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Switchable stiffness morphing aerostructures based on granular jamming

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Switchable Stiffness Morphing Aerostructures using Granular Jamming

J. David Brigido[1], Steve G. Burrow[1] and Benjamin K.S. Woods[1]

Abstract
One of the persistent challenges facing the development of morphing aerostructures is the need to have material and structural solutions which provide a compromise between the competing design drivers of low actuation energy and high stiffness under external loads. This work proposes a solution to this challenge in the form of a novel switchable stiffness structural concept based on the principle of granular jamming. In this paper, the concept of using granular jamming for controlling stiffness is first introduced. Four-point bending tests are used to obtain the flexural rigidity and bending stiffness of three different granular materials under different levels of applied vacuum loading. Non-linear Finite Element Analysis simulations using experimentally derived non-linear material properties shows good agreement with experiment. A specific application of this concept it then proposed based on the Fish Bone Active Camber morphing airfoil. A unit cell of this concept is built, tested, and analyzed, followed by the first prototype of a complete switchable stiffness Fish Bone Active Camber morphing airfoil, which is experimentally shown to be able to achieve an increase in stiffness of up to 300% due to granular jamming.

Keywords
Morphing wings, variable stiffness, granular jamming, adaptive structures, non-linear materials, non-linear Finite Element Analysis.

Introduction

Removing discontinuities from aerodynamic surfaces

Control surfaces like ailerons, elevators, and rudders are essential for directional control of aircraft whilst other deployable surfaces such as slats and flats provide adaptation to different flight speeds; however, their conventional implementation incurs an aerodynamic penalty in the form of drag. This drag penalty limits their ability to be used continuously over the course of a mission to optimise aerodynamic performance. The increased drag is due in part to the discontinuities in the aerodynamic surfaces caused by traditional discrete, mechanism-based (e.g., trailing edge flaps) control surfaces. To improve upon this situation, there has been growing interest in the use of adaptive or morphing structures to create smooth and continuous changes in wing shape (Barbarino et al. (2011), Sun et al. (2016)), in a manner which removes the discontinuities of traditional approaches and allows for more complex, three-dimensional changes in shape.

One promising morphing concept under development by the authors is the Fish Bone Active Camber concept (FishBAC) introduced by Woods and Friswell (2012), shown in Figure 1, which is inspired by the internal structure of fish. Fish can achieve large deflections while swimming motions by bending their bodies around a central internal spine, with rib bones to support their cross-sectional shape and elastic, deformable skin to maintain a smooth fluid contact surface. The FishBAC uses a similar idea to create smooth and continuous changes in airfoil camber from a compliance-based morphing concept, with a central bending spine, stringers to maintain the airfoil profile, and a pre-tensioned elastomeric skin. Camber change is driven by an antagonistic tendon system which transfers actuation torque into bending moments on the trailing edge. The resulting smooth and continuous camber change has been experimentally shown to increase the lift-to-drag ratio by 20% to 25% when compared against traditional, discontinuous trailing edge flaps (Woods et al. (2014)).

An undesirable aspect of compliance-based morphing concepts is that energy must be put into the structure during morphing to overcome the elastic stiffness of the compliant mechanism. While this energy can be minimized during the design process through careful selection of geometry and material parameters (Woods and Friswell (2016)), there is still an intrinsic coupling between the stiffness of the device experienced by the actuator (which we desire to be low) and the stiffness of the device when encountering external loads (which we desire to be high).

Since these competing requirements for stiffness are present in many different morphing concepts, several materials and structural concepts have been proposed to address the issue (Hemmelgarn and Pelley (2015), Philen et al. (2006), Kuder et al. (2013), Imamura et al.

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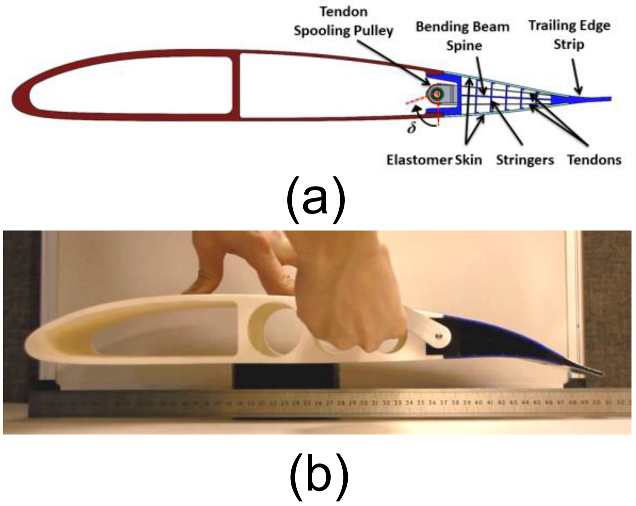


Figure 1. The FishBAC a) concept schematic and b) prototype deflected downwards

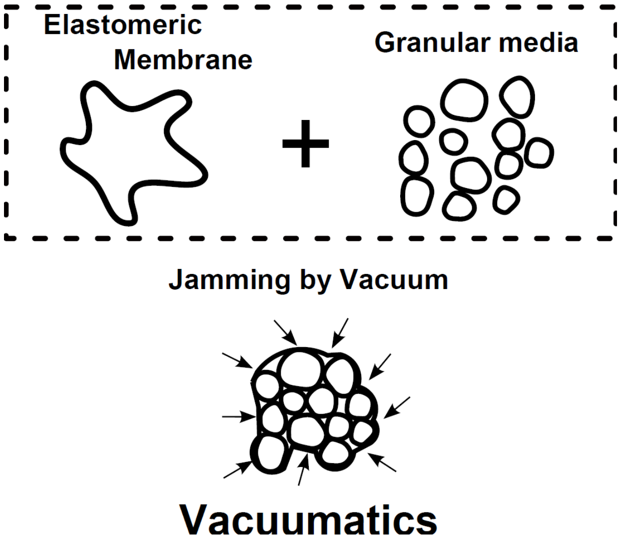


Figure 2. Granular jamming by vacuum (vacuumatics)

(2017)). This work proposes another approach to the problem, one that adopts the mechanical concept of granular jamming to create a switchable stiffness morphing structure. The use of granular jamming allows for rapid, substantial changes in stiffness with zero energy required to hold. When applied to morphing aerostructures in general, or the FishBAC in particular, this creates a structure with significantly increased resistance to external loads, the ability to maintain deflection without actuator input, and only modest increases in actuation energy requirements when deforming the structure.

Granular Jamming and Vacuumatics

Granular materials like sand, glass beads, coffee grains, etc., typically exist in a free-flowing, liquid-like state. They can easily be poured and have low resistance to deformation (Bi et al. (2011)). However, if compressive forces are applied to the bulk material the grains are forced into each other (in a process known as 'jamming') in a manner which creates a mechanical interlocking, allowing for force transfer from particle to particle and creating a significantly stiffer and stronger bulk material. The degree of jamming present in a given body of granular media is often considered with respect to its packing fraction, ϕ, which describes the fraction of volume of the particles to the total volume, approximated as:

$$\phi = \frac{\sum N_p V_p}{V_s} \qquad (1)$$

Where N_p is the number of particles in the structure, V_p is the volume of the particle, and V_s is the volume of the structure. This parameter is highly dependent on the type of arrangement or packing. Granular jamming systems have different packing volume properties and different types of contacts known as kissing numbers (the number of connections from one particle with the surrounding particles). In order to create a system with variable jamming, and therefore variable stiffness, a variable volume container can be created for the granular media. One common approach to this is to contain the granular media within a flexible, sealed membrane. Applying vacuum to this container will then lead to reductions in volume as the external atmospheric pressure forces the particles closer together. The stiffness of the device will then be proportional to the applied vacuum pressure differential, which tunes ϕ. This type of mechanism is known as 'Vacuumatics' or 'Deflateables' (Gilbert et al. (1970), Knaack et al. (2008)). Figure 2 shows a schematic representation of this approach. This type of jammed system has previously been used to create deformable structures for civil engineering and soft robotics applications.

Ivan Petrovic introduced the first granular jamming-based variable-stiffness structural application controlled by vacuum in 1970 (Gilbert et al. (1970)). He created a dome structure built of Polystyrene beads as granular material and Polyvinyl chloride as the elastic membrane. His idea was to use a vacuum pump to generate internal vacuum pressure with the aim to stabilize the whole structure in a specific position. His primary objective was to be able to use these structures for buildings or architecture devices. Petrovic was also the first person to use the term "Vacuumatics" (Svetel (2002)). This definition describes the integration of granular jamming into a deformable structure and control by vacuum.

One of the first robotics applications of granular jamming is found in the area of medicine; Loeve et al. (2010) from TU Delft university created a flexible endoscope that can change shape and stiffness at the same time using granular jamming media. The idea of this mechanism is that the endoscope should be flexible and soft when is inserted into the patient and when it reaches the desired position, it will transition to a rigid and robust state during surgery.

