Structured fabrics with tunable mechanical properties

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ABSTRACT: Structured fabrics, like woven sheets or chain mail armors, derive their properties both from the constitutive materials and their geometry [1, 2]. Their design can target desirable characteristics, such as high impact resistance, thermal regulation, or electrical conductivity [3-5]. Once realized, however, the fabrics' properties are usually fixed. Here we demonstrate structured fabrics with tunable bending modulus, consisting of 3D particles arranged into layered chain mails. The chain mails conform to complex shapes [2], but when pressure is exerted at their boundaries, the particles interlock and the chain mails jam. We show that, with small external pressure (~93 kPa), the sheets become >25 times stiffer than in their relaxed configuration. This dramatic increase in bending resistance arises because the interlocking particles have high tensile resistance, unlike what is found for loose granular media. We use discrete-element simulations to relate the chain mail's microstructure to macroscale properties and to interpret experimental measurements. We find that chain mails, consisting of different non-convex granular particles, undergo a jamming phase transition that is described by a characteristic power-law function akin to the behavior of conventional convex media. Our work provides routes towards light-weight, tunable, and adaptive fabrics, with potential applications in wearable exoskeletons, haptic architectures, and reconfigurable medical supports.

Smart fabrics are wearable materials that sense and respond to environmental stimuli, varying their properties [6, 7], and/or measuring and communicating data to external recording devices [5, 8]. Their applications include medical monitoring, wearable computing, and energy harvesting [5, 8-10]. They are usually fabricated by integrating in conventional fabrics with "smart" components, like flexible electronic circuits for sensing and computing [5, 8, 9], phase changing materials for thermal regulation [6], or photovoltaic materials for solar energy harvesting [10]. However, most of these solutions focus on sensing and data communication. Fabrics with adaptable or tunable mechanical properties are desirable to provide mechanical feedback to human bodies and perform functions such as joint assistance, support and haptic perception [11]. Here, we introduce a new type of architected fabric, consisting of chain mail layers with designed particles, which can reversibly and gradually switch between soft and rigid states. These fabrics with tunable mechanical properties serve as a promising candidate for smart wearable applications.

Unlike other fabrics that are woven or knitted with continuous material (e.g., fibers and wires) [1, 8], the basic building blocks of our designed fabrics are discrete, granular particles. Assemblies of granular particles or laminar structures are known to undergo changes in their mechanical

properties during jamming [12-16]. Jamming is a phase transition that does not rely on temperature changes, like in ordinary materials, but it is instead controlled by local geometric constraints in granular matter. The jamming transition enables disordered granular systems to switch reversibly between deforming with fluid-like plasticity or with solid-like rigidity, with a change of packing fraction. Jamming has been used to create smart materials with adaptive mechanical properties, for example, in soft robotic grippers, impact absorption materials, and reconfigurable architectures [17-19]. However, conventional granular materials are dense and large volumes are needed to provide enough mechanical stiffness when jammed. In addition, assemblies of convex particles do not support tensile forces. This limits their bending stiffness and tensile strength, making them unsuitable for wearable fabrics.



Figure 1. The design and prototype of the architected chain mail fabrics. a, Schematic of a single architected particle (left) and three interlocking particles (right). **b**, A 3D printed chain mail. **c**, Numerical simulation of two chain mail layers, without boundary confining stress. **d**, Digital image of two chain mail layers in the soft state. **e**, Configuration of the particles shown in **c**, after a confining stress is applied. **f**, Digital image of the jammed chain mails, which become a stiff load-bearing structure.

Fabrication and mechanical characterization of the structured fabrics

Inspired by ancient chain mail armors [2, 11, 20] and topologically interlocked elements [21, 22], we design a structured fabric consisting of two layers of interlocked granular particles. In our materials each particle is a hollow, three-dimensional (3D) structure, constructed from connecting trusses, designed to reduce the overall density and enhance contacts between elements (Fig. 1a). We choose octahedral particles, because their 90-degree rotational symmetry enables forming of a square 2D lattice in the interlocked configuration, and their sharp corners increase contacts between layers. The chain mail is created by rotating neighboring particles 90 degrees with respect of each other and by topologically interlocking all particles without forming solid connections. The interlocked lattice is manufactured using a selective laser sintering (SLS) method, which prints the lattice in one piece without extra supports (Fig. 1b). We stack two chain mail layers to increase the number of contacts. Like chain mail armors, the resulting structured sheets can freely bend, fold and drape over curved objects (Figs. 1c&d). We avoid 3D-printing chain mails with particles interlocked through thickness to allow sliding between layers, which results in higher flexibility.

To tune the effective mechanical properties of our fabric, we seek to trigger jamming between the interlocked particles, by applying variable compression at the boundary (Figs. 1e,f). We enclose the two layers in an air-tight, flexible envelope, where the layers are weakly coupled and can still bend easily. To induce jamming, we apply a confining gauge pressure (pumping air out of the envelope), which causes confinement stress at the fabrics' boundaries. This increases the particles' overall packing fraction, triggering a jamming transition that increases the bending modulus and turns the fabrics into load-bearing structures (Fig. 1f).

To quantify the change in mechanical properties as a function of increasing confining pressure, we perform three-point bending tests and calculate the apparent elastic bending modulus of the fabrics (see Methods). In these experiments, the samples are supported at two edges, and a line-shaped indenter is applied to the center of the top layer. The measured force-displacement curves (displacement controlled, Fig. 2a) show an initially linear regime, at small indentation depths, governed by the elastic behavior of the jammed granular structure. As indentation increases, a nonlinear response is observed, likely due to frictional sliding and local rearrangement of the particles. Although our fabrics are discrete and strongly anisotropic, we use an apparent elastic bending modulus E^* as a parameter to compare the fabrics' mechanical property under different conditions (see Methods). E^* can be calculated as [23]:

$$E^* = KL^3/(4bh^3)$$
 (1).

