composed of a network of rigid elements linked together in an established pattern, similar to medieval chain armour made by linkages of metal rings. These structures show quite a loose bending stiffness at ambient pressure. Imposing a confinement pressure on structured fabrics augments their bending stiffness. These are referred to as tunable structured fabrics (TSF) due to the capability of adjusting their bending stiffness through varying the applied confinement pressure.

A breakthrough in TSF was demonstrated by Wang et al. [4], who developed layered chain mail sheets composed of interlocking 3D particles. These fabrics exhibit dramatic stiffness modulation, up to a 25-fold increase, when subjected to external pressure, transitioning from a flexible state to a rigid, jammed configuration. Discrete-element simulations further revealed that such systems follow a jamming phase transition akin to conventional granular media, but with enhanced tunability due to their designed microstructures.

Recent studies have demonstrated the potential of tunable structured fabrics in adaptive mechanical systems, particularly for vibration mitigation and dynamic stiffness control. Rustighi et al. [5, 6] explored how vacuum-induced jamming in 3D-printed chain mails alters bending stiffness and damping properties, with experimental characterization under four- and six-point bending setups. The study revealed that compressive frictional forces and geometric interlocking significantly enhance stiffness, positioning these materials favourably in Ashby diagrams for lightweight adaptive applications. Building on this, the dynamic response of beam-like specimens with single- and multi-layered fabrics was investigated, showing that vacuum pressure effectively tunes bending stiffness and consequently resonance frequencies, though energy dissipation remained low due to minimal inter-particle friction post-jamming.

Further applications to vibration mitigation were introduced by Gardonio et al. [7], who developed an adaptive beam element with hollow truss-like particles, functioning as a tunable vibration absorber (TVA) via vacuum-modulated flapping modes. The study highlighted the role of particle geometry and stacking layers in defining tunable bandwidths, with non-convex contacts enabling broader stiffness ranges. Similarly, they proposed a multi-resonant TVA using vacuum-jammed structured fabrics [8]. The absorber, composed of a tree of deflated composite beams, demonstrated a tunable frequency band of 8 Hz (5–80 kPa vacuum), reducing plate vibrations by 10–20 dB. Together, these works underscore the versatility of structured fabrics in real-time adaptive systems, bridging granular jamming physics with practical vibration control solutions.

The concept of jamming, where disordered systems transition from fluid-like to solid-like states under compression or shear, has been extensively studied in granular and soft matter

physics [9, 10]. Frictionless soft spheres, for instance, exhibit an isostatic (marginally stable) state at the jamming point, where mechanical properties scale with the distance to this critical transition [9]. Recent work has extended this understanding to frictional and non-spherical particles, demonstrating that contact number and packing geometry play crucial roles in determining jamming behaviour [10]. The basic principles underlying the modelling of granular materials can significantly aid in the understanding of tuneable structured materials. Consequently, within the scope of this paper, we present a physical model aimed at elucidating the relationship between varying levels of confinement pressure and the material's stiffness.

2 TUNEABLE STRUCTURED FABRICS

2.1 Geometry of the Structured Fabric

The structured fabric design draws inspiration from medieval chain mail, where individual rigid structures are linked to form flexible garments. These fabrics are characterized by the geometry of the rigid base element, i.e. the grain, and the lattice arrangement of these elements. Figure 1 depicts the rendering of the base element and its connections to other elements within the fabric. The base elements feature a truss structure composed of curved beams arranged to create an octahedral sphere. They are connected in a lattice formation. Each element is a closed structure, produced and interconnected through rapid prototyping, as detailed in the subsequent section, thereby eliminating discontinuities from welding, gluing, or plastic deformation. Although previous research by the authors has examined various grain shapes, only the rounded octahedral sphere shape was analyzed in this instance, as its smooth exterior provides more consistent contact between grains. The rounded octahedral shape was explored in four distinct dimensions, as shown in Figure 1. Two outer diameters, $D = 6$ mm and $D = 10$ mm, along with two truss thickness d , $d/D = 0.1$ and $d/D = 0.15$, were investigated.

