ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

3D PRINTING OF INFILL-BASED TPU AUXETIC METAMATERIALS: A SLICER-CONTROLLED DESIGN-TO-FABRICATION EXPERIMENT

M.Sc. THESIS

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

3B BASKIYLA DOLGU TABANLI TPU OKSETİK METAMALZEMELER: DİLİMLEYİCİ KONTROLLÜ TASARIMDAN ÜRETİME BİR DENEY

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KASIM 2025

Fatıma AYECH, a M.Sc. student of İTU Graduate School student ID 523221011, successfully defended the thesis/dissertation entitled "**3D PRINTING OF INFILL-BASED TPU AUXETIC METAMATERIALS: A SLICER-CONTROLLED DESIGN-TO-FABRICATION EXPERIMENT**", which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Date of Submission : 18 January 2026
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To my grandma,

FOREWORD

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November 2025 Fatıma AYECH
(Architect)

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ABBREVIATIONS

3MF	: 3D Manufacturing Format
AM	: Additive Manufacturing
CNNs	: Convolutional Neural Networks
FDM	: Fused Deposition Modeling Neural Network
FGMs	: Functionally Graded Materials
ML	: Machine Learning
NPR	: Negative Poisson's Ratio
PLA	: Polylactic Acid
SMP	: Shape Memory Polymers
STL	: StereoLithography
TPMS	: Triply Periodic Minimal Surfaces
TPMS	: Triply Periodic Minimal Surfaces
TPU	: Thermoplastic Polyurethane

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3D PRINTING OF INFILL-BASED TPU AUXETIC METAMATERIALS: A SLICER-CONTROLLED DESIGN-TO-FABRICATION EXPERIMENT

SUMMARY

In recent years, designs disciplines across architecture, aerospace, product development, and wearable technology, have witnessed increasing interest in materials and structures capable of responding to external conditions through controlled flexibility, deformation, and recovery. Within this spectrum, auxetic metamaterials have emerged as a notable class of engineered systems defined by negative Poisson's ratio (NPR) behavior, in which lateral expansion occurs under tension rather than contraction. This counterintuitive response is ruled primarily by micro-architectural configuration, the arrangement of cells, hinges, joints, and voids, rather than by material composition alone. Given that, auxetics provide a geometry-driven path toward lightweight structures with tunable porosity, localized deformation, and repeatable mechanical behavior. In parallel, additive manufacturing, particularly fused deposition modeling (FDM), has enabled the accessible fabrication of such micro-architectures. This thesis investigates infill-based 3D printing as a design-to-fabrication medium for developing elastomeric auxetic metamaterials. Using rigid PLA as an initial evaluation material and TPU 95A as the primary elastomeric medium, the study frames slicer logic and toolpath decisions as an active layer of design control and decision-making, through which deformation tendencies, porosity, and material efficiency can be embedded directly into fabricated specimens.

Following a focused literature review of metamaterials, auxetic deformation mechanisms, pattern-based design strategies, and additive manufacturing workflows, the research positions itself at a specific underexplored junction. While auxetic behavior has been widely examined through geometry and material selection, the systematic role of slicer-controlled infill strategies as a means of programming deformation and response remains inadequately explored. The thesis therefore investigates how infill pattern, density variation, and toolpath configuration can be treated as primary design variables influencing the observable behavior of 3D-printed auxetic metamaterials. Rather than approaching infill as a secondary structural filler, it is reframed as a micro-architectural mediator between digital geometry and physical performance, enabling the controlled production of lightweight, deformable, and recoverable TPU-based specimens.

