

FlexiFab: Laser-Cutting Volumetric Compliant Structures with Tunable-Stiffness

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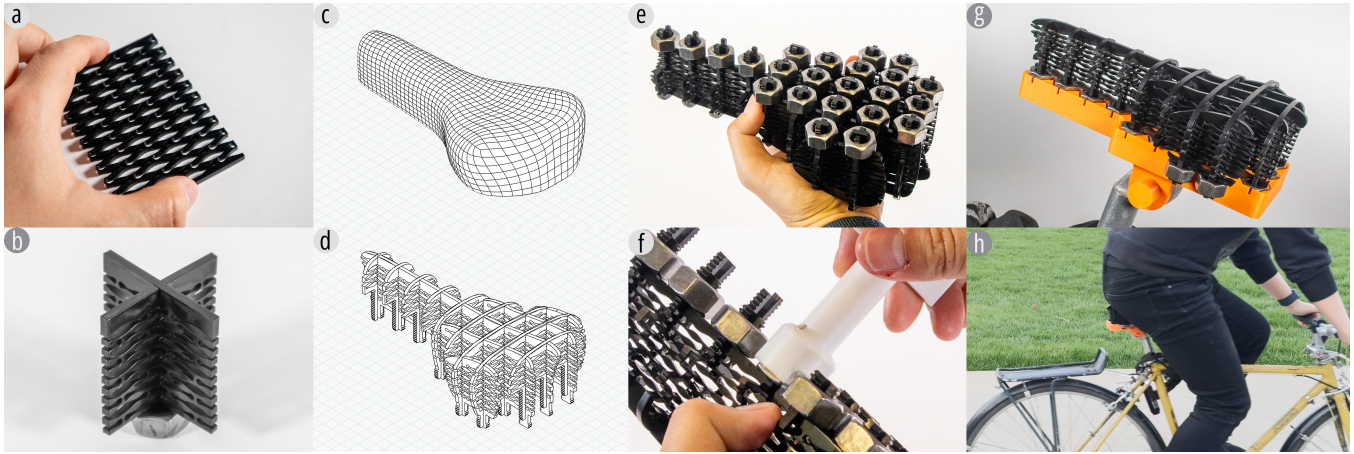


Figure 1: Overview of *FlexiFab*. (a) A planar lattice with kerf-patterned cutout. (b) A lattice intersection assembly with threaded nut. (c) Imported model of a bike seat, and (d) 3D preview of a *FlexiFab* assembly of the bike seat, provided by the design tool. (e) The underside of the fabricated bike seat. (f) Tuning the stiffness of the bike seat. (g) The finished tunable bike seat application. (h) Test ride of the bike seat that has been installed onto a bike, showing its load-bearing capacity and physical robustness.

Abstract

Laser cutting is a powerful fabrication tool for rapidly creating 3D objects from 2D sheet materials. While most research has focused on making these constructions robust and rigid, we expand this area by introducing robust yet compliant laser-cut structures. We present *FlexiFab*, a method for fabricating load-bearing volumetric objects with tunable stiffness. The core of our approach is to utilize planar lattice structures for programmable compliance, integrated into a robust framework via an orthogonal interlocking assembly. By interlocking these elements, the planar sheets provide mutual lateral support that prevents out-of-plane buckling and structural

failure. We also incorporate standard threaded nuts into the assembly, which not only provide structural reinforcement but also allow users to customize local or global stiffness post-fabrication. We demonstrate these benefits through applications such as an adjustable bike seat and provide a parametric design tool to facilitate the end-to-end design process.

CCS Concepts

• **Human-centered computing** → Interactive systems and tools; • **Applied computing** → Computer-aided design.

Keywords

Digital Fabrication, Laser-Cutting, Compliant Structure

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1 INTRODUCTION

Laser cutting has become a cornerstone of rapid prototyping due to its high throughput and accessibility. However, because it is inherently limited to 2D sheet materials, much of the research in digital fabrication has focused on two fronts: developing decomposition strategies to transform 3D volumes into 2D plates [7, 8, 21] and engineering robust joinery to ensure structural strength [3, 16]. Although these methods excel at creating rigid, static forms, they often struggle to replicate the compliance and softness found in everyday objects such as seating, hair brushes, wheels, and many more.

When designers need volumetric compliance, they typically resort to 3D printing using flexible filaments [28] or complex internal geometries (e.g., metamaterials [15, 20]). Yet, these processes remain orders of magnitude slower than laser cutting, limiting the ability to iterate on large-scale, load-bearing objects. Existing laser-cut compliance is largely limited to surface-level deformation, such as kerf bending or compliant hinges, which lack the structural depth to support significant weight.

In this paper, we introduce *FlexiFab*, a fabrication method for creating **volumetric, load-bearing, and compliant objects** that leverage the benefits of laser cutting. As we show in Figure 1, our approach builds on common grid-based assembly of planar sections. The key to our fabrication method is that we add two significant design choices: **robust interlocking** using a nut, and load-bearing kerf-patterned lattices for **tunable compliance**.

We introduce mechanical interlocking using a novel integrated threading and nut system. By cutting planar threads directly into the intersecting slots, we bypass the structural weaknesses of traditional press-fit joints, providing the rigidity needed for load-bearing applications.

The core of our contribution lies in the geometric programming of these sections. By selectively applying kerf-patterned lattices to the vertical plates, we transform a rigid assembly into a compliant volume. This method enables tunable and anisotropic stiffness: by parametrically varying the lattice geometry, designers can locally program the compression behavior across the volume. Furthermore, the integrated nuts serve dual purposes: besides assembly, they act as **post-fabrication tuning** mechanisms to manually adjust the structure's pre-tension and stiffness.

To support this workflow, we present a design tool that allows users to map desired stiffness profiles onto 3D volumes, automatically generating the optimized cut patterns and assembly instructions. We evaluate our method through rigorous mechanical testing and demonstrate its versatility through a range of applications, including customized ergonomic supports and adaptive damping systems.

In summary, our work makes the following **contributions**:

- (1) A *novel fabrication and assembly technique* for volumetric compliant structures using planar-threaded interlocking joints.
- (2) A parametric design for *programming local stiffness* within laser-cut grid structures.

- (3) An *interactive design tool* that facilitates an end-to-end workflow from volumetric specification to fabricated assembly.
- (4) *Mechanical characterizations and application examples* (e.g., adjustable bike seat, airless tire, mallet, etc.) that demonstrate the structural viability and utility of our method.

2 RELATED WORK

As digital fabrication techniques advance, there is an increasing demand for objects that combine structural robustness with complex, programmable mechanical behaviors. The development of load-bearing volumetric objects with programmable mechanical properties requires an integrated system of efficient fabrication, structural stability, and material compliance. Thus, in this section, we situate *FlexiFab* at the intersection of three research domains: the techniques of laser-cutting assembly, the design of compliant mechanisms in HCI, and the strategies for achieving stiffness tuning.