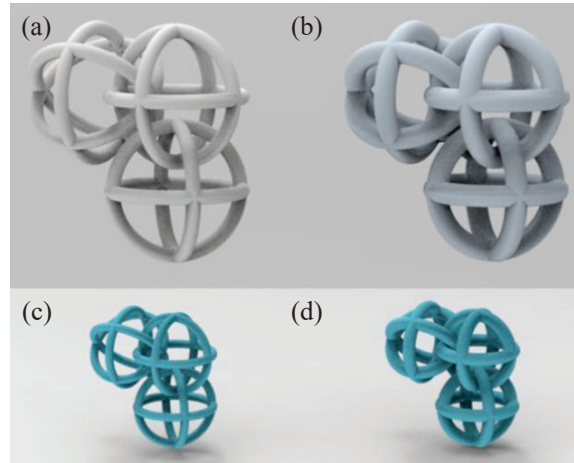


Figure 1: Rounded octahedral structured fabrics of different geometrical ratios: (a) $D = 10$ mm, $d = 0.10D$, (b) $D = 10$ mm, $d = 0.15D$, (c) $D = 6$ mm, $d = 0.10D$ and (d) $D = 6$ mm, $d = 0.15D$

2.2 Manufacturing and assembling

Structured fabrics were produced using Nylon PA12 through the HP Multi Jet Fusion (MJF) technology, a prevalent 3D printing method known for creating highly precise and durable components. MJF 3D printing is a part of the additive manufacturing technology that incorporates powder bed fusion, eliminating the need for support structures and intricate post-processing. During printing, any empty spaces are filled with unused powder, making MJF prints self-supporting. MJF excels in fabricating complex designs, permitting parts consolidation and intricate interconnected geometries, which pose challenges for other technologies. MJF allows for printing in ultra-thin layers, approximately 80 microns, resulting in low porosity and high density, providing excellent resolution and dimensional accuracy. The MJF 3D printing process produces highly isotropic parts with consistent strength across all directions. The printer used was a HP Jet Fusion 3D 4200, which has a build volume of $380 \times 284 \times 380$ mm. The samples were manufactured with extensions of about 20×8 cm. Table 1 presents the precise dimensions of each sample employed in the study. According to the supplier's data, the Nylon PA12 used for the realization of the samples has a tensile elasticity modulus of about 1800 MPa, and a part density of about 1.01 g/cm^3 .

The 3D-printed fabrics are also assembled inside an airtight vacuum bag in order to obtain TSF. In this study, vacuum bags (commonly used for food preservation) have been used to wrap one or multiple layers of the prototyped structured fabrics. Up to five layers have been overlapped in this study. Thermal sealing techniques have been employed to close off the open edges, while butyl tape has been applied to ensure an airtight fit at the junction with the vacuum pipe. Consequently, a diaphragm vacuum pump (KNF NEUBERGER UN726 TTP) was linked to the vacuum bag through a pneumatic conduit, incorporating a pneumatic valve and an analogue vacuum gauge.

2.3 Vibration Response of Tuneable Structured Fabrics

Each sample has been constrained as a beam in a simply supported configuration. The clamps were covered with thin layers of foam, in order to optimize the contact surface area between the clamps and to have an accurate specimen placement within the setup. A shaker applied excitation to the sample's midspan through a metal bar connection. A Modal Shop shaker model 2004E with a SmartAmpTM Series 2100E21 amplifier provided the excitation, while a PCB Piezotronics 288D01 impedance head measured the point receptance at the excitation location. Figure 2(a) illustrates the clamping and excitation arrangement for the TSF samples. Testing was conducted under six varying confinement pressures: 5, 10, 20, 40, 60, and 80 kPa. Figure 2(b) depicts the model which has been used to analyse the testing configuration. The sample fabric can be viewed as a homogeneous, uniform beam with simply supported ends, with a harmonic force applied at its midspan via a bar which is modeled as an additional point mass m .

The measured receptances for the sample fabrics with grains with $D = 10\text{mm}$ and $D/d = 0.15$ are depicted in Figure 2(c). The analysis shows that, within the relevant frequency range,

Table 1: Dimensions and weight of the TSF samples

Shape	Layer	Weight[g]	Length[cm]	Width [cm]	Depth[cm]
$D = 6 \text{ mm}$ $d/D = 0.1$	1	9.17	19	6.5	0.6
	2	18.34	19.5	6.5	1
	3	27.51	20	7	1.5
	4	36.68	20	7	2
	5	45.85	20.5	7	2.5
$D = 6 \text{ mm}$ $d/D = 0.15$	1	25.6	23.0	8.0	0.60
	2	51.2	22.0	9.5	1.25
	3	76.8	22.0	9.5	1.75
	4	102.4	22.5	9.5	2.25
	5	128	23.0	9.5	2.50
$D = 10 \text{ mm}$ $d/D = 0.1$	1	18.35	22.5	7.5	1
	2	36.7	22.5	7.5	1.75
	3	55.05	23	7.25	2.5
	4	73.4	23	7.5	3.25
	5	91.75	23	7.5	4
$D = 10 \text{ mm}$ $d/D = 0.15$	1	41.1	22.5	7.75	1
	2	74	19.5	9	1.75
	3	111	20.5	8.5	2.5
	4	148	21.75	8	3.25
	5	165.5	23	7.75	4