Cheng et al. (2012) from the Massachusetts Institute of Technology designed a soft robotic manipulator composed of several sections that can move to different positions using cables controlled by spooling motors. These sections are easily moved due to the integration of granular jamming. The robot can locally tune the stiffness of each section during actuation to reduce actuation torques and help isolate desired degrees of freedom, allowing for a reduction in the size and power requirements of the driving actuators needed to achieve a given stiffness under load. On the other hand, Cheng does not consider the flexural properties of jamming systems, despite the target application being bending dominated.

This paper introduces and discusses the variable stiffness effect in granular jamming with elastic membrane using vacuum as a control for the packing fraction. The research presented builds on previous work on granular jamming and will focus on the material characterization of jammed systems considering flexural properties, with bending stiffness and flexural rigidity being experimentally measured for three types of granular materials and hybrid combination between them using four-point bending tests. Then, non-linear FEA (finite element analysis) simulations were created to analyzed and compared the change of stiffness of the granular jamming structure using the flexural properties (non-linear stress-strain curves) obtained from the material characterization. This material characterization work naturally led to the design, manufacture and experimental testing of Switchable Stiffness FishBAC prototypes, beginning first with a single unit cell of the repeating spine structure, followed by the first prototype of a full device.

Mechanical characterization of granular jamming devices

Compression properties

Triaxial tests are a common way to investigate how the compression stiffness changes as a function of vacuum, among the first that analyzed this phenomenon, were Zalewski and Bajkowski (2007), and later on Cheng (2013), and Hudson (2012), among others. They found that the stress-strain curves show a linear behavior for small strain values, transitioning to non-linear behavior at higher strain values. Previous work has also shown that the compressive stiffness is dependent on the type of granular material, size, and the shape of the grains.

Hudson (2012) and Cheng (2013) performed tri-axial compression tests varying the size of the different type of particles at different vacuum level variations. They conclude that the change of size can increase the stiffness by less than one order of magnitude; however, the variation of vacuum can vary the stiffness by more than one or two orders of magnitudes depending on the type of material.

The type of material can change the stiffness significantly for different vacuum variations up to 1 bar. For some materials, an increase of stiffness can vary from less than one order of magnitude; for others can vary more than two orders of magnitude, this variation gap is due to friction. Rough surface materials tend to be stiffer than smooth surface materials.

Among the most interesting properties is the change in stiffness when the shape of the granular material changes; the first to highlight these properties was Athanassiadis et al. (2014) using the same granular material but a different shape with vacuum variation. Results showed that it is possible to increase the level of rigidity by “about one order of magnitude” when the shape of the particles changes. On the other hand, Athanassiadis concluded that the best way to change the magnitude of the stiffness is by controlling the packing fraction using vacuum variation and found that it is possible to increase the rigidity at least “two orders of magnitude” (Athanassiadis et al. (2014)).

One aspect which complicates comparisons between results from the previous works mentioned above, or indeed the application of those results to new work, is the lack of standardized test methods for these types of material. It has been attempted to analytically model the change of rigidity as a function of the vacuum level; however, Zalewski and Pyrz (2013) were the first to impose a model based on a visco-plastic behavior known as the Chaboche model.

Flexural properties

When a bending load is applied to the structure, the granular material will work in compression in the upper section of the system, and the membrane would work in tension in the lower section. For small strains, the rigidity of the system can be analyzed by only considering the material properties of the granular media and ignoring the elastic properties of the skin (Figure 3(a)). However, the elastic skin or membrane plays an essential role in flexural properties for high strains and cannot be ignored. When the bending curvature (and strains) increases with applied load, a splitting point appears (Figure 3(b)). At a particular value of bending load, the particles of the bottom layer start to separate, causing load transfer to the skin, and the curvature affects the way the skin is withstanding the load (Huijben (2014)).

In granular mechanics, structures such as bridges are analyzed as beams with flexural loads; however, those structures are designed to only withstand compressive loads (Andreotti et al. (2013)). The granular material is very resistant to compression; the more compressive force the material is subjected to, the higher the number of contacts per particle and with it the compression strength and rigidity increases (Andreotti et al. (2013)). However, the behaviour under tension is intrinsically different and can lead to a softening effect as progressively less of the material is carrying load (Naaman (1982)).

Vacuumatic structures subjected to bending can be considered in a similar manner to prestressed/reinforced concrete beams, which are also made from a material that is not well suited to loading under tension. However, in the case of granular jammed by vacuum, the pressure difference under vacuum pushes the elastic membrane inwards and wraps it firmly around the outer surface of the grains. The contact between the skin and the granular material creates a pre-stress force, which maintains the granular media locked with the elastic membrane. The axial pre-stressing force allows the structure to resist tension. At a certain point, the tension induced by the applied loading will be greater than the pre-compressive stresses, leading to localized splitting between particles (Huijben (2014)). In pure bending (no shear stresses are considered) the stresses in a beam vary with their distance from the neutral axis, grain separation will initiate at the skin surface on the ‘tension’ side of the beam, and they move progressively towards the center. As will be seen, this happens in a smooth and regular fashion, leading to a softening non-linearity in the beam. Interestingly, the progression of this region of ‘inactive’ material leads to the movement of the neutral axis.

Huijben et al. (2009) were the first to study the impact of elastic membranes on granular jamming structures in bending. Huijben proposed an analytic model of the flexural properties of vacuumatic systems and used discrete element method (DEM) based numerical analysis to attempt to predict the resulting behavior. Furthermore, Huijben found that the for the cases considered, grain size did not significantly change the rigidity of the system (Huijben (2014)). This work includes an analytical model of pre-stressing forces, DEM and FEA modelling of bending behaviour considering the linear properties of the granular media and the skin obtained in triaxial and uniaxial tests. Initially, his experimental results and numerical simulations were not in good agreement, but he was able to improve matching by instead fitting the compression modulus of the granular media to better match the experiments, in which he considered a modulus range from 0.13GPa to 1.3GPa (Huijben (2014)). Huijben (2014) concludes that it is not possible to model the flexural behavior using the linear parameters obtained from triaxial and uniaxial tests due to the high non-linearity of this type of structures. Accordingly, it is essential to consider non-linearities in bending from the beginning in order to model this behavior adequately, and the high computational cost of DEM limits its ability to be used as an effective tool for the design and analysis of systems with a large number of grains.

Analytical models for granular matter are well understood only for specific applications like soil mechanics (Iwashita and Oda (1999)), but the flexural properties of the structure employing granular jamming are very complicated to model, and except for straightforward cases, it is not possible to develop closed-form analytical expressions to describe their behaviour. Further work is therefore needed in order to capture the complexity of the response of these systems in a manner which is computationally efficient enough to be useful in a design and optimization context. Non-linear FEA methods are a promising option to analyze those properties in a numerical way.

It is important to mention that it is possible to model the non-linear behavior in bending using plasticity models, however, taking into account that the system is not working in a plastic range, but that it always remains elastic during the analysis. The plasticity of vacuumatics structures has not been studied yet, and there are still many doubts about what kind of behavior would be appropriate to model these characteristics. Some authors such as Zalewski and Pyrz (2013), stipulate that this type of structure present a viscoelastic behavior because the device can shift from a solid-like state to liquid-like behavior. Otherwise, the nonlinearities of the structure are faithfully modeled using models such as Chaboche and the non-linear FEA model used in this research; both models are based on plasticity.

Experimental characterization of flexural properties

In order to experimentally quantify the behaviour of granular jamming beam structures in bending, a series of four-point bending tests were carried out. For this testing, a switchable stiffness beam with a rectangular cross-section shape was built from granular material held within an elastic membrane. The dimensions of the beam and loading rig were determined in accordance with ASTM Standard C880/C880M (ASTM (2018)). For the membrane, a material with low modulus, high strain capability, and resistance to fatigue was desired, and a silicone sheet (SuperClear centrifugally cast silicone from Silex Silicones, LTD) with a thickness of 0.5mm was found to be suitable. Rigid end fittings were used at each end to set the cross-sectional shape and to simplify the installation of ports for filling the membrane and applying vacuum pressure.

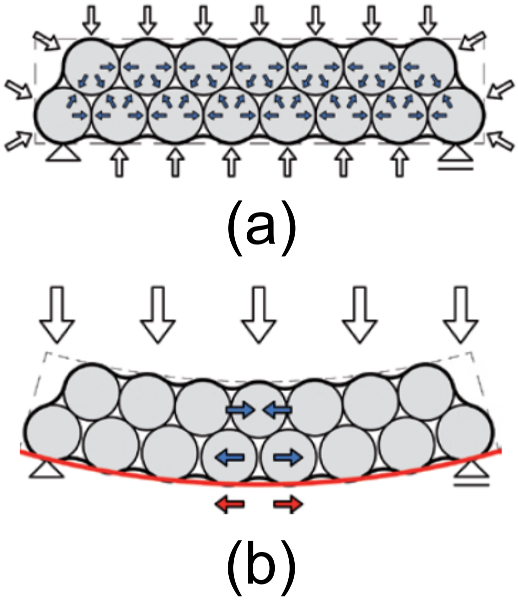


Figure 3. Compression stiffness (a) and flexural property known as splitting point (b). Picture taken from Huijben (2014)

A number of different granular materials were to be tested to allow for performance comparison. Comparing the stiffness of a non-frictional material against a frictional material was sought. Both spherical and irregular shaped materials were considered, with attempts made to source similar grain sizes to minimize one potential source of variation. Smooth, spherical glass beads of $250\mu m$ circumference were used. Glass bead is one of the most common materials for testing in granular applications. Glass allows to have a very smooth surface (the friction among particles can be meaningless), that is ideal for some models were the friction is not considered, and the spherical shape can be used to analyze contact in an easy manner (Hertzian contact models are used to analyze this type of materials). Sand of $500\mu m$ circumference was chosen because the relation weight/volume is approximately equal to the glass bead; however, it has a rough surface and can be considered as a frictional material (non-Hertzian contact models are used for this type of materials).