2.1 Fabricating Volumetric Objects from Laser-Cutting

Laser-cutting technology has been one of the most accessible digital fabrication tools. As a result, there is a significant body of research in HCI that has focused on extending the capabilities of laser cutters to produce 3D volumetric forms. The early foundational design systems focused on the generation of rigid 2.5D assemblies through box-like construction [7, 8] and grid-like construction [21], utilizing tools [45] such as Autodesk's 123D Make [6] and FlatFab [11] to automate joint generation. To facilitate the manual assembly process, subsequent research introduced methods for automated part packing and instructional assembly guidance [29, 30]. Other approaches utilize localized material deformation, such as heat-bending or kerf-folding, to achieve 3D shapes with minimal assembly effort [1, 2, 19, 22]. These methods typically produce static objects that lack mechanical movement. Although certain specialized patterns have been proposed to introduce non-rigid articulated behaviors [10, 32], there is a growing body of literature focused on laser-cut articulated assembly and specialized computational tools for compliant mechanism design. However, they often prioritize shape transformation over the load-bearing capacity, which is required for structural mechanical applications. In addition, although some systems incorporate auxiliary components such as springs to allow movement [31], they do not integrate compliance directly into the structural framework. *FlexiFab* builds upon these 3D assembly techniques and introduces a customizable lattice system that enables both significant vertical displacement and high structural resilience within a volumetric shape.

2.2 Compliant Mechanisms in HCI

Compliant mechanisms have been widely adopted in HCI to create interactive devices that perform complex kinematic transformations without the need for traditional mechanical joints. A significant body of research has investigated metamaterials that utilize periodic 3D geometries to program macro-scale elasticity and localized deformation [15, 20, 23, 25, 33]. While these systems achieve sophisticated non-rigid behaviors, they primarily rely on additive manufacturing, which can limit fabrication efficiency at larger scales

and typically results in fixed mechanical properties that cannot be modified after production.

Alternatively, researchers have explored compliant structures with various configurations, such as flexible rods [13, 27, 35] and laser-cut sheet materials [9, 44], to deliver customized haptic feedback and articulation. Although these methods offer high fabrication speed, they are largely constrained to surface-level or thin-shell interactions and lack the load-bearing capacity of truly volumetric structures. Although some recent systems have introduced mechanical tunability through the use of active components or tensioning cables [40, 41], such approaches often require external power sources and complex control hardware. Furthermore, while existing computational tools support the authoring of localized compliant features [14, 17], few systems provide an integrated approach to customize both global structural performance and local mechanical variations in a passive large-scale assembly. Our work addresses these limitations by providing a framework that maps 2D parametric variables to the physical characteristics of 3D volumetric structures, thereby offering highly customizable results.

2.3 Fabricating Structure with Tunable Stiffness

The ability to modulate mechanical properties post-fabrication is essential for creating versatile interactive objects. Prior research has largely focused on active stiffness tuning through jamming mechanisms [12, 24, 26], phase-change materials [4, 5, 39], pneumatic devices [42, 43], 3D printed linkages [34], or electronic actuators [18, 36]. While these methods offer high tunability, they typically require external power or bulky hardware that limits their scale and integration into passive objects. Parallel work in mechanical metamaterials has introduced geometric tuning strategies, such as hierarchical unit cells [37] and Poisson’s ratios [38], yet these often rely on specialized additive manufacturing that hinders fabrication efficiency. Furthermore, while simulations exist for complex spring groups [31], there is a lack of computational support to design large-scale, volumetric assemblies that can be manually adjusted. Our work bridges this gap by introducing a purely passive tuning mechanism; by utilizing a threaded assembly to apply pre-tension or pre-compression to the lattice planes, we enable precise, manual adjustment of global stiffness without the need for active energy input or complex material states.

3 FLEXIFAB SYSTEM

To achieve compliant properties on volumetric objects from planar fabrication techniques, we need a system that implements a 2D-to-3D construction method. This system is organized into two levels: the individual components of a planar lattice and the collective assembly of lattices.

3.1 Basics of Planar Lattice Structures

3.1.1 Lattice geometry. In this system, the lattice geometry (Figure 2a) features a periodic 2D array of dumbbell-shaped cutouts, chosen for its ability to produce significant compression and tension along the vertical axis. As shown in Figure 2b, its kinematic behavior can be modeled as a linkage system consisting of rigid beams and flexible joints, or flexures. Within this geometric pattern, the beams are defined by the wider regions of the lattice unit,

whereas the flexures are the narrow segments. During compression, the beams rotate relative to their original positions as the flexures absorb or release elastic potential energy, collectively acting as a compliant mechanism (Figure 2c).

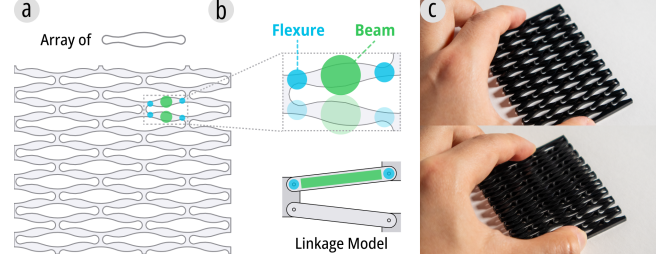


Figure 2: (a) A 2D diagram representing an example of a compliant planar lattice. It contains an array of dumbbell-shaped cutout, which is referred to as lattice unit. (b) The linkage model of a planar lattice can be used to generalize its kinematic behavior. Each lattice unit contains a collection of thin flexures (highlighted in blue) and thick beams (highlighted in green). (c) The compression process of a lattice in action.

3.1.2 Displacement, force, and stiffness. To investigate the elastic behavior of our lattice structure, we utilize four metrics to characterize the deformation process. **Displacement** (D) is defined as the total in-plane vertical deformation of the structure relative to its initial state. Every lattice has a limited distance of displacement: at the end of the compression process, every beam inside the lattice makes contact with its vertical neighbors, preventing further movement. This is defined as the range of compression R . The mechanical response to this deformation is quantified by **force** (F), which is applied at the lattice boundary and aligned with the vertical axis (Figure 3a). Since this study aims to produce volumetric forms, our investigation primarily focuses on lattice compression rather than tension; consequently, the force vector is oriented toward the structure’s center to induce a reduction in height. **Stiffness** (k) is defined as the derivative of force with respect to displacement ($k = \frac{dF}{dD}$) (Figure 3d), representing the instantaneous resistance of the structure to deformation. Although a constant k (Hooke’s Law) is often assumed when studying a simple spring, our lattice can exhibit non-linear behavior where k varies throughout the compression process due to material properties and the kinematic reconfiguration of the lattice geometry.

3.1.3 Controlling stiffness and range of compression. Given a fixed array, the mechanical response of the lattice is governed by the geometric dimensions of the dumbbell cutouts, specifically the flexure width (w_a) and the beam width (w_b). By adjusting these parameters, we can independently tune the stiffness and the range of motion of the structure.