The study consists of an experiment-driven, prototype-based methodology structured into 3 sequential phases. It begins with exploratory pattern investigation, moving from analog and visual inspection to computational pattern generation and digital simulation. During this stage, auxetic pattern families are sorted in an exploratory prioritization list based on geometric clarity, deformation legibility, and frequency in literature, setting a structured design space rather than a performance ranking. Typologies of highest potential are translated into parametric definitions using visual programming, enabling calculated variation and comparative evaluation. Physical prototyping initially proceeds through PLA-based specimens to validate geometric

articulation, print fidelity, and deformation logic independently of elastic material behavior. A material transition stage follows, using silicone to observe elastomeric response while revealing restrictions in controlling micro-scale architecture through inverse mold-based casting. The central experimental stage then shifts to TPU 95A, where infill-based fabrication becomes the primary mechanism for producing elastomeric auxetic metamaterials. Across prototypes, slicer-dependent parameters are systematically modified and documented to examine how fabrication decisions influence deformation clarity, porosity, elastic recovery, and structural resilience. Digital simulation supports comparative observation, while results are consolidated through a prototype documentation matrix that records typology, infill strategies, printing parameters, and observed behavior across all tested categories.

The core contribution of the thesis lies in establishing a slicer-dependent design-to-fabrication workflow that links auxetic typology to infill-driven behavior in elastomeric 3D printing. Within this framework, deformation is seen as a programmable outcome of micro-architectural decisions, shaped through infill pattern selection, density variation, shell and wall configuration, extrusion settings, and toolpath logic. This approach enables rapid iteration without redesigning base geometry, as a single typology can express multiple behaviors through slicing strategies alone. Through comparative evaluation of non-auxetic categories and multiple auxetic categories, including sinusoidal, fidget, rotating, multidirectional, hierarchical, and functionally graded systems, the study reveals how infill logic directly impacts perceived adaptivity, deformation responsiveness, and elastic recovery. Rotating auxetic configurations consistently emerge as high-priority candidates due to their visible expansion mechanisms and reliable behavior in elastomeric 3D printing, while hierarchical and graded specimens expose how spatial variation in infill density can support programmable elasticity and confined performance tuning.

Sustainability emerges as a parallel finding throughout the study. By relying on infill-based 3D printing rather than solid 3D printing, the prototypes achieve substantial material reduction, lower density, and reduced print time while retaining auxetic behavior. Comparative testing further revealed that while gyroid infill provides superior deformation continuity and isotropic response, 3D honeycomb infill surpasses gyroid in cost efficiency when used volumetrically, requiring less filament and shorter fabrication time. This observation underscores the potential of infill design as a sustainability measure and motivates future research into infill patterns optimized simultaneously for deformation performance and environmental efficiency.

In the final stage, the thesis introduces pneumatic deformation as an experimental observation to examine how nominated auxetic specimens with highest exploratory priority respond under internal air pressure. This stage is viewed explicitly as qualitative rather than as a standardized engineering assessment. Inflation is used to track reversible deformation behavior, elastic recovery, and curvature tendencies emerging from the interaction between auxetic topology, void distribution, hinge behavior, and slicer-controlled micro-architecture. These observations verify the broader claim that planar auxetic textiles can be steered toward volumetric responses through controlled fabrication logic and material elasticity, without positioning pneumatic actuation as the primary force behind the research.

Overall, the study positions infill-based TPU 3D printing as a viable, fabrication-aware approach for producing lightweight, breathable, and deformation-responsive auxetic metamaterials through a replicable and extendable experimental framework. By grounding the investigation in systematic prototyping, exploratory prioritization, and a structured documentation matrix, the research addresses a persistent gap in auxetic metamaterial studies, in which experimental outcomes are often presented in isolation and without a shared foundation suggesting proper comparison. The documentation matrix functions not only as a synthesis of results but as a handy methodological scaffold, enabling future researchers to reproduce, extend, or recalibrate the same parameters, such as infill logic, density gradients, shell configuration, and material selection, while maintaining continuity in evaluation. Beyond its immediate findings, the framework establishes a foundation for future investigations into elastomers of lower hardness, custom infill pattern design, and functionally graded micro-architectures optimized for both mechanical performance and material efficiency. The observed trade-offs between deformation clarity, structural stability, and filament usage point toward opportunities for integrating sustainable infill strategies, in which material reduction and print efficiency are treated as design objectives alongside mechanical behavior. Moreover, the slicer-dependent approach opens opportunities for the development of custom slicing tools or plugins that would allow designers to program deformation logic directly at the toolpath level, democratizing access to programmable metamaterial fabrication even more.