Here, K is the stiffness of the initial elastic regime from the three-point bending test (Fig. 2a), L, b and h are the length, width and height of the fabrics before the three-point loading tests (see Methods). As the internal confining pressure increases from 0 to ~93 kPa, the apparent bending modulus increases monotonically, from ~1.4 MPa to ~36.3 MPa (Fig. 2b), by over 25 times. We note that the plateau reached by the apparent bending modulus at high confining pressures (Fig. 2b) depends on our experimental setup (i.e., the choice of the envelope). Different confinement solutions may allow for reaching higher bending moduli. It is important to underline that the jamming effect is largely controlled by contact topology. Compared to other variable-modulus materials [24, 25], like shape memory alloys [26, 27], magnetorheological materials [28] or electroactive polymers [29], our smart fabrics have the advantage of achieving high modulus

tunability without the need for applying large temperature changes or high electrical/magnetic fields, which are undesirable in wearable applications.



Figure 2. Bending and tensile tests with variable confining pressure. a, Measured forcedisplacement curves for the fabrics at different confining pressures, *P*. The colored lines represent the average values, and the shaded areas represent the standard deviation between five different tests. b, Apparent bending modulus as a function of the confining pressure, *P*, comparing experiments and numerical simulations. Simulation results for discrete octahedral particle aggregates (non-interlocked) are also shown here (hollow blue circles). The shaded areas in grey and blue are standard deviations obtained from four separate simulations, each of which has a different initial particle configuration. The inset shows the change of the fabrics' overall volume obtained from simulation results. c, Schematic of tensile tests performed along different directions. The bottom fabric consists of a lattice rotated 45° from the lattice at the top (which has loading directions oriented at 0°/90° along the reference configuration). d, Simulations of apparent bending and tensile moduli along various loading directions showing anisotropy. The error bars represent the standard deviation between three simulations with different initial configurations.

Level Set-Discrete Element Method (LS-DEM) modeling of the fabrics

To understand the fundamental mechanisms leading to the increase in bending stiffness, we study the micro-structural interactions and displacements between particles using numerical simulations (Fig. 2a). In the range of confining pressure imposed in our experiments, the constituent particles' elastic deformation is much smaller than the particles' rigid body motion (e.g., rearrangement) and can be neglected. We model the chain mail architecture as a granular system, using the Level Set-Discrete Element Method (LS-DEM [30]). LS-DEM can reveal the detailed micro-structures formed from granular particles of arbitrary shape [31, 32]. We model the fabrics by constructing a "digital twin" of the hollow octahedral particle (Extended Data Figs. 1a,b), which is then replicated and rearranged to reproduce the 3D-printed fabrics (Extended Data Fig. 1c). We model the flexible envelope used in the experiments as a discretized elastic layer [33] (see Methods and Extended Data Figs. 1c,d). After calibration (see Methods), the model captures the temporal evolution of the dynamics (Extended Data Figs. 2a-2c and Supplementary Movies S1,S2), and predicts quantitatively the fabrics' apparent bending moduli, at different confining pressures (Fig. 2b).

We show that the stiffening of the fabrics requires very small volume shrinkage (below 5%, see Fig. 2b inset). This is because jamming is a sharp phase transition with a small change in the particle packing fraction [12-15]. As comparison, we perform the same virtual experiments on assemblies composed of the same hollow octahedrons, but without topological interlocking (See Methods and Extended Data Figs. 1c,d). We observe that interlocked fabrics outperform loose aggregates by exhibiting a higher bending modulus at the same confining pressure (about three times higher, Fig. 2b). This enhancement of modulus at the jammed state can be attributed to the tensile resistances between particles due to the topological interlocking, which is not present in the loose particle aggregates. In addition, we tested the anisotropy of the fabrics by performing bending and tensile simulations along different directions (Figs. 2c,d). The anisotropy for tensile deformations is much stronger than for bending deformations. This is because the 0°/90° loading direction in the reference configuration are principal directions of the particle connections.

Relating macroscale properties to micro-structural quantities

In jammed granular media, the macroscale mechanical rigidity is directly related to the number of contacts (a micro-structural quantity) formed within the system [13]. Constitutive material properties play a secondary role, as long as the particles remain rigid. In our system, we analyze the variation of contact number for each particle within the fabrics, at different confining pressures. We observe that higher confining pressures induce more inter-particle contacts (Figs. 3a,b). We further divide inter-particle contacts into "compressive" and "tensile" categories (Extended Data Fig. 2d) and show their spatial distributions under different pressures (Figs. 3c,d). Two observations can be made: (i) "Tensile" contacts encompass clusters of "compressive" contacts in a semi-periodic pattern. This observation can be explained by the specific interlocking topology of the hollow octahedron: "tensile" contacts (marked as "tensile type" in Extended Data Fig. 2d) can only occur near each particle's vertices, which are away from the particle's centroid. "Compressive" contacts (marked as "compressive type 2 and 3" in Extended Data Fig. 2d) can occur in the void volume occupied by each particle, which are closer to the particle's centroid. This kind of "compressive" contacts within a particle's occupied volume is typically not possible for conventional convex granular particles. (ii) Inter-particle contacts between two fabric layers (near h=0 in Figs. 3c&d) are all "compressive" contacts (Compressive type 1 in Extended Data Fig. 2d), which is due to the fact that there is no interlocking between fabric layers.

We plot the corresponding probability distribution (see Methods) of normal (F_n) and tangential contact forces (F_t), at two different confining pressures (Figs. 3e,f). The observed distribution patterns for both normal and tangential forces are similar to the well-established patterns for granular materials composed of conventional convex particles under isotropic compression [34]: The tangential and normal force distributions both show exponential tails. The normal force distribution is broad around the mean and larger normal forces (those well above the mean) decay faster than forces around the mean. Such distributions also seem to be insensitive to the applied confining pressure, at least for the range considered in our study. Interestingly, the distributions of "compressive" and "tensile" contacts are nearly identical, especially when the confining pressure is large (Fig. 3f, where P = 93 kPa). This result suggests that the well-established force distribution patterns for conventional, convex granular materials also apply to non-convex granular materials, where "tensile" contacts can also exist, provided that the imposed boundary conditions are the same (isotropic compression in this case).