The **stiffness** (k) is primarily controlled by w_a . Grounded in the Timoshenko-Ehrenfest beam theory (rather than the Euler-Bernoulli beam theory, due to the significantly short beam length in relation to its cross section), the compression resistance of these flexure hinges is proportional to the shear stiffness, defined as

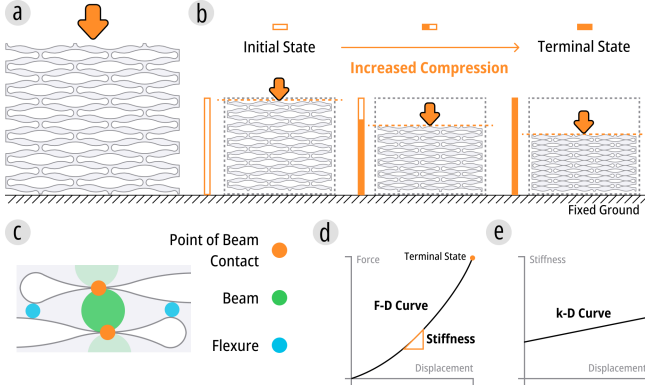


Figure 3: (a and b) The compression process of a lattice, including its initial state and terminal state. (c) The point of contact between neighboring beams. (d and e) The force-displacement plot and the stiffness-displacement plot of a linear elastic spring. Stiffness is defined by the slope of the F-D curve, or the derivative of the force with respect to distance.

$$k_{shear} = \frac{\kappa G(w_a b)}{L}$$

where κ is the shear correction factor, determined by the shape of the cross-section ($\kappa \approx 5/6$ for rectangular cross-section); G is the shear modulus, which is intrinsic to the material. It is worth noting that, while this first-order Timoshenko-based approximation does not capture complex geometric or material non-linearities, it was selected to ensure the computational efficiency required for a real-time, interactive parametric design tool.

Exemplified in Figure 10, Given a fixed lattice thickness b and a fixed length of the flexure L , the shear stiffness should scale linearly with the flexure width w_a so that $k_{shear} \propto w_a$. Zooming out of the micro level, since the cutout unit inside the lattice is organized in a 2D array, given the number of columns n_x along the horizontal axis, the vertical compression stiffness k of the lattice can be generalized as $k = n_x k_{shear}$.

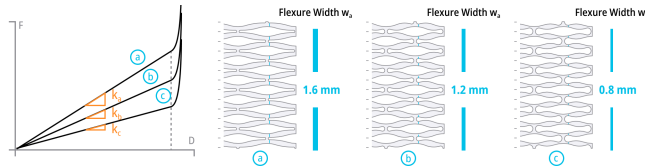


Figure 4: The effect of flexure width on lattice stiffness. A wider flexure will result in a stiffer lattice, and vice versa.

In contrast, the **range of compression** R is dictated by w_b . Because R is limited by the lattice densification process (Figure 3b and c) (which will be discussed in Section 3.2), wider beams should means smaller spaces for the structure to deform under compression, as exemplified in Figure 5. Given the number of rows n_y along

the vertical direction, and the vertical distance y between neighboring rows, the range of compression can be characterized as the following:

$$R = (n_y - 1)(y - w_b)$$

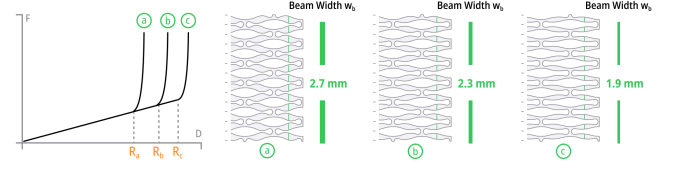


Figure 5: The effect of beam width on range of compression. A wider beam will result in a smaller range of compression, and vice versa.

3.2 Elastic Behaviors of Planar Lattice

3.2.1 Linear lattice. A linear lattice is designed to strictly follow a 2D periodic arrangement, and each lattice unit contains the same set of geometric parameters. As a result, a linear lattice typically operates in two phases under compression (Figure 6a): the linear phase and a narrow dense state. Because the deformation is uniform across the lattice geometry, every unit reaches the fully compressed state almost simultaneously.

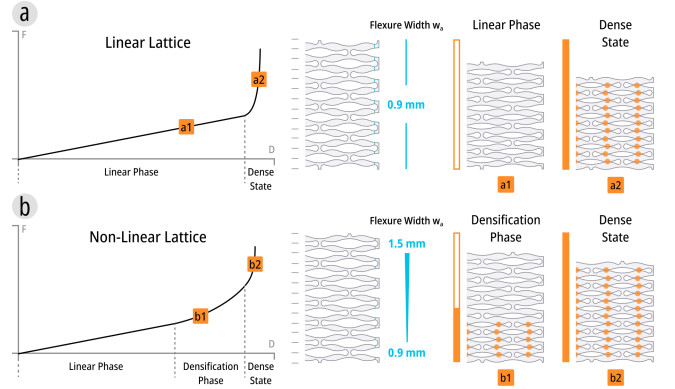


Figure 6: Elastic behavior of linear and non-linear lattices. Constant flexure width in linear designs leads to abrupt densification immediately following the linear phase (a). Conversely, non-linear lattices vary width vertically, enabling a gradual densification phase (b) and extended displacement before reaching a dense state.

3.2.2 Non-linear lattice. On the other hand, a non-linear lattice is designed with variable flexure width along the vertical direction. Towards the end of compression, the non-linear lattice gradually establishes points of beam contact, and consequently stiffens until fully densified (Figure 6b). Therefore, during the densification phase, the lattice behaves non-linearly due to the increase of stiffness, while the linear phases are similar between both linear and non-linear lattice. It is worth mentioning that the behavior of non-linear

spring resembles that of a variable pitch spring, as the latter also exhibits a densification process as the coils lock up and become inactive due to compression.

3.3 Volumetric Lattice Assembly

3.3.1 Interlocking lap joint. Since the planar lattice system that has been discussed above can achieve customizable compliance, our goal now is to extend these planar mechanical behaviors into the third dimension to create volumetric compliant objects. Here, we utilize interlocking lap joints (Figure 7a) as the primary assembly method. These joints consist of matching slots cut into intersecting lattice planes, allowing individual planar lattice to slide freely and overlap at perpendicular junctions. This assembly technique allows localized spring-like behavior (shown in Figure 8) of the 2D patterns to function collectively within a lightweight, 3D structural framework.

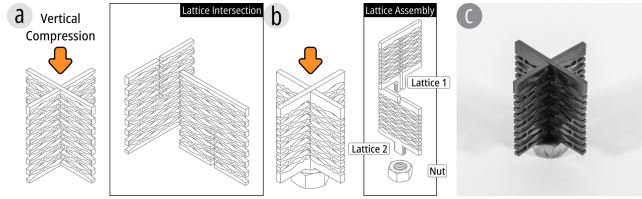


Figure 7: Lattice intersection assembly. (a) Interlocking lap joint of two planar lattices. (b) Integrated threaded profiles and nuts provide mechanical reinforcement. (c) An example of a lattice intersection.

3.3.2 Threaded fastener. To ensure the structural integrity of these intersecting assemblies, we incorporate a type of extended structure on the planar lattice to accommodate mechanical fastening at the lattice intersections. These extended structures are designed as the cross section profiles of a threaded fasteners. Shown in Figure 7b, by intersecting these two planar profiles (with one that contains the extended slots), this technique enables the use of threaded nuts to form a robust assembly, which is critical in a dynamic structure where deformation is expected and desired. Given the type and thickness of the material used in this study (which will be discussed in Section 4) and the wide range of options in mechanical fasteners, we select the standard M12 nut with a 1.75 mm coarse thread pitch, which helps to achieve a balance between clamping force and torque required for tightening.