In this sense, the thesis outcome extends beyond the specific prototypes produced and is not limited to the documentation address too as its only contribution, but rather offers a design-to-fabrication paradigm in which infill geometry is elevated from a secondary printing parameter to a primary architectural design medium, capable of encrypting motion, porosity, and elasticity directly into material systems. By doing so, the research supplies cumulative knowledge-building across different fields of design, and positions infill-based auxetic metamaterial fabrication as a fertile ground for future work at the intersection of computation, material behavior, and sustainable design.

3B BASKIYLA DOLGU TABANLI TPU OKSETİK METAMALZEMELER: DİLİMLEYİCİ KONTROLLÜ TASARIMDAN ÜRETİME BİR DENEY

ÖZET

Son yıllarda mimarlık, havacılık, ürün tasarımı ve giyilebilir teknolojiler gibi tasarım disiplinlerinde, dış koşullara kontrollü esneklik, deformasyon ve geri kazanım yoluyla yanıt verebilen malzeme ve yapılara yönelik ilgi giderek artmaktadır. Bu çerçevede, negatif Poisson oranı (NPR) davranışı ile tanımlanan oksetik metamalzemeler, çekme altında yanal daralma yerine genişleme gösteren tepkileriyle dikkat çeken mühendislik sistemleri olarak öne çıkmaktadır. Bu karşı-sezgisel davranış, büyük ölçüde malzemenin kimyasal bileşiminden ziyade hücrelerin, menteşelerin, eklemlerin ve boşlukların düzenlenmesine dayanan mikro-mimari konfigürasyon tarafından belirlenmektedir. Bu bağlamda oksetik yapılar; ayarlanabilir gözeneklilik, yerel deformasyon ve tekrarlanabilir mekanik davranış özelliklerine sahip hafif sistemlerin geliştirilmesine olanak tanıyan, geometri temelli bir tasarım yaklaşımı sunmaktadır. Paralel olarak, özellikle ergiyik yığma modelleme (Fused Deposition Modeling – FDM) temelli eklemeli imalat teknikleri, bu tür mikro-mimarilerin erişilebilir biçimde üretilmesini mümkün kılmıştır.

Bu tez, elastomerik oksetik metamalzemelerin geliştirilmesi amacıyla dolgu (infill) tabanlı üç boyutlu baskıyı tasarımdan üretime uzanan bir araç olarak incelemektedir. İlk değerlendirme malzemesi olarak rijit PLA, temel elastomerik ortam olarak ise TPU 95A kullanılarak; dilimleme yazılımı (slicer) mantığı ve takım yolu (toolpath) kararları, deformasyon eğilimlerinin, gözenekliliğin ve malzeme verimliliğinin doğrudan üretim sürecine gömülebildiği aktif bir tasarım ve karar verme katmanı olarak ele alınmaktadır.

Metamalzemeler, oksetik deformasyon mekanizmaları, desen temelli tasarım stratejileri ve eklemeli imalat iş akışlarını kapsayan odaklı bir literatür incelemesinin ardından araştırma, literatürde görece az çalışılmış özgül bir kesişim noktasına konumlandırılmaktadır. Oksetik davranış; geometri ve malzeme seçimi üzerinden kapsamlı biçimde incelenmiş olsa da, dilimleme kontrollü dolgu stratejilerinin deformasyonun ve mekanik tepkinin programlanmasındaki sistematik rolü yeterince ele alınmamıştır. Bu nedenle tez, dolgu deseninin türü, yoğunluk varyasyonu ve takım yolu konfigürasyonunun, üç boyutlu yazdırılmış oksetik metamalzemelerin gözlemlenebilir davranışını belirleyen birincil tasarım değişkenleri olarak nasıl ele alınabileceğini araştırmaktadır. Dolgu, ikincil bir yapısal dolgu elemanı olarak değil; dijital geometri ile fiziksel performans arasında aracılık eden bir mikro-mimari katman olarak yeniden çerçevelenmekte ve bu sayede hafif, deformasyona açık ve geri kazanabilir TPU tabanlı numunelerin kontrollü biçimde üretilmesi sağlanmaktadır.