Soft robotics applications as same as morphing structures require light materials. Natural materials like seeds, coffee grains, etc. or some light polymers are used widely used in soft robotics. Moreover, one of the most popular materials for this type of applications is coffee. Coffee is cheap, easy to obtain and has one of the best stiffness/weight relation in granular materials (the best one in triaxial compression tests reported at the moment), for all these reasons was chosen for the development of the following morphing application.

Hybrid materials were made from 1:1 mixtures of each pair of materials (glass/sand, sand/coffee, glass/coffee),

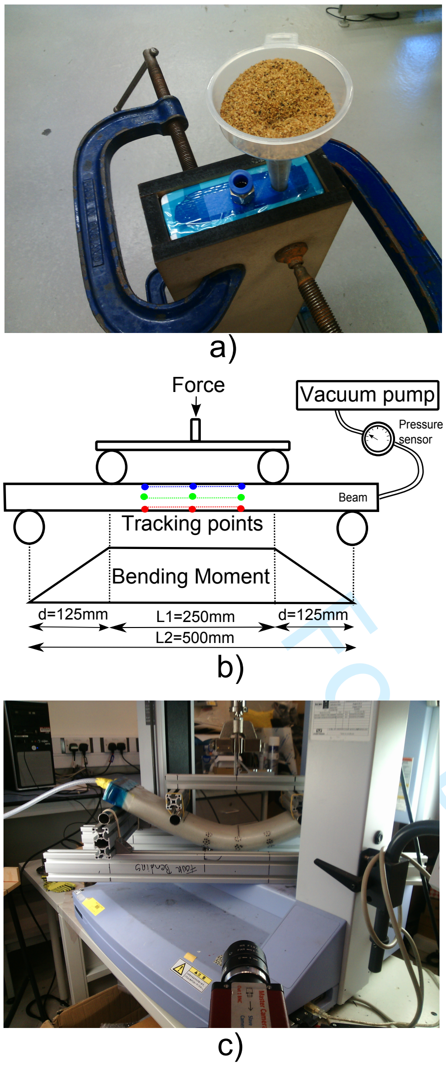


Figure 4. Flexural test setup; preparation(a), schematic (b), and laboratory test (c)

mixed manually until homogeneous mixtures were obtained (approximately mixed for 5 minutes per 130000 mm^3 of granular material).

Three levels of applied vacuum pressure were tested; 0.5 bar, 0.75 bar, and 0.85 bar, with at least eight tests being performed on each combination of material type and vacuum level. The vacuum pressure level applied to the beam was measured by an analogue gauge connected to the vacuum pump regulator valve. The four-point bending load was applied with a material test machine (Shimadzu AGS-X, 10N-10KN) equipped with a 1kN load cell, and displacement ramps of 50mm were applied with a constant displacement rate of 10mm/min. The load is applied by two rollers (load rollers) of 22 mm diameter spaced 250mm apart. A video extensometer (iMETRUM, Allied Vision Manta G-504 B/C GigE Camera 2452x2056) was used to measure the displacements of the beam at a number of tracking points placed between the loading points. Figure 4 shows a schematic of the four-point bending test setup and the experiment as realized in the lab. The objective of the tests is to measure the flexural rigidity of the beam filled with each type of granular material with the aim of obtaining the fundamental underlying nonlinear stress-strain behavior of the granular media at different vacuum pressures.

Figure 5 shows the bending load versus displacement diagrams of all the materials analyzed. For a displacement of 30mm, It can be seen that the achieved stiffness variation for coffee grains is greater than a factor of 2.14x using a vacuum pressure from 0.5 to 0.85 bar. Sand obtained an increase of stiffness of 58% using the same vacuum pressure variation, and glass beads an increase of 77%. While the hybrid combinations, coffee/sand achieve an increase of 99.5% and coffee/glass achieved an increase of 115%. It is worth noting that an applied vacuum pressure of 0.5 bar was set for this testing because of the very low stiffness of the beam at lower pressures. Below 0.5 bar, the deformations due to self-loading were so large and the retained bending stiffness so low that the four-point bending test rig was not able to accurately measure the beams response. This implies that the achievable range of stiffness variation would be larger if the vacuum pressure were decreased further, but in the context of the present bending tests, we restrict our consideration to what could be reliably measured.

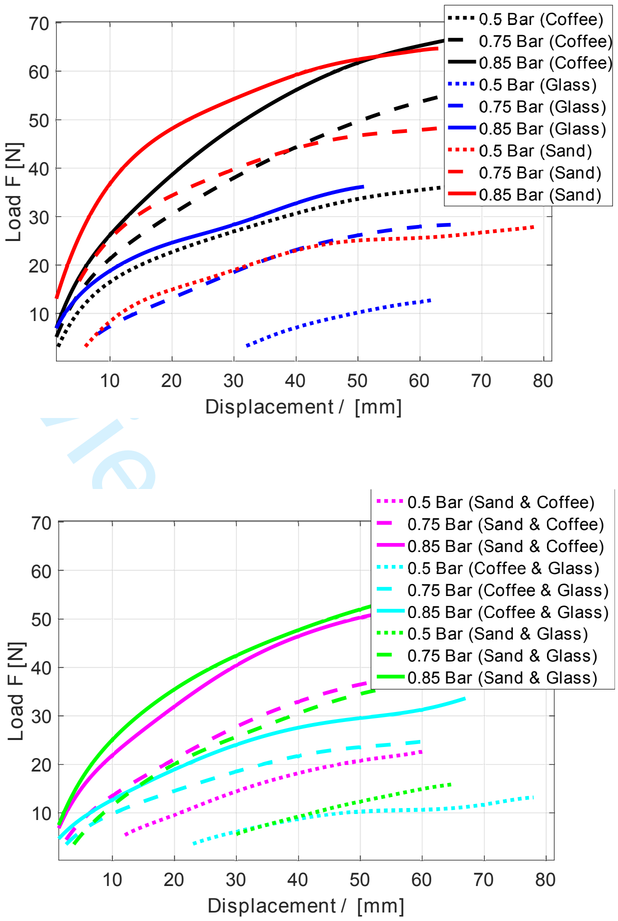


Figure 5. Load vs displacement for coffee grains, sand and glass beads (a). Load vs displacement for hybrid materials (b)

Neutral axis variation

The measurement of 2D displacements/strains on the side of the beam allows for initial interrogation of the distribution of strain through the thickness of the beam. In order to achieve this, a line is fit through the axial strains of the upper and lower tracking points at the centre (lengthwise) of the beam. The point in the thickness direction at which this line passes through zero strain is the neutral axis of the beam at that instant. This process is shown in Figure 6 (a) and (b) for two different vacuum pressure levels, where we see the surface strains measured for the upper (blue line), middle (green line) and lower (red line) section of the beam, and the purple line shows the interpolated position of the neutral axis. The material above this point will be under compression (negative axial strain) while the material below is under tension (positive axial strain). It is, therefore, possible to estimate the position of the neutral axis as a function of the applied bending moment using the video extensometer and the load cell from the test frame machine.

Figure 6 (c) shows a trace of the interpolated vertical position of the neutral axis for a coffee filled beam as a function of the bending load for each vacuum level. A complex non-linear response can be observed, with a general trend of a downwards shift in the neutral axis location by increasing vacuum pressure. This result contradicts previous work by Huijben (2014) which did not show a significant change in neutral axis position with varying vacuum level. This phenomenon is related to the axial pre-stress force discussed in the last section. The experimental results (Figure 6) help to support the hypothesis that increases in applied vacuum pressure lead to higher compressive pre-stressing of the grains, delaying the onset of grain separation and allowing for more of the cross-sectional area to effectively carry load - thereby leading to a neutral axis closer to the center of the beam.