3.4 Stiffness Tuning Mechanism

To enable user-driven adaptation to varying environmental conditions or functional requirements, it is essential to move beyond static geometric programming toward active, post-fabrication control. While geometric parameters of flexure width w_a and beam width w_b establish the lattice's customizability during the design phase, the integrated threaded nut introduces a dynamic layer of post-fabrication control. Beyond its role as a fastener, the nut serves as a mechanical interface that allows rapid reconfiguration of the lattice intersection's structural stiffness. Here, we designed an modified lattice assembly (Figure 9a1 and a2) that leverages the threading

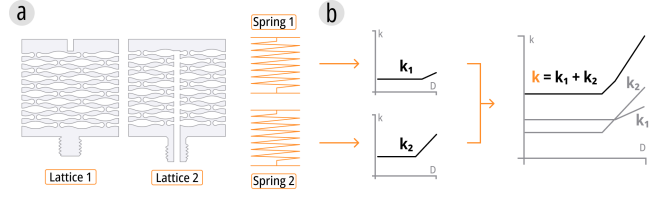


Figure 8: (a) The mechanical behavior of a lattice intersection can be modeled as a parallel spring system. (b) The laws of parallel springs states that, at any given moment, the combined stiffness k of the spring system equals the sum of each individual spring stiffness (in this case, $k_1 + k_2$).

profile to apply tension and compression before load is applied. As demonstrated in Figure 9b1, b2 and b3, by adjusting the nuts, one lattice layer can be **pre-tensioned** while another is **pre-compressed**, effectively shifting their individual stiffness-displacement curves horizontally in opposite directions along the D -axis. This tunable bias between the two intersecting lattices reconfigures the collective initial stiffness of the system before compression, allowing the combined stiffness (k) of the 3D assembly to be tuned to meet specific functional requirements without requiring structural redesign.

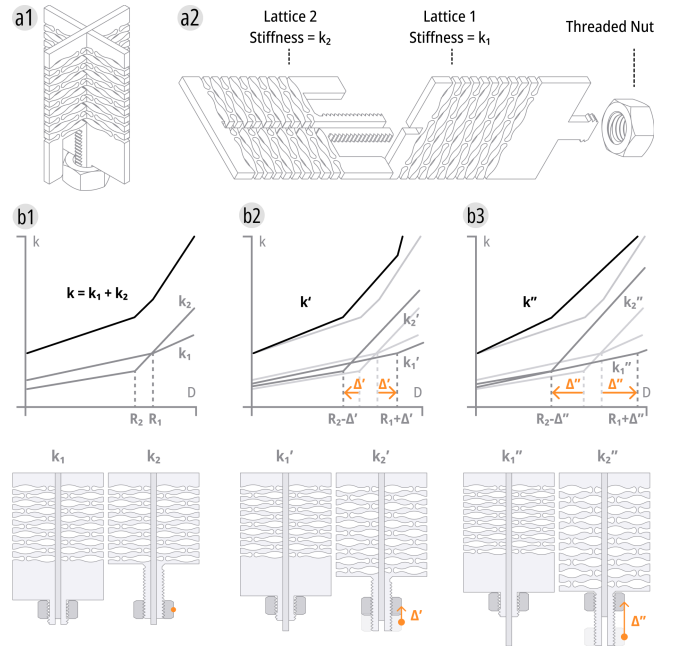


Figure 9: Tuning stiffness post-fabrication by adjusting the nut position. This mechanism is enabled by the threading profile assembly. By pre-tensioning one lattice and pre-compressing another, the stiffness-displacement curve of each lattice is moved horizontally towards opposite directions, effectively changing the stiffness of the lattice assembly.

4 FABRICATION METHOD AND MECHANICAL EVALUATION

This section details the physical implementation of the *FlexiFab* system and presents experimental data to validate our geometric mechanical models. The mechanical experiments are conducted using MARK-10 M5i digital force gauge with a force sensor MR01-500-1 (max. 2500 N, 1 N resolution). This system is mounted on test stand ESM303, which has a maximum loading capacity of 1.5 kN.

4.1 Laser-Cutting POM

When it comes to laser-cutting, there is a wide array of sheet materials for us to choose from, ranging from natural material like plywood to synthetic polymers such as acrylic (PMMA). In typical laser-cutting fabrication, acrylic is often favored for its structural rigidity; however, these materials vary drastically in their mechanical response to loading. The primary challenge in selecting the suitable material is to have the resulting structure to withstand excessive bending stress. Because the deformation process relies on thin flexures, these regions experience significant stress concentrations. Brittle materials lack the capacity for plastic deformation and often fail catastrophically when subjected to the large displacements required by the lattice geometry. In contrast, Polyoxymethylene (POM) (often sold as Delrin) exhibits high ductility and fatigue resistance, allowing flexures to undergo repeated deformation without structural failure. Therefore, throughout this study, we use black POM Delrin sheet with 1/8 inch or 3.175 mm thickness. This thickness is high available through online vendors, and it offers a balance between mechanical strength and the laser energy required to reach full penetration.

Regarding laser cutting equipment, we use a Universal Laser Systems VLS4.60, which is equipped with a 30 Watt (10.6 μm) CO2 laser cartridge, and it delivers consistent results across multiple jobs. For the laser-cutting settings, we use a speed of 6.345 mm/s or 0.25 inch/s, which is 2.5% of its maximum speed; the power is set to 15 Watt (half of its maximum power), and the pulse frequency is set to 500 pulse per inch (ppi), which translates to 125 Hz at the given speed. By running these settings in our laser cutter, we can achieve a clean and fully penetrated cutting path with just a single pass, without encountering excessive melting or fusing caused by heat-affected zones.

4.2 Mechanical Evaluation on Controlling Stiffness and Range of Compression

Previously in Section 3.1, we have proposed the method of controlling stiffness k and range of compression R . To further quantify these relationships and to better understand the compression process, we performed a series of compression tests and recorded the force-displacement data.

The seven test samples for the stiffness-flexure width test are designed with distinct flexure widths $0.5 \text{ mm} \leq w_a \leq 1.7 \text{ mm}$, but with the same beam width $w_b = 2 \text{ mm}$. The lower bound of 0.5 mm is determined in a laser-cutting test, in which we get a failed or inconsistent result with any thin wall features that are thinner than 0.5 mm.

Shown in Figure 10a, the force-displacement curves exhibit the linear phase, with the first two dataset also showing the upward

spike of the dense state, matching the linear lattice model that we illustrated previously (Figure 6a). The range of stiffness measured from the force-displacement curves varies from 0.7 N/mm, which is similar to a dishwashing sponge, to 8.32 N/mm, analogous to the mid-sole of a responsive running shoe. More importantly, by performing another set of linear regression analysis on stiffness k in respect to flexure width w_a , and given the horizontal lattice unit count (number of columns) of n_x , we derived this relationship:

$$k \approx n_x(6.94w_a - 3.21)(\text{N/mm})(R^2 = 0.985)$$

which enables us to customize the stiffness. This high correlation ($R^2 = 0.985$) ensures that the user's intended stiffness is accurately translated into the generated geometry discussed in the following section (Section 5).