Çalışma, deney temelli ve prototip odaklı bir metodoloji ile yapılandırılmış üç ardışık aşamadan oluşmaktadır. İlk aşamada, analog ve görsel incelemelerden başlayarak hesaplamalı desen üretimi ve sayısal simülasyona uzanan keşifsel bir desen araştırması yürütülmektedir. Bu aşamada oksetik desen aileleri; geometrik açıklık, deformasyonun okunabilirliği ve literatürdeki yaygınlık kriterlerine göre keşifsel bir önceliklendirme listesi içerisinde sınıflandırılmakta, performans sıralaması yerine yapılandırılmış bir tasarım uzayı oluşturulmaktadır. Yüksek potansiyele sahip tipolojiler, görsel programlama araçları kullanılarak parametrik tanımlara dönüştürülmekte ve bu sayede kontrollü varyasyon ile karşılaştırmalı değerlendirme mümkün kılınmaktadır.

Fiziksel prototipleme, başlangıçta elastomerik davranıştan bağımsız olarak geometrik eklemlenme, baskı doğruluğu ve deformasyon mantığının doğrulanması amacıyla PLA tabanlı numunelerle gerçekleştirilmektedir. Ardından, silikon kullanılarak elastomerik tepkinin gözlemlendiği bir malzeme geçiş aşaması uygulanmakta; bu süreç, ters kalıp temelli döküm yöntemlerinin mikro-ölçekli mimarinin kontrolünde yarattığı sınırlamaları da ortaya koymaktadır. Merkezi deneysel aşamada ise TPU 95A kullanılarak, dolgu tabanlı üretim elastomerik oksetik metamalzemelerin elde edilmesinde temel mekanizma hâline gelmektedir. Prototipler boyunca, dilimleme yazılımına bağlı parametreler sistematik olarak değiştirilmekte ve belgelenmekte; üretim kararlarının deformasyon açıklığı, gözeneklilik, elastik geri kazanım ve yapısal dayanım üzerindeki etkileri incelenmektedir. Sayısal simülasyon, karşılaştırmalı gözlemleri desteklerken; sonuçlar, tüm test edilen kategorilerde tipoloji, dolgu stratejileri, baskı parametreleri ve gözlemlenen davranışları içeren bir prototip dokümantasyon matrisi aracılığıyla bütünleştirilmektedir.

Tezin temel katkısı, elastomerik üç boyutlu baskıda oksetik tipoloji ile dolgu temelli davranışı ilişkilendiren, dilimleyiciye bağımlı bir tasarımdan üretime iş akışının ortaya konulmasında yatmaktadır. Bu çerçevede deformasyon; dolgu deseni seçimi, yoğunluk varyasyonu, kabuk ve duvar konfigürasyonu, ekstrüzyon ayarları ve takım yolu mantığı aracılığıyla şekillenen, programlanabilir bir mikro-mimari sonuç olarak ele alınmaktadır. Bu yaklaşım, temel geometrinin yeniden modellenmesine gerek kalmadan hızlı iterasyona olanak tanımakta; tek bir tipolojinin yalnızca dilimleme stratejileri üzerinden birden fazla davranış sergilemesini mümkün kılmaktadır. Sinüzoidal, fidget, döner, çok yönlü, hiyerarşik ve fonksiyonel dereceli sistemler dâhil olmak üzere oksetik ve oksetik olmayan kategorilerin karşılaştırmalı değerlendirilmesi, dolgu mantığının algılanan adaptiflik, deformasyon tepkisi ve elastik geri kazanım üzerinde doğrudan etkili olduğunu ortaya koymaktadır. Döner oksetik konfigürasyonlar, görünür genişleme mekanizmaları ve elastomerik üç boyutlu baskıdaki güvenilir davranışları nedeniyle sürekli olarak yüksek öncelikli adaylar olarak öne çıkmaktadır.