To explore the relation between particle geometry and the jammed structure's mechanical properties, we design five other 3D particle geometries and construct corresponding interlocked fabrics (see Methods and Extended Data Fig. 3). We utilize the validated LS-DEM model to study the mechanical responses of these fabrics under three-point bending tests. For each simulation conducted under a different confining pressure, we compute the average contact number per particle (\overline{Z} , summing both compressive and tensile contacts), and the apparent bending modulus (E^*) for a beam subjected to three-point bending tests (see Methods). We observe that the apparent bending modulus increases monotonically with the average contact number (Fig. 3g), after a certain onset value Z_0 . Z_0 is defined as the critical contact number for the granular structure to be structurally rigid [13]. Remarkably, the computed relations between apparent bending modulus and average contact number for different particle geometries all collapse onto a same shaded region (Fig. 3g), which is fitted by adopting a power law function predicted by the critical phenomenon of the jamming phase transition with different Z_0 onset values ([13], see Methods and Extended Data Table 1). Interestingly, we observe that the apparent bending moduli measured on fabrics with a rotated lattice (Shapes #2, #4) also follow this scaling trend, with different Z_0 values from the reference configuration. This indicates the scaling relation is still valid when considering the fabric's anisotropy.

As comparison, we also modeled 2-layer stackings of classical chain mails consisting interlocked ring-shaped and square-shaped particles (see Methods and Extended Data Fig. 4). The results from these classical chain mails also follow the power law scaling observed previously (Fig. 3g). Interestingly, at the same confining pressure, stackings of classical chain mails (consisting of ring or square-shaped particles) present higher apparent bending modulus compared to fabrics consisting 3D structured particles. This is because the classical chain mails have a higher packing fraction (over two times larger) than those with 3D structured particles (see Extended Data Table 1). However, the higher packing fraction leads to higher volumetric density. 3D structured particles offer advantages in applications (such as tunable wearable equipment), where light weight may be a priority. In addition, the 3D structured particles with hollow internal volumes enable future incorporation of smart materials (e.g., shape memory wires or polymers) for different actuation methods.

By connecting a micro-scale geometric quantity (\overline{Z}) to a macro-scale mechanical property (E^*) , the observed power law scaling can have practical implications in rational design of adaptive structured materials for different applications. By customizing the particle shape, the tradeoff between weight and bending modulus tunability can be optimally balanced. In the future, it will be interesting to see whether this power law also holds for fabrics composed of particles with different geometries or made from different constitutive materials, which are not currently considered in this study.



Figure 3. Micro-structural information obtained from simulations at different confining pressures. a, b, Color map distribution of the contact number of each particle (*Z*) in the fabrics at P=2 kPa (a) and P=93 kPa (b). c, d, Spatial distribution of the compressive and tensile contact points in the fabrics at P=2 kPa (c) and P=93 kPa (d). e, f, Probability distributions of normal and tangential contact forces (normalized by the mean normal force $\langle F_n \rangle$), at P=2 kPa (e) and P=93 kPa (f). g, Relation between the apparent elastic bending modulus (E^*) and the average contact number per particle (\overline{Z}), for eight different particle geometries. The results fit to a power law scaling with different onset parameter (Z_0) represented by the grey shaded area. The legend shows the symbol (left) representation for each type of particle geometry (middle), and the unit cells (right) for constructing the fabric sheets. The confining pressures used in these plots are 0.1 kPa, 2 kPa, 13 kPa, 43 kPa, 53 kPa, 80 kPa and 93 kPa respectively for symbols #1, 3, 5, 6; 13 kPa, 53 kPa and 93 kPa for symbols #2, 4; 0.1 kPa, 2 kPa, 13 kPa, 43 kPa for symbols #7, 8; and 0.1 kPa, 13 kPa, 25 kPa, 43 kPa for symbols #9, 10.

Shape reconfigurability and impact resistance

Another feature of the studied fabrics is that they can be shaped into different geometries before being jammed into load-bearing structures. To demonstrate this, we manually configure the fabrics into a flat table (Fig. 4a) and an arch (Fig. 4b) and apply confining pressures. The resulting structures are mechanically stiff and able to bear mechanical loads, over 30 times of their own weight. This shaping ability is especially important for wearable applications and reconfigurable structures, where the fabrics may need to conform to the human body or form complex architectures.

The fabrics can also serve as tunable protective layers against particle's impacts. We demonstrate this property with drop-weight impact tests, dropping a stainless-steel bead (of 30 g mass, 1.27 cm diameter) on suspended fabrics, with an impact velocity of 3 m/s. We study the striker penetration as a function of the confining pressure imparted on the fabric. The impact process is recorded by a high-speed camera (see Supplementary Movies S3,S4). The penetration depth of the projectile can be significantly reduced with increased confining internal pressure: from 26 mm at 0 kPa (Fig. 4c) to 4 mm at 67 kPa (Fig. 4d), achieving over 6 times reduction on the penetration depth.



Figure 4. Shape reconfigurability, tunable impact resistance, and applications. a, The fabrics forming a flat table shape under load of 1.5 kg. b, The fabrics forming an arch bearing the same load. c,d, Snapshots from high-speed camera recording of impact tests on fabrics supported at 2 edges, under two different confining pressures: P=0 kPa (c) and P=67 kPa (d). e, Possible applications of the reconfigurable fabrics at different length-scales, ranging from wearable medical supports and exoskeletons (bottom) to transportable, reconfigurable architectures (top). The two inset images demonstrate the fabrics in soft state printed with two different materials: nylon plastic (left) and aluminum (right).

Discussion

Our work systematically explored the mechanics of structured fabrics consisting of non-convex interlocked particles with precisely controlled geometry, during jamming transition. Reconfigurable fabrics composed of discrete particles can be realized at different scales, as the jamming transition is a scale-invariant physical phenomenon (Fig. 4e). Recent advances in additive manufacturing make it possible, in principle, to scale the fabric thickness from the micro-meter to the meter scales, and to use different constitutive materials (such as metal, Fig. 4e inset), targeting different applications. With the integration of alternative methods for confinement (*e.g.*, electrical or magnetic control), it is possible to envision programming stiffness at different locations within the fabrics, for applications such as haptic interfaces and medical stimulation.