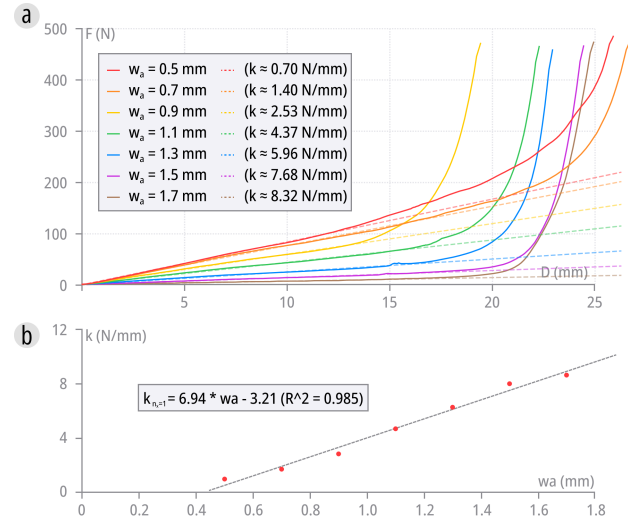


Figure 10: The mechanical evaluation that investigates the effect of changing flexure width w_a on stiffness k . The result in (a) confirms a positive correlation, and the interpolated stiffness for the linear phases of these sample lattice ($0 \text{ mm} \leq D \leq 12.5 \text{ mm}$) further suggests a linear correlation in (b).

Similarly, we conduct another mechanical evaluation that investigates the correlation between range of compression R and beam width w_b (Figure 11). Here, the seven samples have varied beam widths such that $2.0 \text{ mm} \leq w_b \leq 3.2 \text{ mm}$, and a constant flexure width $w_a = 0.9 \text{ mm}$.

The FEA result (Figure 12) further confirms the previously established geometric model $R \approx (n_y - 1) * (y - w_b)$: given the sample parameters $n_y = 12$, $y = 4 \text{ mm}$, $w_b = 2.368 \text{ mm}$, the formula returns $R = 17.952 \text{ mm}$, which matches the FEA result of $R \approx 18 \text{ mm}$. While this non-linear static analysis is limited by its lack of self-intersection detection, the range of compression can be effectively determined by identifying the point of structural densification through visual inspection of the deformed geometry. By implementing this model, the design tool provides a reliable estimation of travel without the need for computationally expensive contact mechanics, and the user can acquire a result that provides

necessary travel without premature stiffening or excessive deformation.

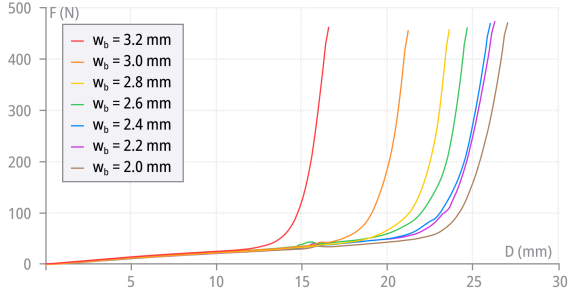


Figure 11: The mechanical evaluation that investigates the effect of changing beam width w_b on the compression characteristics. A negative correlation between beam width w_b and range of compression R can be derived from the force-displacement results.

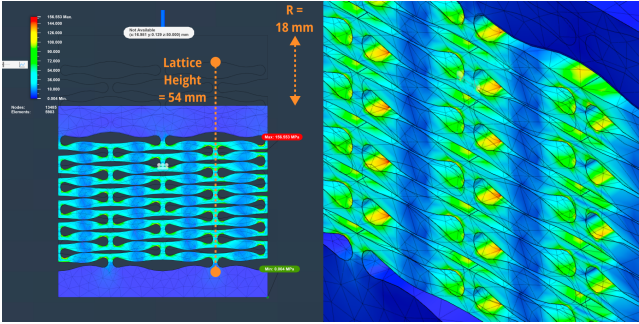


Figure 12: Results of the non-linear static Finite Element Analysis (FEA) performed on a lattice. The heatmap exhibits von Mises stress distribution at the dense state of the lattice.

4.3 Mechanical Evaluation on Stiffness Tuning Mechanism

In this part of the mechanical evaluation, the effect of tightening and loosening the threaded nut in the lattice assembly on compression behavior is also observed. Shown in Figure 13, the result in force-displacement curves displays a clear progressive divergence as the position of the nut p changes. The mechanical bias between the two lattice members due to pre-tension and pre-compression shifts the force-displacement trajectory: at $p = 0$ mm, the structure exhibits a soft, compliant response with a maximum total travel of approximately 13.5 mm. Conversely, at $p = 20$ mm, the initial stiffness increases significantly, requiring nearly 90 N of force to achieve only 6 mm of displacement.

This behavior reveals the nature of stiffness tuning, which is a trade-off between stiffness and the range of compression. Although tightening the nut allows the structure to support higher loads with minimal deflection, it also reduces the remaining range of motion

between lattice units, causing the lattice to reach its dense state much earlier. Furthermore, judging from these patterns in the graph (Figure 13), the leftward shift of the force-displacement curve as the position of the nut progresses is aligned with the presumption of the parallel spring model discussed in Section 3.4, where the stiffness-displacement curves move horizontally against each other.

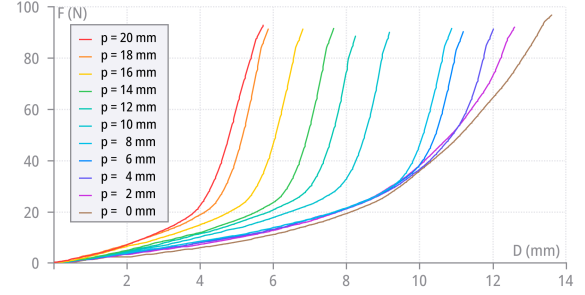


Figure 13: The mechanical evaluation that investigates the stiffness tuning mechanism. The result confirms a positive correlation between the position of the nut and the overall stiffness of the lattice such that the tighter the nut, the stiffer the lattice intersection becomes, and vice versa. And as the by-product of the leftward shift of the force-displacement curve, the increase in stiffness is followed by a decrease of the range of compression.

5 Parametric Pipeline and Design Tool

With the findings gathered from the mechanical evaluation (Section 4), we can deploy these correlations between design parameters and physical properties into our parametric tool, where we aim to convert user-defined models with their preferences on structural compliance into laser-cutting ready vectors.

5.1 Parametric Design for Lattice Unit and Array

To create lattice patterns with exact flexure width w_a and beam width w_b , we first need to define the dumbbell-shaped unit. As indicated in Figure 14, the "dumbbell" is composed of a series of arcs. The center of the three main circular arcs forms a horizontal line segment, ensuring horizontal and vertical symmetry: the smaller arcs have a radius of R_1 , and the larger middle arcs have a radius of R_2 . To create a smoother transition between the main arcs so that there is no concentrated stress upon compression, the main arcs are connected with four additional arcs, each of which has a radius of R_3 . For the dumbbell-shaped unit, the total width and height are defined as d_x and d_y , respectively. And finally, the horizontal and vertical distances between diagonal neighbors are x and y .