Sürdürülebilirlik, çalışma boyunca paralel bir bulgu olarak ortaya çıkmaktadır. Katı baskı yerine dolgu tabanlı üç boyutlu baskının kullanılması sayesinde prototiplerde belirgin ölçüde malzeme tasarrufu, düşük yoğunluk ve daha kısa baskı süresi elde edilirken oksetik davranış korunmaktadır. Karşılaştırmalı testler, gyroid dolgunun deformasyon sürekliliği ve izotropik tepki açısından üstün performans sergilediğini; buna karşın üç boyutlu bal peteği (3D honeycomb) dolgunun hacimsel kullanımda daha az filament ve daha kısa üretim süresi gerektirmesi nedeniyle maliyet verimliliği açısından öne çıktığını göstermektedir. Bu gözlem, dolgu tasarımının sürdürülebilirlik odaklı bir araç olarak potansiyelini vurgulamakta ve deformasyon performansı ile çevresel verimliliği eş zamanlı olarak optimize eden dolgu desenlerine yönelik gelecekteki araştırmaları teşvik etmektedir.

Son aşamada tez, en yüksek keşifsel önceliğe sahip seçilmiş oksetik numunelerin iç hava basıncı altındaki tepkilerini incelemek amacıyla pnömatik deformasyonu deneysel bir gözlem olarak ele almaktadır. Bu aşama, standartlaştırılmış bir mühendislik değerlendirmesinden ziyade niteliksel bir inceleme olarak açıkça tanımlanmaktadır. Şişirme işlemi; geri dönüşlü deformasyon davranışı, elastik toparlanma ve oksetik topoloji, boşluk dağılımı, menteşe davranışı ve dilimleyici kontrollü mikro-mimari etkileşiminden kaynaklanan eğrilik eğilimlerini izlemek için kullanılmaktadır. Bu gözlemler, pnömatik etkiyi araştırmanın ana itici gücü olarak konumlandırmadan; düzlemsel oksetik tekstillerin, kontrollü üretim mantığı ve malzeme elastikiyeti aracılığıyla hacimsel tepkilere yönlendirilebileceği yönündeki temel savı doğrulamaktadır.

Genel olarak çalışma, dolgu tabanlı TPU üç boyutlu baskıyı; hafif, nefes alabilir ve deformasyona duyarlı oksetik metamalzemelerin üretimi için, tekrarlanabilir ve genişletilebilir bir deneysel çerçeve sunan, üretim farkındalığı yüksek bir yaklaşım olarak konumlandırmaktadır. Sistematik prototipleme, keşifsel önceliklendirme ve yapılandırılmış bir dokümantasyon matrisi üzerine kurulu olan bu yaklaşım, oksetik metamalzeme çalışmalarında sıklıkla karşılaşılan ve deneysel sonuçların birbirinden kopuk biçimde sunulmasına yol açan karşılaştırma eksikliğini gidermeyi hedeflemektedir. Dokümantasyon matrisi, yalnızca elde edilen sonuçların bir sentezi değil; aynı zamanda dolgu mantığı, yoğunluk gradyanları, kabuk konfigürasyonu ve malzeme seçimi gibi parametrelerin sürekliliğini koruyarak yeniden üretim, genişletme veya yeniden kalibrasyona olanak tanıyan pratik bir metodolojik iskelet işlevi görmektedir.

Bu bağlamda tez çıktısı, yalnızca üretilen prototiplerle ya da dokümantasyon matrisiyle sınırlı kalmamakta; dolgu geometrisini ikincil bir baskı parametresi olmaktan çıkararak, hareketi, gözenekliliği ve elastisiteyi doğrudan malzeme sistemlerine kodlayabilen birincil bir mimari tasarım aracı olarak ele alan bir tasarımdan üretime paradigması önermektedir. Böylece araştırma, farklı tasarım alanları arasında kümülatif bilgi üretimine katkı sağlamakta ve dolgu tabanlı oksetik metamalzeme üretimini; hesaplama, malzeme davranışı ve sürdürülebilir tasarım kesişiminde gelecekteki çalışmalar için verimli bir araştırma zemini olarak konumlandırmaktadır.