Non-linear stress-strain curves

Once the bending load is obtained from the diagram mentioned above, then the bending moment is calculated in the following way as a function of the bending force $M = F_b/d$, where the distance d is obtained by mechanical equilibrium, or it can also be obtained from the shear and moment diagram (when the moment is maximum or constant, and the shear is zero). The stress is obtained using Euler-Bernoulli bending beam equations. Furthermore, the position of the neutral axis is different for each vacuum variation, and it is necessary to change the equations in the following way.

$$\sigma_c = \frac{MZ_c}{I}; \sigma_t = \frac{MZ_t}{I} \tag{2}$$

Where σ_c the compression stress, σ_t is the tensile stress, M is the bending moment, Z_c is the distance from the neutral axis to the uppermost part of the beam, Z_t is the distance from the neutral axis to the lowermost part of the beam. As can be seen in the Euler-Bernoulli equations, the stresses can be calculated as a function of the bending load, and the neutral axis can also be obtained as a function of the same load as shown in Figure 6 (c). Figure 7 displays the resulting nonlinear stress-strain curves in tension and compression for coffee grains, as estimated using beam theory.

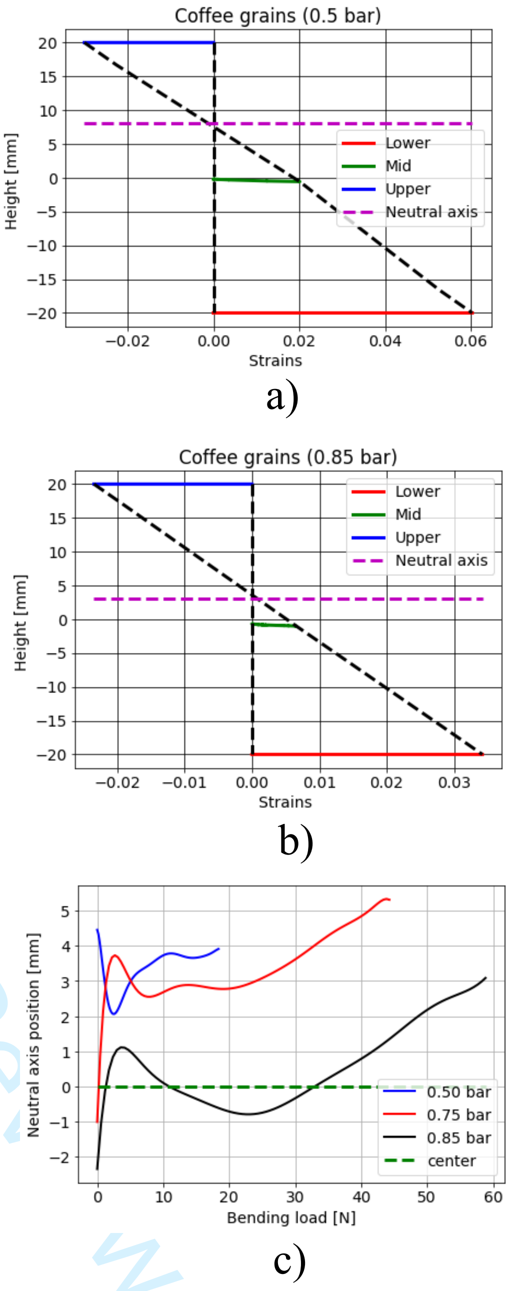


Figure 6. Strains and neutral axis locations

Non-linear FEA

Non-linear FEA analysis was implemented in ABAQUS version 6.14. The material properties for the numerical simulation were defined assuming a Von Mises plasticity model, using the nonlinear material stress-strain curves taken from the four-point bending test in the last section as inputs. While it is not considering the granular material to be operating in a plastic regime, this Von Mises plasticity model, as implemented within ABAQUS, provides a manner of inputting custom, non-linear stress versus strain behaviour.

The four-point bending analysis was simulated in the following way. The structure was partitioned into two different material properties. The partition of the structured was divided by the position of the neutral axis (explained in the last section). The material chosen above the partition was the compressive non-linear stress-strain curve taken from the

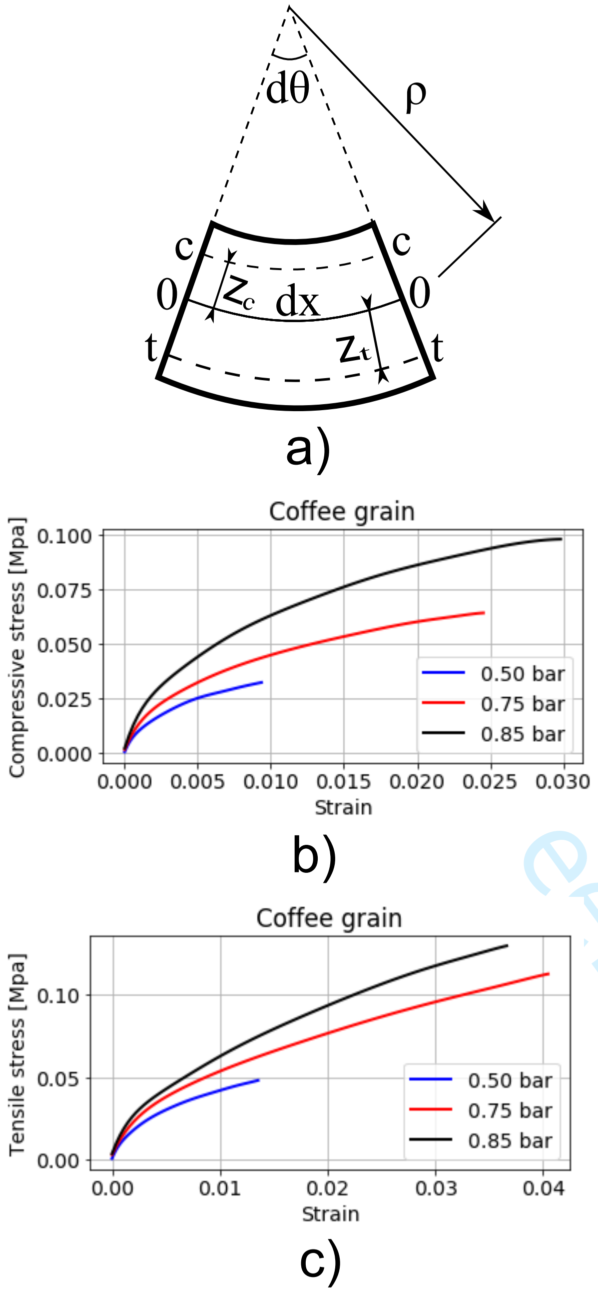


Figure 7. Nonlinear stress-strain curves for coffee grains

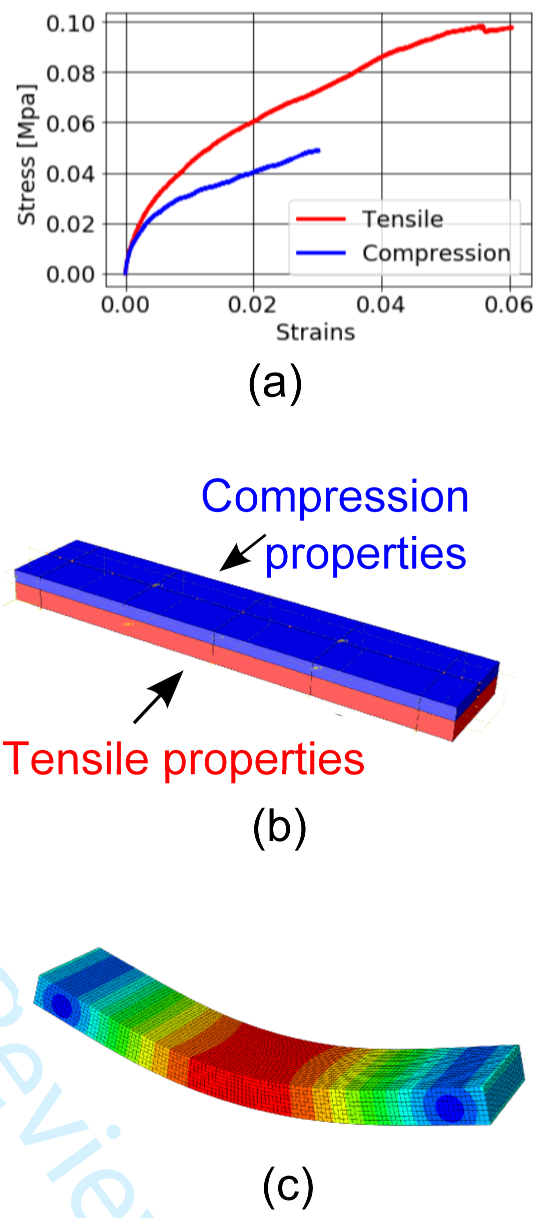


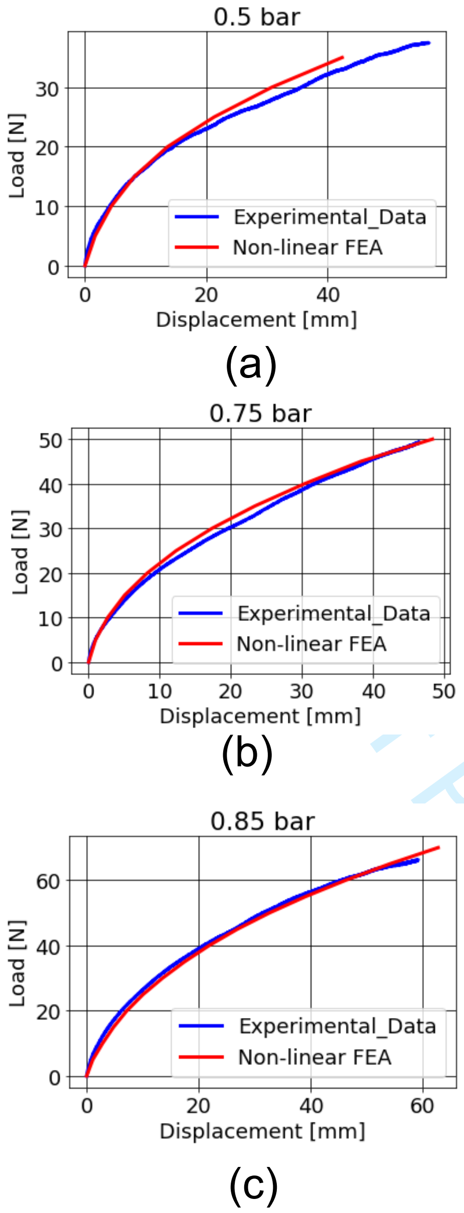
Figure 8. Nonlinear FEA of four-point bending tests