After defining these parameters and setting up this parametric model, we formalize the expression for w_a and w_b as the following:

$$w_a = \sqrt{(R_2 + y)^2 + \left(x - \frac{d_x}{2} + R_1\right)^2}$$

$$w_b = \sqrt{4R_2^2 + x^2} - 2R_2$$

To minimize customization workload while maintaining sufficient degree of geometric freedom of this parametric model, we established additional geometric constraints between these parameters.

$$d_x = 2x - 1, \quad y = \frac{x}{3}, \quad d_y = y, \quad R_2 = x$$

This simplification allows the parametric pipeline to prioritize the relationship between the functional outputs — stiffness (k) and compression range (R) — and the primary inputs, which are the flexure width w_a and beam width w_b to achieve viable and predictable results. In particular, $d_x = 2x - 1$ ensures 1 mm horizontal spacing between each cutout unit; $y = \frac{x}{3}$ dictates the width to height ratio of the cutout; $d_y = y$ further simplifies the staggered array by assuming horizontal symmetry between any horizontal neighbors regarding their shared vertical neighbors; $R_2 = x$ regulates the shape of the center arcs to avoid extreme curvature. And now, it is necessary to gather user-defined values to determine the value of R_1 and R_3 in the design tool.

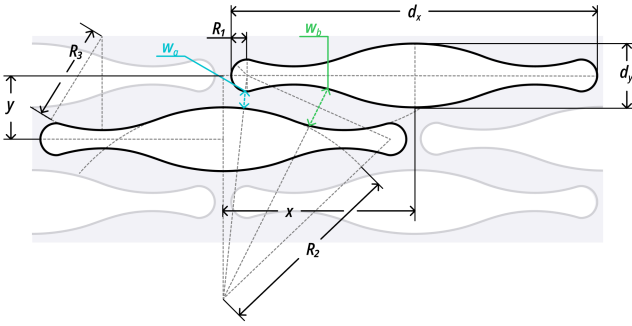


Figure 14: Parametric modeling of the lattice.

5.2 Design Tool

With the parametric system defined, we developed the parametric design pipeline in Grasshopper, which is a visual programming environment for Rhino that enables real-time geometric manipulation and mechanical property mapping. The tool streamlines the transition from a 3D form to a laser-ready assembly through the following four steps, presented in the four corresponding four tabs shown in Figure 15:

5.2.1 Model Import (Figure 15a). The user is prompted to import a model into Rhino that represents the target geometry, either as a mesh or B-rep object. After import, they also have the option to scale and rotate the model in Rhino, which can change the slicing result in the next step.

5.2.2 Global Settings (Figure 15b). Then, the pipeline performs a volumetric slicing based on the input *GridSpacing* and the three dimensions of the model's bounding box. The *GridSpacing* defines two arrays of orthogonal cutting planes, each parallel to the XZ and YZ planes; to adjust the stiffness and the range of compression

on the object, the user is prompted to select a stiffness coefficient k_{coef} , $0.0 \leq k_{coef} \leq 1.0$, and a range of compression coefficient R_{coef} , $1.0 \leq R_{coef} \leq 10.0$. With these inputs available, we can establish the following

$$x = \frac{GridSpacing}{2}$$

and

$$R_1 = \frac{GridSpacing(3 - 2k_{coef})}{36}, \quad R_3 = \frac{GridSpacing}{R_{coef}},$$

given the definitions and constraints discussed in Section 5.1. Similarly, these constraints are empirical knowledge that we have gathered during development, and are established to facilitate the production of usable design from the parametric pipeline. With these parameters available, the design tool provides an estimate of the stiffness in N/mm and compression range in mm, a preview of the 2D lattice pattern, in addition to the cutting grid projected onto the original model, shown in Figure 15b.

5.2.3 Local Settings (Figure 15c). The global settings presented in the previous page have been applied to the entire object. To support local customization, the design tool gives the option of defining localized variations within a lattice pattern. Using intersection-based selection, where the user selects the two intersecting lattice members, they can individually adjust the stiffness at this target intersection using the *local stiffness multiplier*, and the pipeline automatically applies numeric smoothing (Bézier) for k_{coef} on the lattice generation of the two affected lattice members, which forms horizontal gradients towards four orthogonal directions. Additionally, there is the option to turn on tunability for each intersection. When tunability is turned on, the pipeline modifies the default linear lattices into non-linear lattices by implementing a similar smooth vertical numerical gradient for the value R_{coef} , where the average of this gradient is kept at the value set at the global settings. Finally, the *interface Z level* makes the vertical position of the lap joint interface adjustable, which can be useful when dealing with some local geometric complexities that can benefit from some special treatments. The *interface Z level* is defined by the distance between where the two lap joints meet and the upper limit of this intersection, and has a default value of $2y$. During the local settings, the 3D assembly is previewed in real time within the Rhino viewport, which accurately reflects the final result after fabrication and assembly. To achieve that, for each update of the user settings, the pipeline performs a boolean subtraction operation between the part contours of the sliced model and the lattice cutout array, adds additional tunable or non-tunable thread profiles, performs solid curve extrusion of the subtraction results, and reposition (or digitally assemble) them into the 3D space. During the subtraction, we specify the segments of the part contours that are facing up by calculating the normal vectors on the curves, and suppress the lattice units that intersect with these curve segments during the subtraction operation, so that the integrity and the smoothness of the top of the lattice members can be preserved.

5.2.4 Preview and Export (Figure 15d). Once finalized, the pipeline rearranges the curves used previously in extrude operation by performing 2D nesting optimization to ensure material efficiency during laser cutting. After the user reviews the 2D vectors and 3D assembly preview, they can export the objects from Rhino as vector files for laser cutting fabrication.

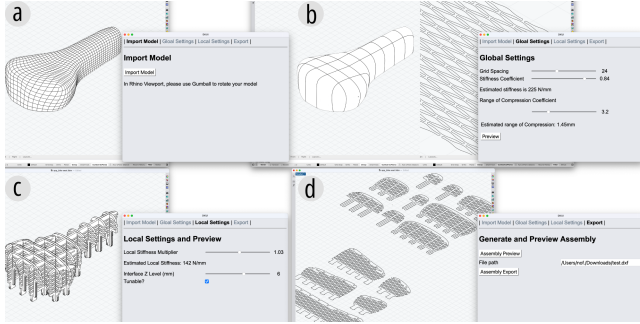


Figure 15: The user-interface of the design tool, which consists of a Rhino viewport and a customization window. The design process contains four steps: import model, global settings, local settings, and export.

6 APPLICATION

We demonstrate the real-world utility of *FlexiFab* through five functional applications that showcase the system’s capacity for load-bearing volumetric compliance and post-fabrication mechanical tuning.