1. INTRODUCTION

The pursuit of lightweight, adaptive, and materially intelligent surfaces has gained renewed urgency in the fields of architecture, product design, and wearable technology. As design disciplines progressively engage with responsive systems, the role of materials has shifted from static enclosures to active agents of performance. Among the materials at the forefront of this shift are metamaterials, and more specifically, auxetic metamaterials, defined by their negative Poisson's ratio (NPR). This counterintuitive behavior proposes opportunities for applications requiring high elasticity, localized deformation, and tunable porosity. Auxetic materials represent a significant evolution in geometry-based design. Unlike conventional materials that contract transversely under tension, auxetics expand laterally, offering superior energy absorption, shear stiffness, and fracture resistance. These advantages stem not from the base material but from the structure's internal geometry. Gatt et al. (2015) highlight the benefits of hierarchical auxetics, which augment local deformation through geometry alone. Likewise, Jiang et al. (2022) classify auxetic structures across foam, lattice, and textile domains, illustrating their adaptability in wearable, biomedical, and architectural contexts.

Architectural research involving auxetic materials has steadily embraced computational logic to redefine surface behavior and spatial responsiveness. The early work of Naboni and Mirante (2015) laid the groundwork for adopting generative design tools and metamaterial simulation to create adaptive facades capable of real-time mechanical transformation. Their particle-spring physics approach exhibited the feasibility of embedding programmable features into architectural skins so they could bend and shift in response to solar radiation or wind load, signalling a transition from passive cladding to active, morphing facades. This vision positions auxetic metamaterials as living, responsive interfaces and ultimately sets an example for integrating auxetic logic into architectural design computing.

In parallel, the convergence of textile engineering and computational design has sparked the development of auxetic materials that combine flexibility with performance. Ou et al. (2018) triggered the intersection of these domains by showcasing how actuated auxetic geometries could be fabricated for dynamic, wearable applications, offering motion-driven expansion and embedded tactual sensation. Likewise, Hu (2016) proposed a framework for auxetic composites that prioritize breathability, stretchability, and structural recovery, all of which are critical parameters in both wearable tech and architectural shading systems. These innovations move beyond conventional post-processing techniques by weaving performance into the design and fabrication process itself, engineering materials of which the structural integrity is programmed within the geometry itself independent of add-on components. In this context, thermoplastic polyurethane (TPU) stands out as a particularly promising material. Its elasticity, strength, and compatibility with fused deposition modeling (FDM) make it ideal for generating intricate auxetic metamaterials. Unlike traditional textiles, TPU-based metamaterials can be fabricated accurately using slicing software that determines infill pattern, toolpath continuity, density, and wall configuration. Typically treated as a secondary technical detail, infill is perceived in this scenario as a primary design variable capable of controlling flexibility, permeability, deformation, and material behavior at the microstructural scale.

1.1 Research Questions

Current advances in additive manufacturing technologies, specifically FDM, play a significant role in the physical realization of auxetic metamaterials with increasing geometric and material intricacy. Although auxetic behavior is primarily governed by geometry, its manifestation in elastomeric systems is strongly relies on fabrication strategies, particularly when infill logic and toolpath control are treated as design variables. Despite rising interest in infill as a fabrication parameter, there remains limited understanding of how slicer-controlled decisions shape the physical behavior of auxetic metamaterials across different geometric typologies. This uncertainty motivates the research questions outlined below. The question at the core of this research is: How can slicer-controlled infill strategies be employed to embed deformation behavior within 3D-printed auxetic metamaterials? In order to address this key question, the study is directed by the following subsidiary questions: How does the transition from rigid to elastomeric polymers affect the realization and recoverability of auxetic metamaterials? How does the progression from non-auxetic baseline configurations to increasingly intricate auxetic typologies translate into evident outcomes in infill-based 3D-printed metamaterials?

1.2 Research Aim

This thesis aims to examine how infill-based, slicer-controlled fabrication strategies impact the behavior of elastomeric auxetic metamaterials (Figure 1.1). The study evolves from rigid to elastomeric polymers and from baseline non-auxetic to increasingly intricate auxetic typologies, using infill-based 3D printing as a means of governing material behavior at the micro-architectural scale. Through systematic prototype documentation, the study seeks to establish a replicable, scalable design-to-fabrication framework valid for future inspections of auxetic metamaterials.