four-point bending tests (shown in blue in Figure 8 (a)), and below the same partition, the nonlinear tensile stress-strain was chosen (shown in red in Figure 8 (a)). The Poisson's ratio of the different granular media was estimated using Lame's relation (Mott and Roland (2013)):

$$\nu = \frac{1}{2} - \frac{E}{6K} \tag{3}$$

Where E is the modulus of elasticity, and K is the bulk modulus. For this work, the bulk modulus for coffee grains was taken from the tri-axial compression tests performed by Cheng (2013). Because E is a value that depends on applied vacuum pressure, Poisson's ratio is recalculated for different vacuum levels. The beam was meshed using eight-node 3D brick elements (ABAQUS element type C3D8R). For the convergence of the results a sequence of meshes was performed, according to the global number of size. The smaller the size, the greater the number of elements generated by mesh. The size number was compared with the difference between the experimental and the numerical analysis; showing a good agreement with a total of 230000 elements.

There was a simulation for each applied vacuum level, the Figures 9 (a) - (c) show the comparison between the experimental data and the non-linear FEA using coffee grains for a vacuum level of 0.5 bar, 0.75 bar, and 0.85 bar. The results show a good agreement between the experimental data and FEA simulations. As a highlight, it can be observed an increase in stiffness of 107% when the vacuum pressure increases from 0.5 to 0.85 bar. The following section describes the development of a morphing aerostructure using granular jamming as a variable stiffness mechanism.



(a)

(b)

(c)

Figure 9. Nonlinear FEA results and experimental data comparision

Switchable Stiffness Morphing Concept

Switchable Stiffness Fish Bone Active Camber morphing airfoil (SwitchBAC)

Having established the ability of granular jamming to provide a significant variation of bending stiffness, the following section presents an application of this material to a bending dominated morphing concept known as the Fish Bone Active Camber (FishBAC), to create a novel Switchable Stiffness FishBAC - the SwitchBAC. The underlying motivation is to use the granular media to allow for real-time control of the bending stiffness of the FishBAC. The combination of these two concepts is shown schematically in Figure 10. Through active control of the vacuum pressure applied inside of the elastic membrane containing the granular media (and therefore the net pressure acting on the grains), the total bending stiffness in the camber direction can be varied. The applied vacuum pressure can be decreased during actuation to reduce actuation torque and energy requirements, and then increased once the SwitchBAC is in the desired position to increase its resistance to variations in external loading. One additional benefit is the possibility of turning the actuator off once the desired position is achieved, with the shape then being maintained by the jammed granular media. If achievable, this would provide a zero-energy hold capability which would significantly reduce the total energy required by the device over the course of a mission.

While there are many different possible design approaches to combining granular jamming with the FishBAC concept, in this work we start with what is perhaps the simplest. The existing cavities formed between the stringers of the FishBAC are simply filled with granular media (coffee in the first instance) and covered in a silicone membrane to create multiple sealed compartments along the chord of the FishBAC. A manifold at the forward end of the FishBAC connects to the upper and lower cavities, which are connected by channels through the stringers. In this way, application of vacuum pressure to the manifold will evacuate the air inside the cavities, leading to stretching of the membrane and compression of the granular media under the external atmospheric pressure. Consequently, this leads to granular jamming and restricts the bending of the FishBAC spine through the additional stiffness provided, which of course can be tuned by varying the applied vacuum pressure.

An interesting secondary aspect of this design configuration is that while applying vacuum pressure to the entire device leads to the aforementioned stiffening effect, applying differential pressure above and below the spine will induce bending moments in the spine (due to the pressure forces acting on the inside faces of the stringer walls) which can be used as an actuation mechanism for the concept. While previous work on the FishBAC has considered antagonistic tendons driven by various actuators as the driving mechanism (Woods and Friswell (2012)), this combined actuation and variable stiffness effect opens up other alternatives worth considering.

In order to better understand the operating principle of this concept, and to show its viability, we will first consider the performance of a single ‘unit cell’ of the device, which is taken to be a single segment of spine with granular media above and below, contained within structures representative of the stringers and covered in an elastomer membrane.

SwitchBAC unit cell experimental characterization

A single representative unit cell of the SwitchBAC concept was built and subjected to bending tests with the aim to measure the stiffness variation of the device using the same test frame machine of the four-point bending tests, but with modifications to the loading and gripping devices. The unit cell was 3D printed out of Nylon and has a loaded length of 156 mm (of which 40 mm contains the granular media), a thickness of 100 mm, a height of 60.22 mm and a spine thickness of 2.22 mm. The grip and support of the mechanism were designed as an L-shaped base, which allows the unit cell to be mounted horizontally to align with the motion of the test machine. The load is applied through

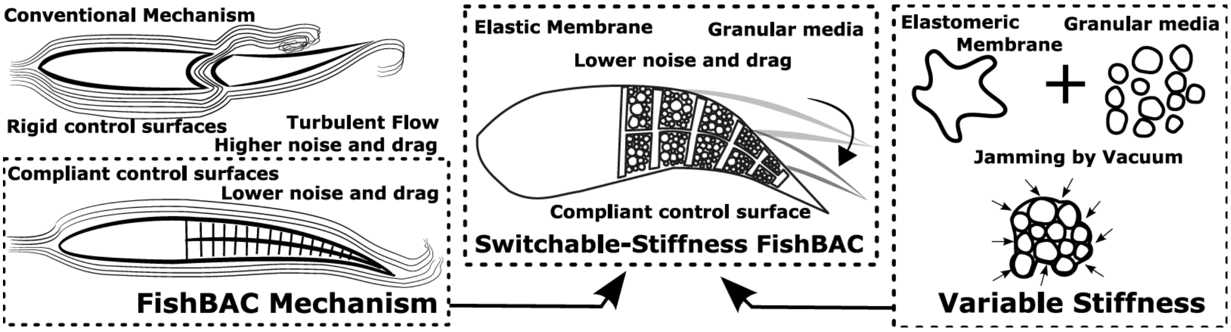


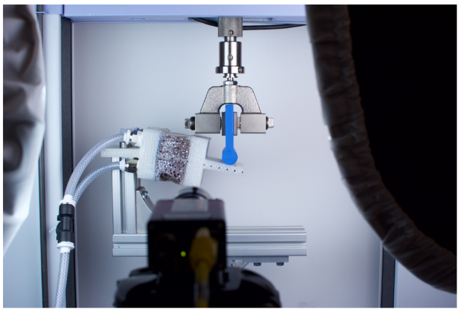
Figure 10. Switchable Stiffness FishBAC concept (SwitchBAC)

a cylindrical loading bar attached to the load cell, which moves with the cross-head of the machine. The machine is programmed to displace the load at a speed rate of 10mm / min. When the head reaches a displacement of 19mm, the load stops for 5 seconds and begins unloading at the same rate. For these tests equivalent levels of vacuum pressure were applied above and below the spine. Figure 11 (a) shows the unit cell installed on the test machine.

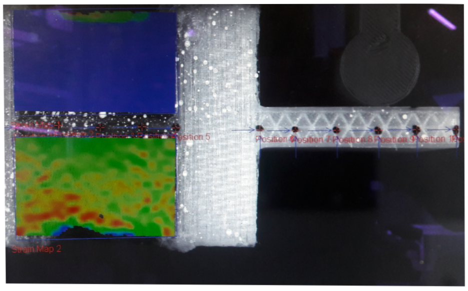
In order to be able to separate out the different components which contribute to the overall stiffness of the unit cell, the unit cell was initially tested with no granular material inside of it and with no applied vacuum pressure. Then the device was tested with the granular material and without vacuum. After that, the unit cell was tested with granular material and varying the vacuum level (from 0 to 0.85 bar). The results of the tests are shown in Figure 11 (c). It can be seen how the stiffness varies according to the vacuum pressure, and the unit cell shows the ability to increase its stiffness by a factor of 2.4 through the application of 0.85 bar of vacuum.