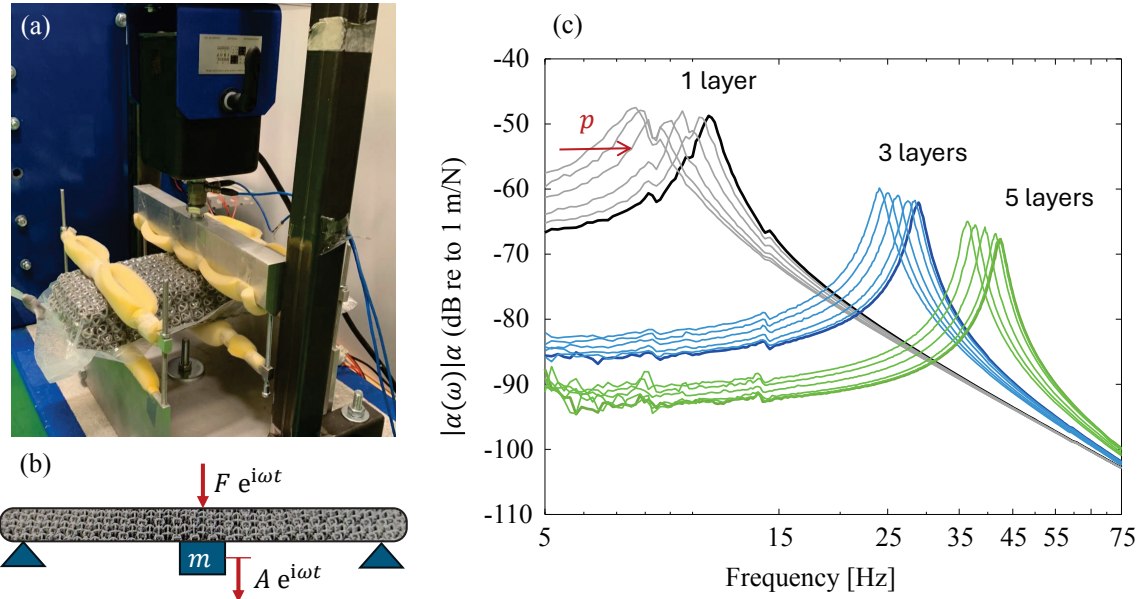


Figure 2: Experimental setup (a), equivalent model (b) and exemplary mobility responses of samples with $D = 10\text{mm}$ and $D/d = 0.15$ (c)

the system behaves as a single degree-of-freedom system. The confinement pressure modifies the effective Young's modulus of the structured fabrics, i.e. an increase in the confinement pressure p raises the resonant frequency.

3 MODEL OF THE VACUUM CONTROLLED RESPONSE

This section proposes a model illustrating the relationship between Young's modulus and confinement pressure. The subsequent section outlines the sphere-pack model as sourced from soil dynamics literature. The following subsection modifies the soil model for application to the TSF, while the concluding subsection evaluates the model against experimental data.

3.1 The soil sphere-pack model

To explain the dependence of the macroscale Young's modulus on the confinement pressure, a sphere-pack model that makes use of the Hertz theory can be considered [11]. This model encompasses an elementary volume made of identical spheres lined up in rows parallel to the coordinate axes, as depicted in Figure 3(a). Utilizing Hertzian contact theory [12], the stiffness of contact among two perfectly elastic spheres is formulated as

$$k_c(F) = \left[\frac{3 E_s^2}{8(1 - \nu_s^2)^2} \right]^{1/3} D^{1/3} F^{1/3} \quad (1)$$

where E_s and ν_s denote the Young's modulus and Poisson's ratio of the sphere material, D reflects the spheres' diameter, and F represents the force causing their contact. The stiffness