6.1 Tunable Bike Seat

We demonstrate the volumetric and load-bearing capabilities of *FlexiFab* through a customizable bicycle saddle (Figure 16). The prototype, which has 23 total lattice intersections, successfully supported a 75 kg rider during a 20-minute test ride on urban roads and remains fully intact and functional. To achieve essential ergonomic compliance, seven key intersections located in the front and back of the bike seat utilize our tunable intersection design to support post-fabrication tuning. The rider can manually tighten or loosen these nuts to modify the local stiffness from approximately 5 N/mm to 8 N/mm, according to factors such as road conditions and personal preferences. The fabrication workflow required approximately 80 minutes for laser cutting and 15 minutes for manual assembly.

6.2 Tunable Mallet

We present a tunable mallet (Figure 17a), which demonstrates *FlexiFab*’s utility in creating functional tools with compliance and high impact-resistance. The tunable mallet features a lattice assembly that provides essential damping, and the tunable mechanisms are positioned opposite the striking face. Using a hex socket wrench, users can manually adjust the stiffness (Figure 17c) to match specific requirements of the task. A softer setting (with looser nuts) provides a damped impact similar to a firm cushion, and thus is suitable for delicate operations, such as the assembly of thin plywood

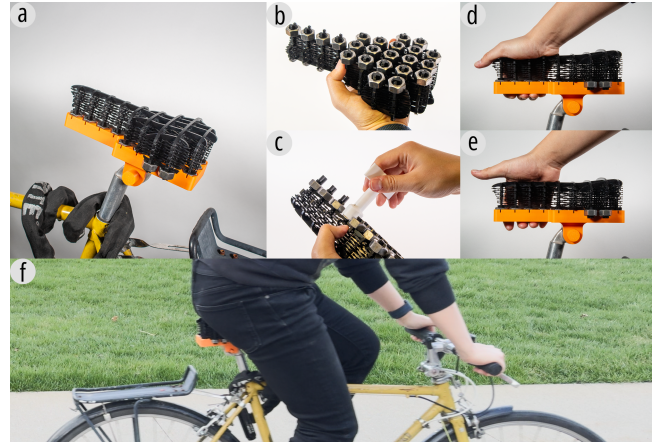


Figure 16: Tunable Bike Seat. (a) Assembled lattice on bicycle; (b) underside with 23 nuts. (c) Post-fabrication tuning via wrench. (d and e) Unloaded and loaded localized compliance; (f) prototype supporting a 75 kg rider.

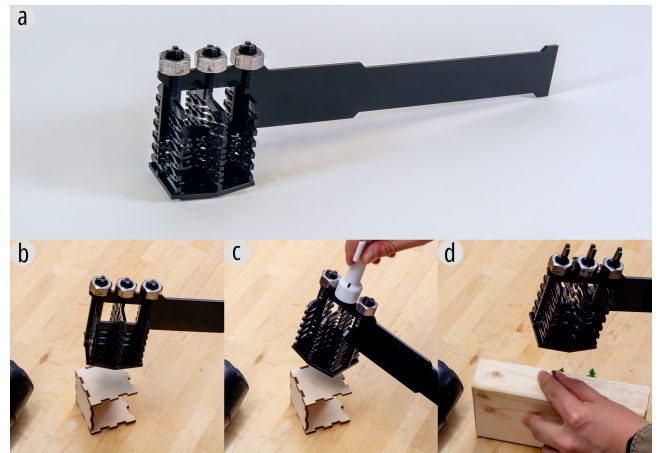


Figure 17: Tunable Mallet. (a) Overview of head and tuning nuts. (b) Soft setting for delicate assembly; (c) tuning process. (d) Stiff setting for high-impact tasks.

structures connected to box joints without surface marring (Figure 17b). In contrast, a stiffer setting (with tighter nuts) transforms the tool into a stiffer mallet, suitable for high-impact tasks, such as driving a nail into a dense wood log (Figure 17d). This application showcases how the tuning mechanism dynamically reconfigures the tool’s mechanical response, which reduces the need for multiple tools. The fabrication workflow required approximately 17 minutes for laser cutting and 1 minute of assembly.

6.3 Airless Wheel

Next, we demonstrate circular configurations of *FlexiFab* lattices at the example of an airless wheel with adaptable damping (Figure 18). This wheel contains an assembly of a lattice ring, multiple lattice spokes, a rigid center disk, and a circular lattice track. The compliant

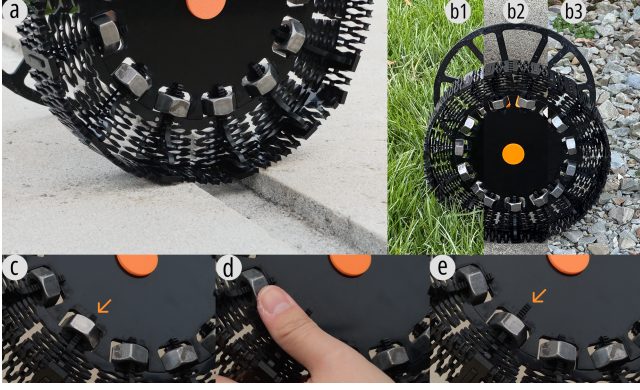


Figure 18: Airless Wheel. (a) Deformation showing shock-absorption. (b1, b2, and b3) Adaptation for varied surfaces. (c, d, and e) Changing nut positions for soft/stiff settings and the tuning process.

parts in this assembly provide the necessary compliance for shock absorption (Figure 18a). To optimize performance across different terrains, the wheel supports post-fabrication stiffness adjustment via its integrated threaded nuts. By adjusting the nuts (Figure 18d), users can reconfigure the mechanical response to match the environment. For example, a stiffer setting (Figure 18e) is suitable for grass surfaces (Figure 18b1); medium stiffness can be applied on smooth concrete surface (Figure 18b2); a softer setting allows the wheel to conform more effectively to loose gravel (Figure 18b3). This application highlights how our tunable compliant mechanism enables a single 3D assembly to adapt its mechanical properties to varying environmental conditions without the need for design modification. The fabrication workflow required approximately 70 minutes for laser cutting and 10 minutes for manual assembly.

6.4 Vibration-Driven Robot

We present a vibration-driven robot (Figure 19), which demonstrates how *FlexiFab*'s post-fabrication tuning can be utilized for motion control in a simple lattice assembly. The robot's frame consists of two tunable lattice intersections and one solid plane that supports an eccentric rotation mass (ERM) vibration motor and an external power source (Figure 19a). By adjusting the integrated nuts, users can reconfigure the mechanical response of the individual lattice "legs" after assembly. Tightening a single nut (Figure 19b and c) while leaving the other loose introduces an asymmetric stiffness bias. When the motor is activated, this mechanical bias causes the robot to steer either to the left or right (Figure 19d). This application illustrates that the ability to tune local compliance can be used to program complex behaviors, such as directional locomotion, through simple and rapid mechanical adjustments. The fabrication workflow required approximately 20 minutes for laser cutting and 2 minutes for manual assembly.