Actuation through differential pressure

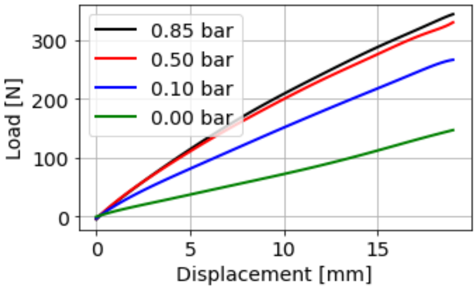
As alluded to above, another feature of this design configuration is the ability to actuate the camber deflection of the SwitchBAC through differential pressure. This phenomenon was shown experimentally with the unit cell by applying vacuum pressure to the granular media on one side of the spine while leaving the other open to atmospheric pressure. In this way, large, bidirectional bending deformations were achieved. As a simple means of capturing the complex deformation of this device, a nominal geometric deflection angle can be considered, as shown in Figure 12, the unit cell demonstrator can achieve ±18° of nominal angular deflection using a vacuum variation from 0 to 0.85 bar for each cell.



a) Bending test



b) Tracking strains



c) Variable stiffness results

Figure 11. Unit cell bending test and variable stiffness results

Non-linear FEA of the unit cell

Finite element analysis of the unit cell under bending was carried out, based again on the non-linear material properties from the beam studies. Using Abaqus FEA (Finite Element Analysis) software, the device was modelled in the following way. The nylon components (the stringers, spine loading/clamping tabs) were modelled using the properties of the 3D printed nylon as obtained from the manufacturer (Markforged). These components were meshed using 3D quadrilateral/brick elements (eight-node brick element with reduced integration C3D8R), with 530,000 total elements. The mesh elements of the granular media also consist of 3D elements similar to the nylon, with a total number of 350000 elements in each of the upper and lower cells. To join the two types of materials is necessary to create tie couplings, which are responsible for restricting the movement of the slave node as a function of the movement of the master node.

Consequently, all the slave nodes of the granular material that come into contact with the surfaces of the cell made of the master nylon nodes were joined. As boundary conditions, all the degrees of freedom are restricted (full-fixed) to the faces that are supported by the clamps to replicate the experiments. The load is then applied to the loading tab as a line contact force. The material properties of the granular

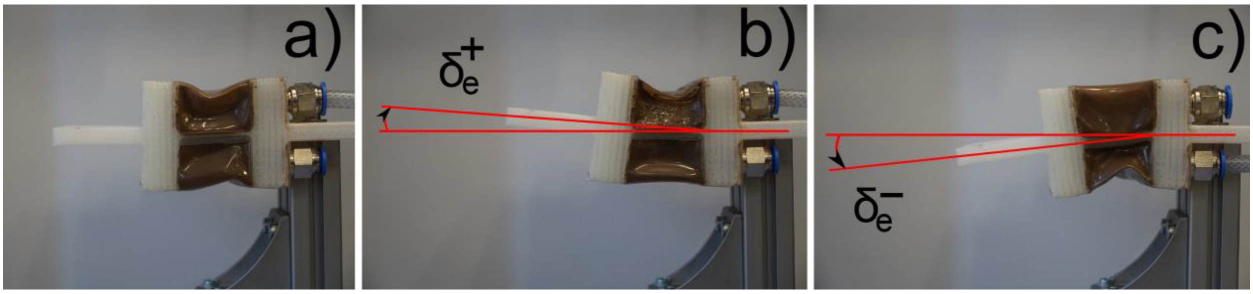
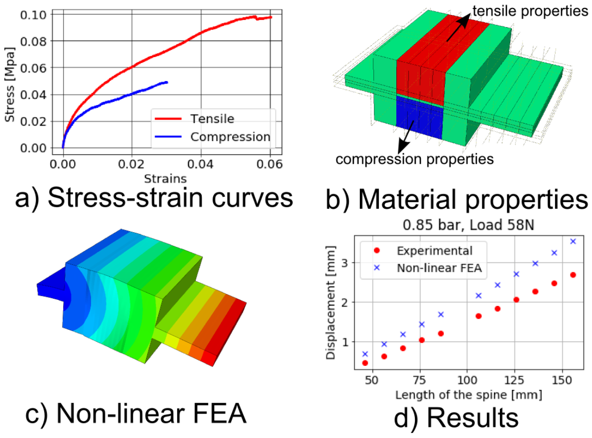


Figure 12. Actuation through differential pressure and control for spine deflection. Image a) No spine deflection. Image b) Upwards deflections on the spine. c) Downwards deflections on the spine.

media are taken from the non-linear stress-strain curves of the four-point bending tests.

Figure 13 (d) shows the displacement along the spine of the unit cell at 0.85 bar vacuum level under a load of 58 N. It should be noted that the trending behavior between the experimental values and the numerical simulation is almost the same; however, there is an offset from 0.1mm to 0.7 mm between them (for a length of spine from 40mm to 150mm). We hypothesize that the offset is due to the following reasons: Even though a bending load profoundly influences the system, the granular jamming properties are only considering flexural properties (pure bending obtained from four-point bending tests), and it is ignoring shear (shear is presented in not slender-beams). Another reason is that the mechanical properties of the 3d printed could be different from our database; probably it is required to perform flexural tests for the 3d printed material. Moreover, we speculate that the granular jamming device has micro leaks (undetectable for the pressure sensor connected to the pump), that could reduce the stiffness.

The numerical analysis can be used as a tool to predict the rigidity of new morphing devices. While further development of the analysis is needed, the unit cell has successfully shown the basic viability of the concept, with an experimentally measured 2.4x increase in stiffness due to granular jamming. It is likely that careful improvement of the design and implementation of the granular jamming concept into the unit cell will lead to even higher levels of stiffness variation.



a) Stress-strain curves b) Material properties

c) Non-linear FEA d) Results

Figure 13. Nonlinear FEA of the SwitchBAC unit cell

It is worth noting here that the selection of coffee as the granular material is mostly based on expedience. While it does perform well relative to heavier materials like sand and glass, it is not being proposed here for use in real-world aerospace applications. Coffee is an organic material whose properties will degrade over time, and it is likely to be subject to mechanical breakdown with repeated use - to say nothing of the possible impact of water ingress. Within this study, coffee is simply a useful, commonly available material that helps to show the basic mechanical viability of using granular jamming in a morphing aerostructure context. Further consideration of the underlying concept would look to more appropriate materials - perhaps even developing bespoke materials combining low density with high stiffness, strength, and wear resistance properties. Ceramic particle coated microspheres, for example, could provide a good combination of properties, but for the time being, we put that question aside.

Switchable Stiffness FishBAC Demonstrator

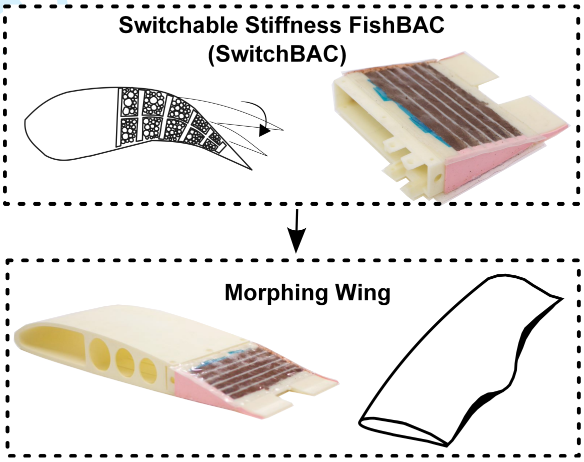


Figure 14. Switchable Stiffness FishBAC Demonstrator for a morphing wing

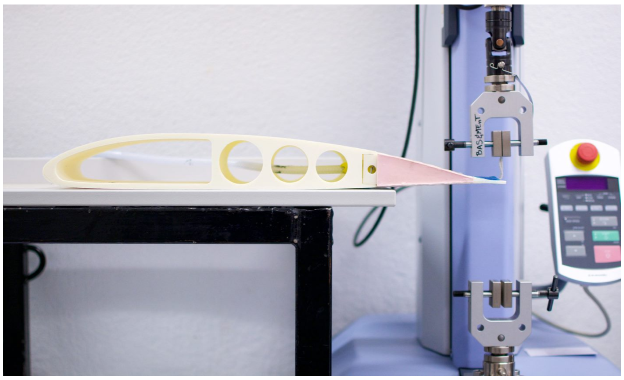
Having shown the basic viability of the SwithBAC concept through the unit cell testing, the first prototype of a complete SwitchBAC was then designed and built. A 600 mm chord section of OA212 airfoil and a spanwise length of 150 mm was selected for the prototype geometry. The SwitchBAC portion of this model starts at the 75 % chord location, giving an overall morphing section length of 140 mm, of which 70 mm can be filled with granular media, due to the presence of a rigid trailing edge strip at the rear of the FishBAC. The model was 3D printed, it has 12 cells (6 in the upper camber and 6 in the lower camber), that are filled with coffee grains. The cells have slots in the stringers to allow the air flow through the stringers, allowing for the vacuum to reach the after cells. The elastic membrane is a silicone sheet which is glued along the upper and lower camber on top of the stringers. Finally, the SwitchBAC was sealed on the sides by bonding in pre-made silicone castings. Figure 14 shows the prototype new switchable stiffness morphing trailing edge.