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Methods

1. Experiments

1.1 Materials and manufacturing: The nylon plastic structured chain mails are 3D printed via selective laser sintering (SLS) using a commercial 3D printing service (Shapeways). The material used to print the fabric is PA 2200 nylon plastic, with density of 0.93 g/cm³, tensile modulus of 1.7 GPa and tensile strength 48 MPa (www.shapeways.com/materials/versatile-plastic). The equivalent density of the printed fabric is ~0.18 g/cm³, which is lower than most wearable materials. The flexile envelop is made of Polyethylene Plastic film (McMaster-Carr) with thickness of h_m=0.076 mm and elastic modulus $E_m \approx 0.3GPa$. The membrane's contribution to the measured apparent bending moduli, E^* , should be no greater than the E^* measured at near zero confining pressure (~1 MPa). At higher confining pressures, the membrane forms wrinkles that significantly reduce the overall tensile resistance and its contribution to the overall bending moduli. Because of the presence of wrinkles, we neglect the membrane's contribution at higher confining pressures in our analysis. The aluminum chain mails (Fig. 4e) are printed on a metal 3D printer (EOS M 290) with customized break-away supports, which allowed us to remove the supports from the chain mail. The material used for printing was EOS Aluminum AlSi10Mg.

1.2 Quasi-static and impact mechanical tests: The bending stiffness of the fabrics enclosed within air-tight envelopes, at different confining pressures, is characterized with 3-point bending tests. The membrane envelope is first placed around the fabrics and the opening is sealed using a heat sealer. A soft tube connects from inside the envelope to a manual vacuum pump with pressure gauge. Different vacuum pressures are applied using the pump and the envelope is then sealed for testing. The membrane naturally wrinkles when vacuum is applied to conform to the fabric surface, which largely reduces its resistance upon stretching. The supports of the bending test have a width of 10 mm. We use an Instron E3000 materials tester, displacement controlled at a loading rate of 0.5 mm/s. 5 separate tests are repeated at each confining pressure. Before each test, the fabrics are manually reset to a flat initial configuration. The colored lines and dashed areas in Fig. 2a represent the average values and standard deviations between the 5 different tests. The deviation observed between the results from different tests at the same pressure arises from the initial configurations of the layers, which have different random initial contacts between the two chain mail layers. In the impact tests, the fabric sheets are suspended between two metal supports at the edges and impacted using a stainless-steel sphere of mass m=30 g. The impact velocity, $v_0=3$ m/s, is set by the sphere's initial drop height. The impact is recorded using a high-speed camera (Phantom Vision Research) at a rate of 3000 frames/second, to track the position of the sphere during impact.

1.3 Calculating the fabric's apparent bending modulus. The stiffness of the initial elastic regime in our 3-point bending measurement was obtained by linearly fitting the force-displacement curve (Fig. 2a) at small indentation depths (0 to 0.5 mm). This small indentation corresponds to in-plane strain of <0.05%, which ensures the fabrics are deforming within elastic limit. The overall dimensions (*L*, *h* and *b*) of the fabrics in the envelope at different confining pressures are measured before the 3-point bending tests. The apparent bending modulus is computed according to Eqn. (1), using the measured dimensions and stiffness (slope) of the elastic regime.

2. Numerical simulations

2.1 Construction of each particle's "digital twin". We first construct a "digital twin" (with the same shape, size and density) of the fabricated hollow octahedron particles. A single "digital twin" is represented by two sets of points that allow for contact computations between two particles. The first set of points (termed as "nodes" hereafter) together with their triangulations (the right-hand side image in Extended Data Fig. 1a) characterize the shape of the hollow octahedron in a discretized manner. The points in the second set (termed as "grids" hereafter) are equally spaced in space along all three directions (x, y and z), and each grid point stores a signed scalar value (positive if outside the hollow octahedron's surface, zero if on and negative if inside) indicating its shortest distance to the triangulated surface formed by the nodes (Extended Data Fig. 1b). Accordingly, these grid points together with their stored values form a discretized level set representation for the hollow octahedron. To clarify this construction, we also highlight in Extended Data Fig. 1b the grid points (colored in blue) whose shortest distances to the hollow octahedron. To clarify this construction, we also highlight in Extended Data Fig. 1b the grid points (colored in blue) whose shortest distances to the hollow octahedron.

After constructing the "digital twins" of all particles, we use them to detect contacts and compute contact forces. We follow the standard penalization formulation adopted in the Discrete Element Method (DEM [33]): A contact between two hollow octahedrons happens if at least one node point of one hollow octahedron (the master) penetrates into the surface of the other (the slave). This is achieved by computing the signed shortest distance of each node point of the master using the grid points (which store a discretized level set function) of the slave, and selecting node points of the master with negative distances to the slave (i.e., inside the slave). These negative distances are penalized following a linear Hookean model to generate the contact forces at each selected node point. We sum the contact forces induced at all selected node points of the master to get the total contact force between the master and the slave. The total contact force is used to update the kinematics of each particle following Newtonian mechanics. For a detailed discussion on the relevant formulation and implementation, we refer to reference [31].

Since we directly sum over all contact forces induced at all of the node points that are in contact, as discussed in reference [32], it is important to match the resolution of both nodes and grids for different particle geometries, in order to ensure consistent and comparable simulation results of different fabrics.

We start by creating a "digital twin" of the hollow octahedrons with a certain node and grid resolution. The node resolution is chosen such that the constructed "digital twin" (Fig. 1c and Fig. 1e and the right-hand-side image in Extended Data Fig. 1a) can reasonably capture the major feature of the actual geometry of the hollow octahedron (Figs. 1a,b and the left-hand-side image in Extended Data Fig. 1a). Next, we create the digital twins of all other considered particle geometries with the respective node resolution matching that of the "digital twin" of the hollow octahedron. Specifically, we match the probability distribution of the triangulation's edge lengths of each particle's digital twin to that of the constructed digital twin of the hollow octahedron (Extended Data Fig. 3 and Extended Data Fig. 4). In this work, we use GMSH to create the "nodes" component of a digital twin and match the number of nodes discretizing each particle scales reasonably well with the total surface area of the respective particle (Extended Data Fig. 3 and Extended Data Fig. 4). This implies a consistent level of spatial discretization homogeneity between different

"digital twins" generated by GMSH. The grid resolution is chosen to be able to resolve the interior and exterior of the hollow octahedron (we choose an inter-grid distance of 0.2 mm in all three directions to resolve the truss members' thickness which is 1 mm, as indicated in the inset figure in Extended Data Fig. 1b). Taking the generated "nodes" component of a digital twin, we use MATLAB to set the grid resolution for all digital twins to be 0.2 mm and generate the "grids" component of the digital twin. These two components are then merged into a single file, which is used as an input for LS-DEM simulations.