6.5 Boxing Target

We demonstrate a boxing target (Figure 20) that utilizes *FlexiFab*'s volumetric compliance and high impact-resistance for reactive athletic training. The target features four individually tunable lattice

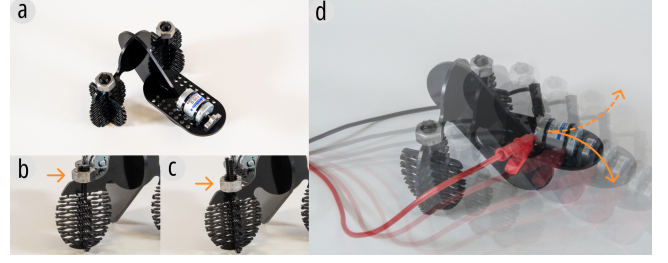


Figure 19: Vibration-Driven Robot. (a) Robot with lattice intersections and motor. (b and c) Soft and stiff intersection states; (d) controlling steering via asymmetric stiffness tuning.

intersections at each corner, allowing the user to program localized mechanical variations across the hitting surface. By applying a biased tuning setting, where the nuts are adjusted to different heights, the target exhibits an asymmetric stiffness gradient. This variability is particularly useful for simulating different physiological strike zones (e.g., the soft abdomen versus a rigid jaw) or for creating an unpredictable training surface that forces the athlete to adapt their force modulation and punch precision in real-time. As shown in the comparison between Figure 20c and Figure 20e, the same volumetric assembly can be reconfigured to provide deep damping or rigid feedback, allowing for personalized and dynamic workout without the need for multiple specialized targets. The fabrication workflow required approximately 20 minutes for laser cutting and 3 minutes for assembly.

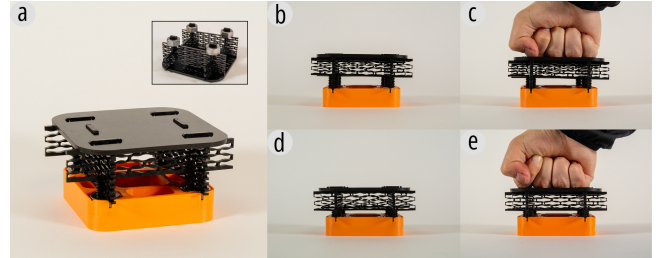


Figure 20: Boxing Target. (a) The structure is installed with corner nuts shown underneath. (b and c) Soft-tuning impact absorption; (d and e) stiff-tuning resistance under load.

7 DISCUSSION

Our work focuses on compliant, load-bearing, laser cut assemblies. We discuss the design space and limitations, which offer room for follow-up work.

7.1 Physical Modeling Fidelity vs. Computational Efficiency

A primary design requirement for the computational pipeline was to maintain high computational efficiency to enable real-time interaction within the parametric environment. To achieve this, we

utilize a first-order approximation based on Timoshenko beam theory (mentioned in Section 3.1.3) to characterize the stiffness of the lattice elements. Although this approximation does not explicitly account for geometric or material non-linearities, our characterization demonstrates high correlation ($R^2 = 0.985$) within the target linear elastic regime. Moreover, we mitigate residual physical uncertainties through an orthogonal interlocking framework designed for lateral stability and optimized joint tolerances to minimize frictional effects. This approach achieves an optimal balance between computational speed and the mechanical predictability required for robust, load-bearing design.

7.2 Design, Assembly, and Fabrication Constraints

To facilitate ease of assembly and ensure accessibility for the 3D-printed hex socket wrench, our current design workflow favors models with a planar or close-to-planar base for nut placement. Although effective for the demonstrated applications, this requirement limits the possibility of complex, doubly-curved volumetric forms where nut access might be obstructed. This limitation could be addressed by introducing cavities for access to the fasteners in the design phase, alternative fastening mechanisms, and features that can decouple the tuning interface from the structural surface, allowing *FlexiFab* to be applied to a wider array of organic geometries and non-orthogonal surfaces.

While the *FlexiFab* system provides highly programmable compliance, achieving absolute deformation uniformity in large-scale assemblies remains a challenge due to the inherent sensitivities of compliant mechanisms to non-uniform loading. As the assembly scale increases, the risk of buckling increases. To counter these effects, we utilize a lattice-free top surface to increase the in-plane rigidity of the assembly. This added in-plane stiffness mitigates the potential for lateral deformation, ensuring that the structural response remains predictable and aligned with the intended compression axis.

These challenges are further compounded by the inherent coupling between lattice resolution and the physical dimensions of the integrated fasteners. In our prototypes using 3.2 mm thick POM sheets, the diameter of the nut serves as the main bottleneck for the density of the grid. Increasing the grid resolution necessitates smaller nuts that come with a tighter pitch, creating a trade-off where higher intersection density compromises the mechanical integrity of each joint due to insufficient thread diameter. We intentionally chose to use standardized nuts to keep this method accessible for a wider audience, who may not have the means to produce custom mechanical fasteners (e.g., small nut diameter with high threading pitch).

7.3 Future Work

Beyond the current implementation, a compelling direction for future research lies in the introduction of non-orthogonal grid architectures and variable intersection densities. While our current orthogonal, uniform grid provides a reliable foundational pattern, allowing for irregular and non-orthogonal cell arrangements would significantly expand the topological complexity of the design space. By enabling varying intersection densities across a single volume,

designers could achieve highly localized, functionally graded stiffness profiles. This capability would move *FlexiFab* from the fabrication of structured lattices toward the creation of truly organic, complex volumetric forms with highly customized mechanical properties.

In parallel with these geometric advancements, the exploration of alternative materials may significantly broaden *FlexiFab* system. While our current implementation utilizes POM due to its high ductility and fatigue resistance, critical for the repeated elastic deflections required by our lattice hinges, alternative material options could significantly expand the system’s applicable scenarios. For example, increasing the material thickness (e.g., to 6 mm or more) would enhance the volumetric load-bearing capacity, though it introduces new challenges regarding thermal management and cut precision using standard CO2 laser systems. Furthermore, investigating a wider palette of materials, including high-performance engineering thermoplastics and advanced composites, would allow us to tailor the balance between stiffness and compliance for increasingly specialized applications.

Finally, we envision future applications of *FlexiFab* to transform from purely passive mechanical structures toward interactive and intelligent object. By embedding conductive pathways and sensors within the interlocked lattice layers, the system could be transformed into a sensing-enabled interface capable of providing real-time tactile feedback or responding dynamically to environmental stimuli. Furthermore, the elastic energy stored within the lattice presents a significant opportunity for kinetic energy applications, such as adaptive damping or even energy-harvesting mechanisms. These advancements would move *FlexiFab* beyond static object fabrication, enabling the creation of highly sophisticated, responsive, and functional volumetric objects capable of complex interaction within diverse physical environments.

8 CONCLUSION

In this paper, we introduced *FlexiFab*, a method for fabricating a volumetric, load-bearing, and compliant structure by extending traditional grid-based laser-cut assemblies. By integrating kerf-patterned lattices with a novel planar-threaded interlocking system, we enable the customization of localized anisotropic stiffness within a structurally resilient 3D lattice network. Our parametric design tool facilitates this workflow by mapping desired mechanical properties to the lattice geometry and providing additional post-fabrication tuning mechanism by tightening or loosening the threaded nuts. Through mechanical evaluations and applications, we demonstrate that our approach offers a practical method for creating large-scale compliant structures using highly accessible 2D fabrication tools. This work provides a foundation for designing functional, compliant objects that require both significant structural depth and mechanical resilience.

Acknowledgments

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