In order to show the ability of this concept to provide switchable stiffness, the bending stiffness of the SwitchBAC prototype was characterised as a function of applied vacuum pressure. Loads were again applied by a test frame machine (the same machine used for the unit cell). In this case, the SwitchBAC prototype was clamped to the bench and loaded at the tip of the trailing edge via cordage attached to the rigged portion of the trailing edge. The objective of the tests is to compare the change of stiffness with and without the application of granular jamming at different vacuum levels. Figure 15 shows the device unloaded (picture a) and with an applied deflection 30 mm (picture b). Finally, the change of stiffness from a vacuum level of 0.00 to 0.77 bar could be observed (picture d). Figure 16 displays the increase of stiffness per vacuum level in the SwitchBAC. The morphing trailing edge presented a maximum increment on its stiffness by more than 300% for a tip deflection of 3 mm, an increase of 180% for a tip deflection of 10mm, and it reduces until obtaining an increase of 120% for a tip deflection of 30mm.

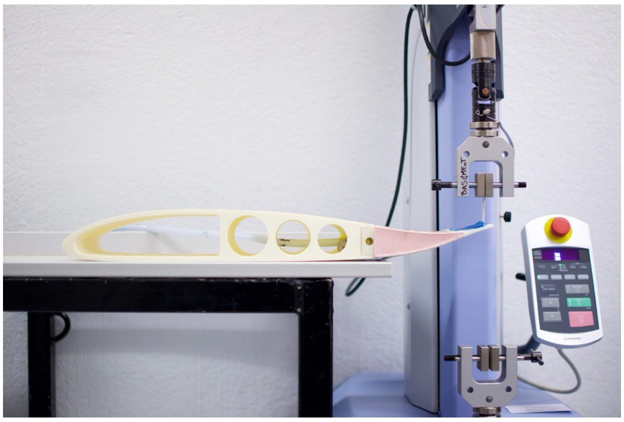
Conclusion

This work has introduced the concept of applying granular jamming to morphing aerostructures as a way of providing them with switchable stiffness. This concept is an attempt to help address the competing design constraints on morphing structures to have both low stiffness during actuation and high stiffness when acted upon by external loads. While this concept has a very broad range of potential applications and implementations, the initial focus of this paper was on bending dominated structures, such as the Fish Bone Active Camber morphing airfoil. Due to the relative lack of bending performance characterization in the existing granular jamming literature, four-point bending studies were performed on a granular media filled beam, with three different materials being tested. This led to non-linear finite element analysis of the beam structure based on the experimentally measured non-linear stress-strain behaviour of the granular media, with different properties being used for compressive and tensile loading. The concept of a Switchable Stiffness FishBAC was then introduced, with initial testing and analysis on a single unit cell of the device motivating the construction and testing of a complete prototype SwitchBAC wing section. Several key conclusion can be drawn from each phase of this research.

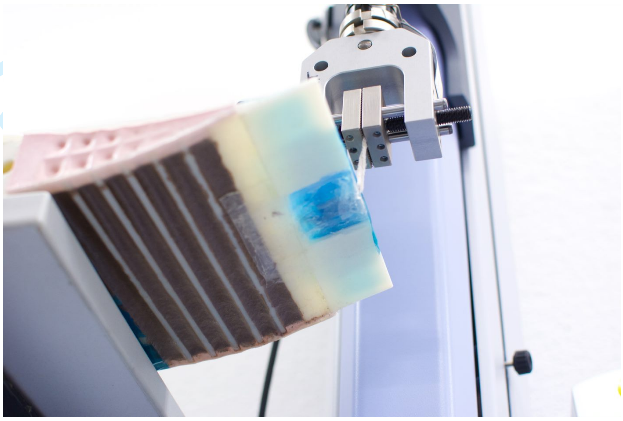
- The flexural rigidity of the four-point bending specimens depends highly on the level of applied vacuum pressure (from 0.5 to 0.85 bar), and as expected, the increase of stiffness can vary more than one order of magnitude and for other types of materials up to more than two orders of magnitude. As it was mentioned before, the difference in stiffness between these materials is due to their shape; the rough materials were stiffer than the smooth materials, the gravel reached an increase of 1.6 while the glass beads



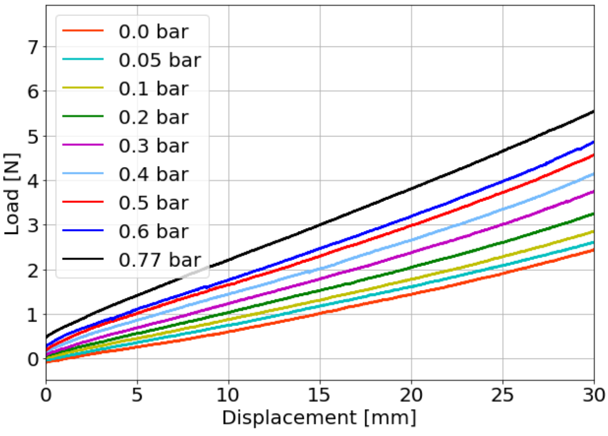
a) Unloaded



b) Loaded



c) Test setup



d) Variable stiffness results

Figure 15. Experimental validation of variable stiffness

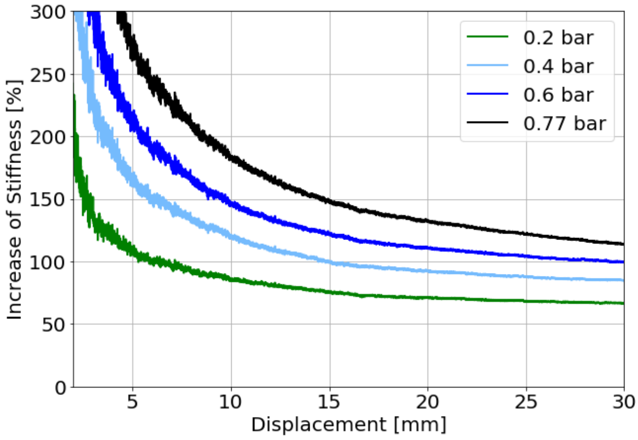


Figure 16. Increase in stiffness

of 1.4. Meanwhile, the combination of these materials can reach peculiar increases of rigidity and in some cases that increase can be higher than two orders of magnitude (coffee/glass achieved an increase of 2.3). The mixing of materials opens up the possibility of studying this type of granular jamming devices in more detail. On the other hand, coffee grains were selected for the development of the SwitchBAC because they have the highest stiff/weight relation in the flexural test performed in this research.

- The non-linear flexural behaviour of granular jamming devices can be characterized using the method proposed in this research. This method allows for the development of numerical models of granular jammed structures in FEA (through adaptation of a Von Mises plastic material model).
- The variation of the stiffness can be predicted using non-linear FEA for the development of switchable stiffness structures. For this case, the prediction of the Unit cell was analyzed. The unit cell is the base for the further analyzed of the morphing trailing edge (SwitchBAC), the SwtichBAC is composed for a serial number of unit-cells. Once the stiffness of the unit cell is predicted, then it is possible to predict the stiffness of the following cells.
- Experimental testing of a SwitchBAC unit cell showed that the unit cell could increase its stiffness by a factor of 2.4, and it could switch stiffness from 1.6 to 2.4 times higher by varying the vacuum pressure from 0.1 bar to 0.85 bar. The required magnitude of stiffness variation will depend on the aerodynamic loads that the trailing edge needs to withstand. It is something that we will require to analyze for our subsequent research.
- Camber deformation can be induced in the unit cell through differential pressurization of the upper and lower portions of the device. This opens up an entirely new method of driving the FishBAC device. Deflections of ±18° deflection of the spine were achieved for a vacuum pressure level of 0.85 bar.
- A full prototype of the SwitchBAC concept was built and tested, and it showed the basic operation of the concept, the FishBAC can switch stiffness (more than three orders of magnitudes) by using granular jamming between their cells. With a measured increase in stiffness of more than 300% for small displacements and it reduces until 120% for higher displacements when increasing applied vacuum pressure from 0 to 0.77 bar. These results in stiffness variation imply that further analyzed between and inside the cells is required with the aim to create a parametric design of the morphing device considering the aerodynamic loads that it requires to withstand (it is speculated that clever design can increase the stiffness of more than three orders of magnitude).

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Supplemental material

All underlying data are provided in full within this paper.

References

A H C M-B M T M Berthold MB and Wittmeir C (2001) Vakuumschale. *Aufgeblasene Architektur. Wien: Technische Universitat Wien* .