We choose the dimensions of all other considered particle geometries such that when two produced fabric sheets are vertically stacked they can be enclosed tightly by the constructed envelope (Extended Data Fig. 1c), and as a consequence, they share, on average, the same total dimension (height, width and length) with that of the sheets composed of hollow octahedron after isotropic compression. We note that maintaining overall the same dimensions of different sheets is important in our work because the results of 3-point bending tests can be sensitive to the geometry and size of the specimen. An additional requirement is that the initial configuration of each produced sheet should be free of inter-particle contacts. To satisfy the two stated requirements, we are able to only adjust particle size while maintaining the same truss members' thickness (1 mm) for all particle geometries *except* for the circular and the rectangular ring. For these two geometries, besides adjusting the particle sizes, we further increase the truss members' thickness to 3.6 mm for the circular ring and to 2.7 mm for the rectangular ring.

The mass of each chain mail layer measured in experiment is 27g. When considering gravity, this corresponds to an equivalent pressure of:

$$\frac{0.027kg \times 9.81m/s^2}{0.21m \times 0.092m} = 13.7Pa \; .$$

Although this pressure could contribute to the bending modulus at zero, or very low, confining pressures, it can be neglected for confining pressures above 2 kPa. For simplicity, the effect of gravity is not considered in our simulations. All particles share the same density equaling the density of the material used in the experiments. Once the "digital twin" is created for each of the considered particle geometries, we replicate and arrange in space these "digital twins", to construct numerically the corresponding fabric sheets (Extended Data Fig. 3 and Extended Data Fig. 4). Lastly, in order to simplify our calibration process (see section 2.7: Determining model parameters, for relevant discussions), we scale the density of every envelope sphere such that they all share the same mass with the hollow octahedron.

2.2 Construction of the envelope. In the experiments within the small strain limit, we observe that the envelope remains wrinkled and conforms to the particles' surfaces. As such, we assume that the membrane only acts as a compliant layer that applies the confining pressure, without contributing to the sample's overall bending stiffness. Based on this assumption, we construct a simplified envelope model that only serves as a compliant elastic layer to transmit the imposed confining pressure to the fabric. Specifically, we construct an envelope with an initially rectangular-box shape, to enclose the fabrics, as in the experiments (Extended Data Fig. 1c). We triangulate the surface of the envelope and assign a sphere at each node and a connection (i.e., a normal and a shear spring) at each edge between two neighboring spheres. Consequently, each sphere is connected to six neighboring spheres. The resting length of each spring is given by the

corresponding initial edge length, while the radius of each sphere is given by the average initial length of the six edges in connection with the sphere. The radius of each sphere is thus different but resides in the range of 0.9 mm - 1.3 mm (Extended Data Fig. 1e). Similarly, the node resolution of the envelope is adjustable and we choose a resolution balancing the tradeoff between representation accuracy and computational expense. Again, once a resolution is determined, we use the constructed envelope in all of our simulations for consistency.

For the simulations of non-interlocked, hollow octahedrons, we construct a slightly higher envelope, to enclose loose octahedrons that are initially positioned into three layers with no mutual contacts or links (Extended Data Fig. 1d). This choice is made to ensure that at the jammed state, the loose particles' samples share approximately the same dimension (height, width and length) with the stacked chain mails' samples (Extended Data Table. 2). Keeping the same sample's dimensions ensures that the results from the simulated three-point bending tests are directly comparable to one another. In order to use the same model parameters for these two different envelopes, we choose a node resolution for the new envelope, such that the statistical distribution of the envelope sphere's radius matches that of the original envelope (Extended Data Fig. 1e).

2.3 Isotropic compression. A given confining pressure *P* is applied to the fabrics by going through each triangle *i* of the envelope, computing its area A_i and inward surface normal n_i , calculating the total force $PA_i \cdot n_i$ and distributing equally to each of the three connecting envelope spheres (Extended Data Fig. 1c). We iterate the above procedure allowing the whole system to relax to equilibrium. Note that at each iteration the values of A_i and n_i are updated following the envelope's deformation. We monitor the total kinetic energy and total contact number of all particles at each time step, and we deem equilibrium to be achieved if both the total kinetic energy and total contact number cease to show any preferred direction of evolution with time, notwithstanding certain small temporal fluctuations (Extended Data Figs. 2a,b).

2.4 Three-point bending. After the whole system equilibrates under isotropic compression as described above, we perform three-point bending simulation by changing the boundary condition. In addition to maintaining the imposed isotropic compression, we fix the dynamics of the particles along the two edges of the fabric to the bottom layer (colored red in the Extended Data Fig. 2a). We impose a constant force pointing downward vertically (i.e., along the *z* direction) that is evenly distributed on particles along the center line of the fabric on the top layer (colored blue in Extended Data Fig. 2a). The value of the applied force is chosen according to the experimental results (Fig. 2a), ensuring the simulated mechanical response is within the small strain limit (i.e., elastic regime). We iterate the above procedure allowing the whole system to relax to equilibrium under the new boundary condition. The average vertical deflection (along the *z* direction) of the loaded particles is monitored in time. We deem equilibrium to be achieved if the average vertical deflection ceases to evolve with time (Extended Data Fig. 2c). Once equilibrium is achieved, we stop the simulation.