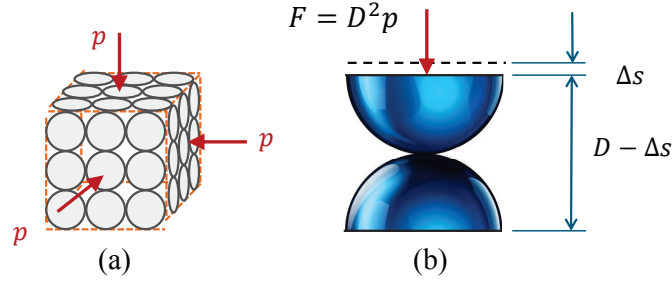


Figure 3: The soil sphere-pack model with all grain disposed in a lattice and confined by the pressure p (a) and the contact between two spheres in the elementary cell of dimension $D \times D \times D$

is evidently force-dependent in a nonlinear fashion, following a cubic root stiffening pattern. The authors suggest that this phenomenon underlies the macroscopic effect of confinement pressure-induced stiffening in a vacuum. They argue that inter-grain frictional forces are not responsible for alterations in the vibrational response, as relative sliding is minimal with small displacements. This aligns with results from a previous study which showed an absence of variation in damping ratio with confinement pressure [6].

Assuming pressure impacts the elementary cell of an equivalent isotropic, homogeneous material, modeled as a cube with side length D , the correlation between contact force F and confinement pressure p is expressed by

$$F = D^2 p. \quad (2)$$

The compressional stiffness for a basic cube with side length D is described by $k_c = ED$, where E represents the effective Young's modulus. Consequently, the expression for the elastic modulus is derived as follows:

$$E(p) = \frac{k_c}{D} = \left[\frac{3 E_s^2}{8(1 - \nu_s^2)^2} \right]^{1/3} p^{1/3}. \quad (3)$$

The soil sphere-pack model yields a nonlinear correlation between the effective Young's modulus E and the cubic root of the confinement pressure, $p^{1/3}$. The model is also independent of the grains geometry. In fact, the grain diameter D and the truss thickness d do not appear in Equation (3).

3.2 The rigid truss-like sphere-pack model

The previous model can be adapted to TSF by considering that the contact happens between two curved beams. Equation (1) can be modified to consider the contact as occurring between two convex surfaces with a double curvature given by the diameter of the grain D and the diameter of the trusses d . Using an approximated expression for the contact curvature, the contact stiffness can be expressed as

$$k_c(F) = \left[\frac{3 E_s^2}{4(1 - \nu_s^2)^2} \right]^{1/3} \left(\frac{1}{D} + \frac{1}{d} \right)^{-1/3} F^{1/3}. \quad (4)$$

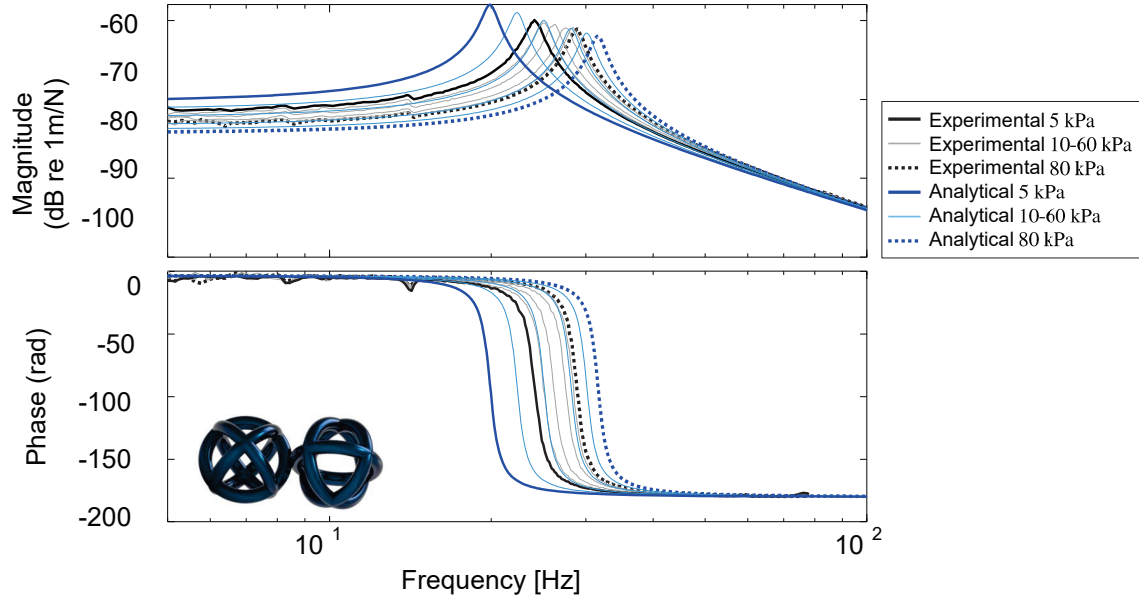


Figure 4: Measured and simulated point receptance of the sample made with five layers of the tuneable structured fabric with $D = 10$ mm and $d/D = 0.10$