Andreotti B, Forterre Y and Pouliquen O (2013) *Granular media: between fluid and solid*. Cambridge University Press.

ASTM (2018) C880/c880m-18 standard test method for flexural strength of dimension stone. URL `https://doi.org/10.1520/C0880_C0880M-18`.

Athanassiadis AG, Miskin MZ, Kaplan P, Rodenberg N, Lee SH, Merritt J, Brown E, Amend J, Lipson H and Jaeger HM (2014) Particle shape effects on the stress response of granular packings. *Soft Matter* 10(1): 48–59.

Barbarino S, Bilgen O, Ajaj RM, Friswell MI and Inman DJ (2011) A review of morphing aircraft. *Journal of intelligent material systems and structures* 22(9): 823–877.

Beaverstock CS, Woods BKS, Fincham JHSM and Friswell MI (2015) Performance comparison between optimised camber and span for a morphing wing. *Aerospace* 2(3): 524–554.

Behringer RP (2015) Jamming in granular materials. *Comptes Rendus Physique* 16(1): 10–25.

Bi D, Zhang J, Chakraborty B and Behringer RP (2011) Jamming by shear. *Nature* 480(7377): 355.

Blanc L, Delchambre A and Lambert P (2017) Flexible medical devices: review of controllable stiffness solutions. In: *Actuators*. Multidisciplinary Digital Publishing Institute, p. 23.

Butt JR (2005) *A study of morphing wing effectiveness in fighter aircraft using exergy analysis and global optimization techniques*. PhD Thesis, Virginia Tech.

Carlson JD, Catanzarite D and St Clair K (1996) Commercial magneto-rheological fluid devices. *International Journal of Modern Physics B* 10(23n24): 2857–2865.

Cheng NG (2013) Design and analysis of jammable granular systems. URL `http://hdl.handle.net/1721.1/81695`.

Cheng NG, Lobovsky MB, Keating SJ, Setapen AM, Gero KI, Hosoi AE and Iagnemma KD (2012) Design and analysis of a robust, low-cost, highly articulated manipulator enabled by jamming of granular media. In: *Robotics and Automation (ICRA), 2012 IEEE International Conference on*. IEEE, pp. 4328–4333.

Eguchi T, Ogata U and Matsuda T (2008) Failure determination system for stepless speed changer and failure determination device for start clutch. US Patent 7,356,399.

Friswell M (2009) The prospects for morphing aircraft. In: *Proceedings of the IV ECCOMAS Thematic Conference on Smart Structures and Materials, Porto, Portugal*. pp. 13–15.

Gilbert J, Patton M, Mullen C and Black S (1970) Vacuumatics, 4th year research project. *Department of Architecture and Planning, Queens University, Belfast* .

Glauert H (1983) *The elements of aerofoil and airscrew theory*. Cambridge University Press.

Hemmelgarn CD and Pelley BM (2015) Passive adaptive structures. US Patent 9,033,283.

Herr H and Wilkenfeld A (2003) User-adaptive control of a magnetorheological prosthetic knee. *Industrial Robot: An International Journal* 30(1): 42–55.

Hudson SW (2012) *Mechanical characterization of jammable granular systems*. PhD Thesis, Massachusetts Institute of Technology.

Huijben F (2014) *Vacuumatics: 3D formwork systems*. PhD Thesis, PhD thesis, Eindhoven University of Technology.

Huijben F, Van Herwijnen F and Nijsse R (2009) Vacuumatics 3d-formwork systems: customised free-form solidification. In: *Proceedings of International Conference on Textile Composites and Inflatable Structures, Stuttgart*.

Imamura H, Kadooka K and Taya M (2017) A variable stiffness dielectric elastomer actuator based on electrostatic chucking. *Soft matter* 13(18): 3440–3448.

Iwashita K and Oda M (1999) *Mechanics of granular materials: an introduction*. CRC press.

Jaeger HM (2015) Celebrating soft matters 10th anniversary: Toward jamming by design. *Soft matter* 11(1): 12–27.

Jiang A, Xynogalas G, Dasgupta P, Althoefer K and Nanayakkara T (2012) Design of a variable stiffness flexible manipulator with composite granular jamming and membrane coupling. In: *Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on*. IEEE, pp. 2922–2927.

Knaack U, Klein T, Bilow M, Bergsma A, Borgart A, Van Sabben R and Van Swieten P (2008) Imagine 02: Deflateables. 010 publishers.

Kuder IK, Arrieta AF, Raither WE and Ermanni P (2013) Variable stiffness material and structural concepts for morphing applications. *Progress in Aerospace Sciences* 63: 33–55.

Langewiesche W and Collins LH (1944) *Stick and rudder: An explanation of the art of flying*. Whittlesey House, McGraw-Hill Book Company, Incorporated.

Liu AJ and Nagel SR (1998) Nonlinear dynamics: Jamming is not just cool any more. *Nature* 396(6706): 21.

Loeve AJ, van de Ven OS, Vogel JG, Breedveld P and Dankelman J (2010) Vacuum packed particles as flexible endoscope guides with controllable rigidity. *Granular matter* 12(6): 543–554.

McGowan AMR, Vicroy DD, Busan RC and Hahn AS (2009) Perspectives on highly adaptive or morphing aircraft .

Molinari G, Quack M, Dmitriev V, Morari M, Jenny P and Ermanni P (2011) Aero-structural optimization of morphing airfoils for adaptive wings. *Journal of Intelligent Material Systems and Structures* 22(10): 1075–1089.

Moorhouse D, Sanders B, Von Spakovsky M and Butt J (2006) Benefits and design challenges of adaptive structures for morphing aircraft. *The Aeronautical Journal* 110(1105): 157–162.

Mott P and Roland C (2013) Limits to poisson's ratio in isotropic materialsgeneral result for arbitrary deformation. *Physica Scripta* 87(5): 055404.

Murugan S, Woods B and Friswell M (2015) Hierarchical modeling and optimization of camber morphing airfoil. *Aerospace Science and Technology* 42: 31–38.

Naaman AE (1982) *Prestressed concrete analysis and design: Fundamentals*. McGraw-Hill New York.

Philen M, Shan Y, Bakis C, Wang KW and Rahn C (2006) Variable stiffness adaptive structures utilizing hydraulically pressurized flexible matrix composites with valve control. In: *47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference 14th AIAA/ASME/AHS Adaptive Structures Conference 7th*. p. 2134.

Sun J, Guan Q, Liu Y and Leng J (2016) Morphing aircraft based on smart materials and structures: A state-of-the-art review. *Journal of Intelligent material systems and structures* 27(17): 2289–2312.

Svetel I (2002) Prof. ivan petrovic, phd, m. arch (1932-2000). *Automation in Construction* 2(11): 129–130.

Telleria MJ, Hansen M, Campbell D, Servi A and Culpepper ML (2010) Modeling and implementation of solder-activated joints for single-actuator, centimeter-scale robotic mechanisms. In: *Robotics and Automation (ICRA), 2010 IEEE International Conference on*. IEEE, pp. 1681–1686.

Thill C, Etches J, Bond I, Potter K and Weaver P (2008) Morphing skins. *The aeronautical journal* 112(1129): 117–139.

Van Hecke M (2009) Jamming of soft particles: geometry, mechanics, scaling and isostaticity. *Journal of Physics: Condensed Matter* 22(3): 033101.

Wikimedia (2017) Granular jamming. URL `https://en.wikipedia.org/wiki/Jamming_(physics)`.

Woods B, Bubert E, Kothera C and Wereley N (2008) Design and testing of a biologically inspired pneumatic trailing edge flap system. In: *49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 16th AIAA/ASME/AHS Adaptive Structures Conference, 10th AIAA Non-Deterministic Approaches Conference, 9th AIAA*

Gossamer Spacecraft Forum, 4th AIAA Multidisciplinary Design Optimization Specialists Conference. p. 2046.

Woods BK, Bilgen O and Friswell MI (2014) Wind tunnel testing of the fish bone active camber morphing concept. *Journal of Intelligent Material Systems and Structures* 25(7): 772–785.

Woods BK and Friswell MI (2014) Structural characterization of the fish bone active camber morphing airfoil. In: *22nd AIAA/ASME/AHS Adaptive Structures Conference*. p. 1122.

Woods BK and Friswell MI (2016) Multi-objective geometry optimization of the fish bone active camber morphing airfoil. *Journal of Intelligent Material Systems and Structures* 27(6): 808–819.

Woods BKS and Friswell MI (2012) Preliminary investigation of a fishbone active camber concept. In: *ASME 2012 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*. American Society of Mechanical Engineers, pp. 555–563.

Zalewski M and Bajkowski J (2007) Influence of granular material on a viscous stress resulting from uniaxial compression tests of the special granular structure. *Inżynieria Materiałowa* 28(3-4): 350–353.

Zalewski R and Pyrz M (2013) Experimental study and modeling of polymer granular structures submitted to internal underpressure. *Mechanics of Materials* 57: 75–85.