2.5 Computing the fabric's dimension at jammed state. We define the jammed state in our work as the state of the fabric right after the completion of the isotropic compression, before the three-point bending simulation. The height (along z direction), width (along y direction) and length (along x direction) of a given fabric at the jammed state are computed as follows (here we take height as the illustrative example): we first identify and group particles belonging to the top and bottom layers. Next, for each group, we go through each particle within the group, identify the

nodal point with the largest (for top layer group) or smallest (for bottom layer group) value along the z direction, and average along the z direction all identified nodal points for both the top layer group and bottom layer group. Lastly, we compute the height as the difference between these two averaged values. For the simulated results of apparent bending modulus, shown in Fig. 2b, the corresponding height, width and length of both interlocked fabrics and loose assemblies are summarized in Extended Data Table 2.

2.6 Modeling the interactions between particles and envelope spheres. To describe the model parameters, we use a subscript notation, as follows: we use "n" ("t") to represent the normal (tangential) direction for a contact, "p" to represent the particle (e.g., the hollow octahedron", "s" to represent the envelope sphere, and "-" to represent the interaction). For example, $k_{n,p-p}$ means the normal ("n") contact stiffness ("k") between two particles ("p - p"), and $\gamma_{n,p-s}$ means the normal ("n") contact damping (" γ ") between a particle and an envelope sphere ("p - s"). Interactions between particles are modeled as being linear Hookean, with Coulomb friction. Associated model parameters are the contact normal (tangential) stiffness $k_{n,p-p}(k_{t,p-p})$, the contact normal (tangential) viscous damping $\gamma_{n,p-p}(\gamma_{t,p-p})$ and the friction coefficient μ_{p-p} . The viscous damping can be determined from the respective coefficient of restitution $e_{n,p-p}(e_{t,p-p})$, following $\gamma_{n,p-p} = -\ln (e_{n,p-p}) \sqrt{m_p k_{n,p-p}} / \sqrt{\pi^2 + \ln^2 e_{n,p-p}}$ [35] ($\gamma_{t,p-p}$ can be computed analogously using $e_{t,p-p}$). Here m_p is the mass of a single hollow octahedron. The value of a coefficient of restitution resides between 0 and 1, with 0 indicating perfectly plastic binary collision and 1 indicating perfectly elastic binary collision. Interactions between particles and envelope spheres are also modeled as being linear Hookean, but without any friction. This frictionless assumption is a reasonable approximation since the envelope used in the experiments is compliant enough to conform to the surface of the particles upon isotropic compression. Associated model parameters are contact normal stiffness $k_{n,p-s}$ and contact normal viscous damping $\gamma_{n,p-s}$ (where $\gamma_{n,p-s}$ can be determined from $e_{n,p-s}$). Lastly, for the interactions between envelope spheres, each envelope sphere only interacts with its six nearest neighbors via the connecting normal and shear spring. Since the envelope used in the experiments is very compliant to shear and compression but resistive to tension, we use three parameters to describe the behavior of the spring: normal compressive stiffness $k_{n,compressive}$, normal tensile stiffness $k_{n,tensile}$, and tangential stiffness k_t . We note that overlap between envelope spheres may occur due to envelope contraction, but such interactions are not penalized. The introduction of all viscous damping parameters (γ_n and γ_t) along the normal and tangential springs serves as regularization, used for numerical convenience. From a physical standpoint, the damping parameters may be interpreted as to account for the unavoidable experimental dissipation that occurs both within the material itself (deformation of the envelope) and during the interactions between different objects (between the envelope and the particles and between particles themselves).

2.7 Determining model parameters. In all we have a total of 5 (between particles) + 2 (between particles and envelope spheres) + 5 (between envelope spheres) = 12 model parameters whose values are in need of determination. For the ease of parameter calibration, we further enforce several constraints in advance to reduce the dimension of calibration. These constraints are based on a combination considering common DEM practice, physical arguments and computational expenses. First, since the effect of gravity is negligible and accordingly all spheres are scaled to share the same mass with the hollow octahedrons, we set $k_{n,p-s} = k_{n,p-p}$ and $\gamma_{n,p-s} = \gamma_{n,p-p}$. The

choice of setting $k_{n,p-s} = k_{n,p-p}$ also prevents excessive penetrations between the envelope and the fabric particles, avoiding unphysical long-range contacts between chain mail particles and distant envelope spheres. Second, we set $k_{t,p-p} = \alpha k_{n,p-p}$, with α being a value between 0 and 1. It has been shown that for modeling flow of rigid spheres, the steady state dynamical response (e.g., velocity profile and packing fraction) is not sensitive to the specific value of α and to the coefficient of restitution for various tested strain rates, provided a rigid limit is ensured (i.e., k_n is large enough). A smaller value of the coefficient of restitution mainly reduces the time needed to reach steady state, by dissipating kinetic energy more quickly, thereby reducing the number of time steps needed. Since we are only interested in the equilibrated states (i.e., equilibrated state of isotropic compression and that of the three-point bending loading), following common DEM practice we set $\alpha = \frac{2}{7}$, $e_{n,p-p} = e_{n,p-s} = 0.1$, $e_{t,p-p} = 1(\gamma_{t,p-p} = 0)$, $e_n = 0.1$ and $e_t = 1(\gamma_t = 0)$. Lastly since the envelope is very compliant for both compression and shear, we assume $k_{n,compressive} = k_t$.