Subsequently, the effective Young's modulus is determined as

$$E(p) = \frac{k_c}{D} = \left[\frac{3 E_s^2}{8(1 - \nu_s^2)^2} \right]^{1/3} \left(1 + \frac{D}{d} \right)^{-1/3} p^{1/3}. \quad (5)$$

The final evaluation of Young's modulus serves as a basis for calculating the point mobility of a simply supported beam excited at its midpoint under confinement pressures of 5, 10, 20, 40, 60, and 80 kPa. The outcomes derived from the model for a specimen with five layers, where $D = 10$ mm and $d/D = 0.1$, are presented in Figure 4 alongside the empirical results. In this configuration, there is a notable correspondence, though the model slightly over-predicts the stiffness variation with confinement pressure compared to empirical observations.

Figure 5 provides a comparison of resonant frequency shifts from both experimental measurements and the rigid-truss sphere-pack model. Concerning the average natural frequency, the model effectively delineates the stiffness variation with confinement pressure, displaying high precision for structured materials with $d/D = 0.1$, while underestimating shifts in the central resonant frequency for those with $d/D = 0.15$. As for the bar sizes and thereby the tuneability range, the model accurately represents TSF with smaller grains ($D = 6$ mm) but overestimates the adaptability range for larger grains ($D = 10$ mm).

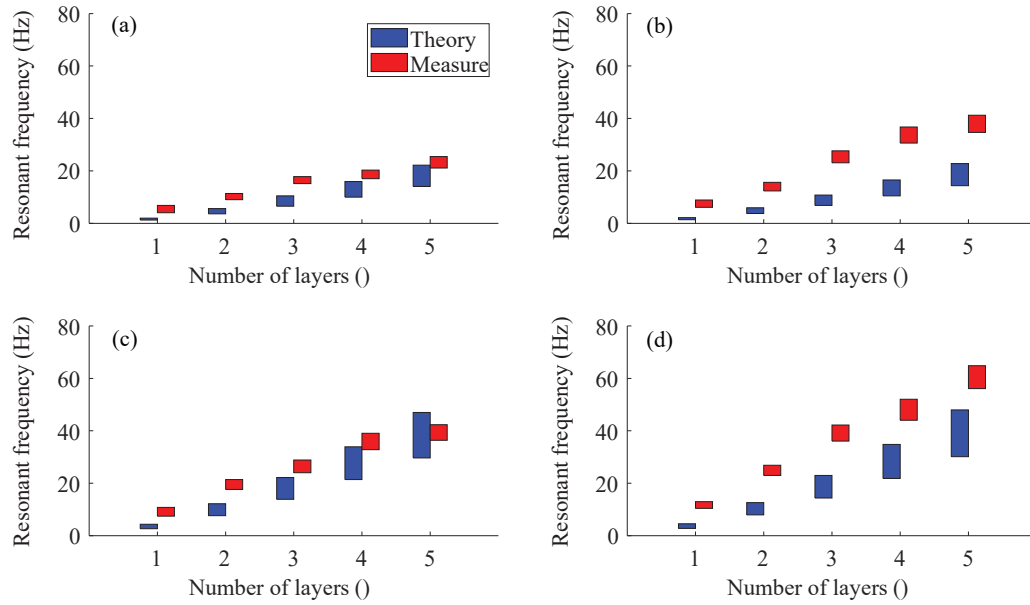


Figure 5: Measured and simulated ranges of resonant frequency tuneability for confinement pressure from 5 to 80 kPa: (a) $D = 6$ mm, $d = 0.10D$, (b) $D = 6$ mm, $d = 0.15D$, (c) $D = 10$ mm, $d = 0.10D$ and (d) $D = 10$ mm, $d = 0.15D$

4 CONCLUSIONS

A homogenized physical model that describes the variation in elastic properties of in-vacuo structured fabrics with confinement pressure has been presented. The model incorporates the effects of grain geometry and contact topology. The proposed approach has been applied to predict the resonant response of finite beam structures realized with tunable structured fabrics. Predictions have been validated through experimental results, demonstrating the model's capability to capture the mechanical adaptation of the structured fabrics. The relationship between Young's modulus and the cubic root of the confinement pressure is derived, displaying high precision for structured materials with $D = 6$ mm, while underestimating shifts in the central resonance frequency for those with $d/D = 0.15$. This research provides a scientific understanding of the adaptability of tuneable structured fabrics, suggesting an initial strategy toward the engineering of granular jamming mechanics for effective vibration control applications.

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