With these pre-enforced constraints, the number of parameters in need of calibration reduces to four: $k_{n,p-p}$, μ_{p-p} , $k_{n,compressive}$ and $k_{n,tensile}$. One additional parameter is the time step Δt . We pick Δt to be a small fraction of the characteristic binary collision time $t_c = \pi (\frac{2k_{n,p-p}}{m_p} \frac{\gamma_{n,p-p}^2}{4}$)^{-1/2} [35]. As larger contact stiffness leads to smaller time steps, and thus leads to an increase of time steps required to achieve equilibrium, we do not use the true mechanical property of the material to determine the value for $k_{n,p-p}$, but rather we pick a value that is large enough to ensure rigid limit, such that the physical results at equilibrated states are no longer affected by the particular value of $k_{n,p-p}$. For spheres and convex-shaped solid particles in general where only one contact is possible between two particles, studies have shown that picking $k_{n,p-p} \ge 10^4 P$ is enough to ensure rigid limit, where P is the confining pressure. In our case however particles are no longer convex and are discretized into nodes and multiple contacts can occur between two particles. We choose a value for $k_{n,p-p}$ such that the contact penetration does not exceed 1% of the truss members' thickness (0.01 mm). Since we model the envelope as a collection of interacting spheres, values for $k_{n,compressive}$ and $k_{n,tensile}$ must be determined together with the value of $k_{n,p-p}$, so that the model as a whole can capture the experimental results. In this work, we use the experimentally obtained apparent bending modulus value at the highest confining pressure (P =93 kPa) to calibrate our model. Specifically, the values of $k_{n,p-p}$, $k_{n,compressive}$ and $k_{n,tensile}$ are determined by matching the simulated apparent bending modulus and experimental results at P =93 kPa. With these parameters being determined, we further employ a global damping ratio β = 0.001 to facilitate the relaxation process. (The corresponding implemented global damping is $\xi =$ $\beta \sqrt{k_{n,p-p}/m_p}$ [32]). Lastly, we set $\mu_{p-p} = 0.25$, a value determined by calibrating and validating against triaxial compression experiments on 3D-printed spheres [36].

The calibrated values for all model parameters (Extended Data Table 3), once determined, remain unchanged throughout this study. Our simulation results show that our calibrated model is robust against different confining pressures and different initial configuration of the particles (Fig. 2a) and give physical representation of the shape of the deformed envelope (Extended Data Fig. 2). However, we acknowledge that the values of the parameters are not unique in terms of capturing the experimental results, and they depend on the specific calibration process. **2.8 Computing the probability distribution of normal and tangential contact forces.** The probability distribution functions are computed in their discretized form by partitioning the contact force magnitudes into bins with a uniform width, calculating the probability associated with each bin as the count of contact force in each bin divided by the total count of contact forces, and defining the force magnitude corresponding to each probability by the mid-point of each bin.

2.9 Validating the model with other particle geometry. In order to ensure that the LS-DEM model generalizes beyond the octahedral unit cell, we fabricated another sample consisting of interlocked particles constructed from 3 orthogonal rings. The apparent bending moduli for different confining pressures are compared between experiment and simulation (Extended Data Fig. 5a) and show good agreement.

2.10 The power law fitting between E^* and \overline{Z} . To fit the relation between apparent bending modulus E^* and average contact number per particle \overline{Z} , we adopted a power law function predicted by the critical phenomenon of jamming transition [13]. The functional form is:

$$E^* = a(\bar{Z} - Z_0)^b$$

Where *a* is the fitting coefficient, *b* is the scaling exponent, and Z_0 correspond to the isostatic coordination number. Since Z_0 depends on the specific particle geometry, we use different Z_0 values for different particle shapes, while keeping *a* and *b* the same for the fitting. The fitting parameters used are shown in Extended Data Table 1. We would like to note that due to expensive cost of the LS-DEM simulation process, we do not obtain data with enough orders of magnitude to validate the power law scaling or to claim a power exponent. The study of a generalized scaling behavior for particles with complex shapes and interlocking topology remains an open area of research.

2.11 Uniaxial tensile tests of fabrics under confinement. Since our fabrics are highly anisotropic, we numerically tested their apparent tensile moduli along various directions at different confining pressures (Figs. 2c,d and Extended Data Fig. 5b,c). In contrast to the apparent bending moduli, the tensile moduli extrapolate to non-zero values at zero pressure due to the resistance offered by the chain links. For the octahedral particles and particles with 3 orthogonal rings, the tensile moduli along length and width directions are approximately the same, as these are also symmetry axes. However, for the cubic particles, since the symmetry axes do not fall along the samples' length or width, the tensile moduli along these two directions are different. The Poisson's ratio measured in these tensile tests are also shown in Extended Data Table 4.

2.12 Poisson's ratio under bending and beam versus plate assumption. In order to evaluate the fabrics' Poisson's ratio under bending deformation, we analyzed the fabrics' curvature along length (κ_L) and width (κ_W) directions in LS-DEM simulation. For the octahedra fabrics at 13 kPa confining pressure, we obtained $\kappa_L = 3.2 \times 10^{-1} m^{-1}$ and $\kappa_W = -2.5 \times 10^{-2} m^{-1}$. The Poisson's ratio under bending is then calculated as [37]:

$$v_{WL} = -\frac{\kappa_W}{\kappa_L} = 0.078.$$

Due to this relatively small Poisson's ratio, the difference of apparent bending modulus (E^*) calculated using the elastic beam model (Timoshenko beam theory) versus plate model (Kirchhoff-

Love plate theory) will be: $v_{WL}^2 = 6 \times 10^{-3} < 1\%$. Thus, we adopted the elastic beam model when calculating apparent bending modulus (1) for simplicity.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request and online (<u>https://github.com/Daraio-lab/StructuredFabricsTunable-WangY</u>).

Code availability

The codes that support the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

Y. W. and C. D. designed the sample structure and the experiments. Y. W. fabricated the sample, performed the experiments and analyzed experimental data. L. L. and J. E. A. designed the LS-DEM model. L. L. performed the LS-DEM simulations and analyzed numerical results. D. H. assisted with the realization of the metal fabrics and prototyping. Y. W., L. L. and C. D. wrote the manuscript. All authors interpreted the results and reviewed the manuscript.

Competing Interests

The authors declare no competing interests.

Additional Information

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Confining Pressure P (kPa)		Ð		\Diamond			0	
93	0.164	0.159	0.192	-	0.166	-	-	-
79	0.165	0.160	0.189	-	0.167	-	-	-
53	0.165	0.160	0.188	0.103	0.169	0.143	-	-
40	0.166	0.160	0.188	0.116	0.170	0.142	0.419	0.405
25	-	-	-	-	-	-	0.418	0.404
13	0.161	0.157	0.181	0.109	0.169	0.143	0.417	0.403
2	0.155	0.152	0.175	0.09	0.161	-	0.417	0.397
Fitting Parameter Z ₀	4.89 ± 0.05; 5.29 ± 0.13 (45°)	$5.07 \pm \\ 0.20; \\ 3.66 \\ \pm 0.16 \\ (45^{\circ})$	4.68 ± 0.20	4.52 ± 0.28	4.24 ± 0.12	5.06 ± 0.25	4.03 ± 0.16	4.72 ± 0.42
Fitting Parameters a, b	a=0.159, b=2.348							

Extended Data Table 1. Packing fraction of different fabric sheets under considered confining pressures, and fitting parameters used for the power law relation shown in Fig. 3g. The packing fraction in each simulation is computed as the total volume of constituent particles divided by the total occupied volume, where the total occupied volume can be computed from the overall dimensions (L, h and b) of the respective fabric sheet at the jammed state.

Confining	Length	L (mm)	Width	<i>b</i> (mm)	Height h (mm)		
Pressure P (kPa)	Interlocked	Non- interlocked	Interlocked	Non- interlocked	Interlocked	Non- interlocked	
93	209.87	204.39	92.34	98.41	16.11	16.95	
	± 0.52	± 0.86	± 0.33	<u>+</u> 2.14	± 0.45	<u>+</u> 0.66	
79	210.03	203.68	92.06	97.40	16.18	16.94	
	± 0.59	± 0.55	± 0.25	<u>±</u> 1.78	± 0.40	± 0.71	
53	210.25	201.52	91.66	96.39	16.23	16.91	
	± 0.40	± 0.36	± 0.41	<u>+</u> 2.46	± 0.40	± 0.74	
40	209.77	202.15	91.48	95.86	16.22	16.71	
	± 0.67	± 1.33	± 0.30	± 2.06	± 0.43	± 0.72	
13	211.03	201.97	92.38	94.54	16.42	16.88	
	± 0.73	± 0.42	± 0.39	<u>+</u> 1.27	<u>+</u> 0.34	<u>+</u> 1.02	
2	208.38		95.76		16.66		
	<u>+</u> 0.33	-	± 0.14	-	<u>+</u> 0.32		

Extended Data Table 2. Average dimensions computed from four separate simulations. The standard deviations are calculated with varying initial configuration of both the interlocked fabrics and the non-interlocked assemblies at the jammed state.

Model parameters	Values
$k_{n,p-p} (k_{t,p-p} = 2/7k_{n,p-p}) [kg/s^2]$	$9.7 imes 10^4$
$k_{n,p-s} (k_{t,p-p} = 2/7k_{n,p-s}) [kg/s^2]$	$9.7 imes10^4$
$e_{n,p-p}(e_{n,p-s},e_n=e_{n,p-p})$	0.1
$e_{t,p-p}(e_{t,p-s},e_t=e_{t,p-p})$	1.0
$\beta(\xi = \beta \sqrt{k_{n,p-p}/m_p})$	0.001
$\Delta t [s]$	4.66×10^{-7}
μ_{p-p}	0.25
$k_{n,compressive}(k_t = k_{n,compressive}) [kg/s^2]$	50
$k_{n,tensile} \left[kg/s^2 \right]$	800

Extended Data Table 3. Values of the model parameters used throughout this study.

				(
	Poisson's ratio							
Confining Pressure P (kPa)	Along length	Along width	45°	Along length	Along width	45°	Along length	Along width
93	0.195	0.173	0.440	0.245	0.199	0.515	0.118	0.168
53	0.219	0.230	0.697	0.300	0.236	0.527	0.133	0.197
13	0.369	0.259	0.768	0.369	0.250	0.593	0.192	0.310

Extended Data Table 4. The Poisson's ratio obtained during uni-axial tensile tests under different pressures for fabrics with 3 particle geometries.



Extended Data Figure 1. Construction of the "digital twin" and the envelope. a, The actual particle geometry (left) and the corresponding nodes and surface triangulations of the constructed "digital twin" (right). **b**, The corresponding "grids" of the constructed "digital twin" with color indicating the signed shortest distance to the particle surface. **c,d**, The initial configurations of the

envelopes (represented by connected spheres) and of the granular assemblies with (c) and without (d) topological interlocking. e, The probability distribution of the constituent spheres' radii of the envelope used for interlocked fabric sheet (blue, c) and non-interlocked assembly (red, d).



Extended Data Figure 2. The bending test simulation and illustration of how we categorized each contact into either the "compressive" type or the "tensile" type. a, Evolution of total kinetic energy (blue) and total contact number (red) of all constituent particles of a fabric sheet under two confining pressures: 13 kPa (upper panel) and 93 kPa (lower panel). **b**, Evolution of total contact number for the same fabric sheet during the "isotropic compression only" simulation

stage for six different applied confining pressures. **c**, Evolution of average deflection of loaded particles during the "three-point bending added" simulation stage for the same six different applied confining pressures. **d**, In each of the subfigures, **F** is the total contact force vector while $\mathbf{n_1}$ and $\mathbf{n_2}$ are vectors pointing from the contact position to the respective centroid location of each contact particle.



Extended Data Figure 3. Details on the 3D architected particles and fabrics. Left column: Probability distribution of digital twin's edge lengths of all five additionally considered shape

(colored in red) in comparison to that of the hollow octahedron (colored in blue). In the inset, S and N represents the total surface area of the considered particle geometry and number of nodes of the corresponding digital twin, while S_0 and N_0 represents those of the hollow octahedron and its digital twin. **Right column:** The corresponding assembled sheets (one layer) together with a closer look on the associated interlocking pattern.



Extended Data Figure 4. Details on the classical chain mail fabrics. The same comparison as in Extended Data **Fig. 4** for classical chain mails consisting ring-shaped (**a**) and square-shaped particles (**b**). **Left column:** Probability distribution of digital twin's edge lengths of two different chainmail shapes (colored in red) in comparison to that of the hollow octahedron (colored in blue). **Right column:** The corresponding assembled chain mail sheets (one layer) together with a closer look on the associated interlocking pattern.



Extended Data Figure 5. Comparing experimental and numerical results of 2-layer fabrics consisting particles of different shapes and loaded along different directions. a, Comparison

between experimental and simulation results on fabrics consisting interlocking particles constructed from 3 orthogonal rings. **b**,**c**, Bending and tensile modulus along different directions for fabrics consisting particles constructed from 3 orthogonal rings (**b**) and cubic frame (**c**).