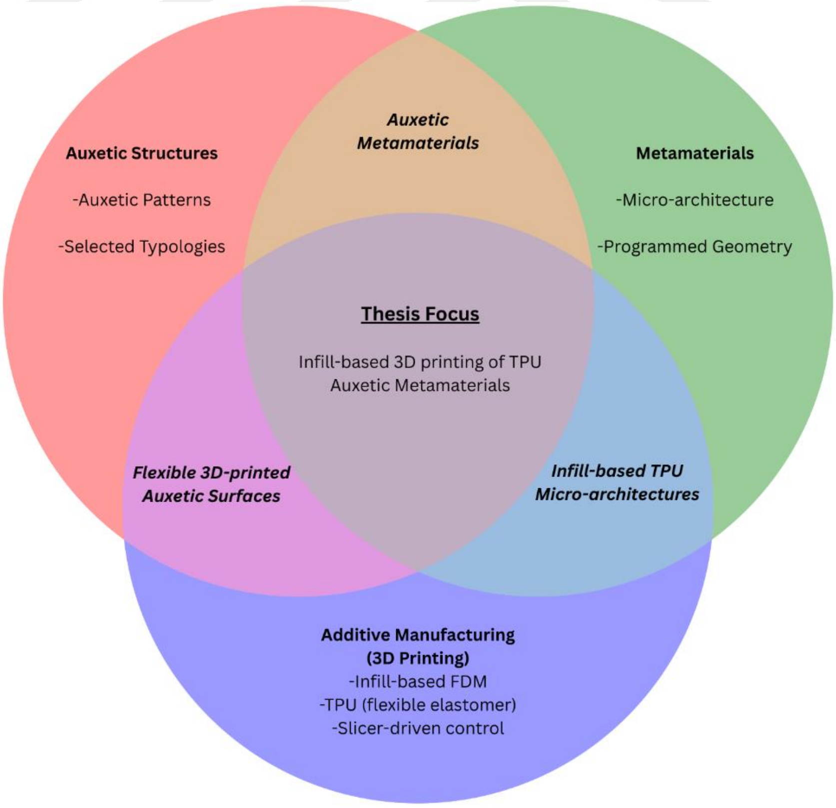

Figure 1.1: Venn diagram showing thesis domains and focus.

1.3 Research Gap

Preceding research has proved that lightweight auxetic metamaterials with retained NPR and reduced material usage are achievable via hierarchical design, but the potential of infill-based, slicer-controlled 3D printing to offer a comparable approach remains underexplored.

1.4 Methodology Overview

This research adopts an experiment-driven, prototype-based design-to-fabrication methodology in which knowledge is earned through the systematic design, fabrication, and documentation of physical prototypes. Prototypes are treated not as mere outcomes but as consecutively associated data for analysis, aiding the investigation of how geometric design decisions, material choice, and fabrication strategies, in this case 3D printing and specifically slicer parameters, vastly impact the behavior of the produced auxetic metamaterials.

As illustrated in Figure 1.2, the methodology is structured into three sequential stages. The first stage focuses on exploring the domain of auxetics, progressing from computational pattern generation and digital simulation to rigid polymer 3D printing using PLA. This stage concludes with a material transition experiment in which nominated patterns are cast in inverse 3D-printed molds using silicone, prompting an initial investigation into elastomeric behavior and highlighting the limitations of mold-based approaches in controlling micro-scale geometry.

The second stage establishes the core experimental frame of the research and focuses on infill-based auxetic metamaterials fabricated using thermoplastic polyurethane (TPU). In this stage, micro-architectural control is accomplished through a slicer-dependent workflow, where infill logic, density, and toolpath configuration are treated as design parameters interceding between digital geometry and physical behavior. The outcomes of this stage are methodically consolidated through a prototype documentation matrix, which records geometric typologies, fabrication parameters, role in research, and observed material behavior across all specimens, allowing the experimental synthesis of the design-to-fabrication relations inspected.

The final stage encompasses the study through pneumatic deformation experiments, introduced solely as a qualitative observation of emergent behavior rather than a quantitative performance evaluation. Throughout the research, feedback loops are applied locally within each experimental phase without reinitiating the overall workflow from scratch, guaranteeing a controlled and progressive design-to-fabrication workflow.

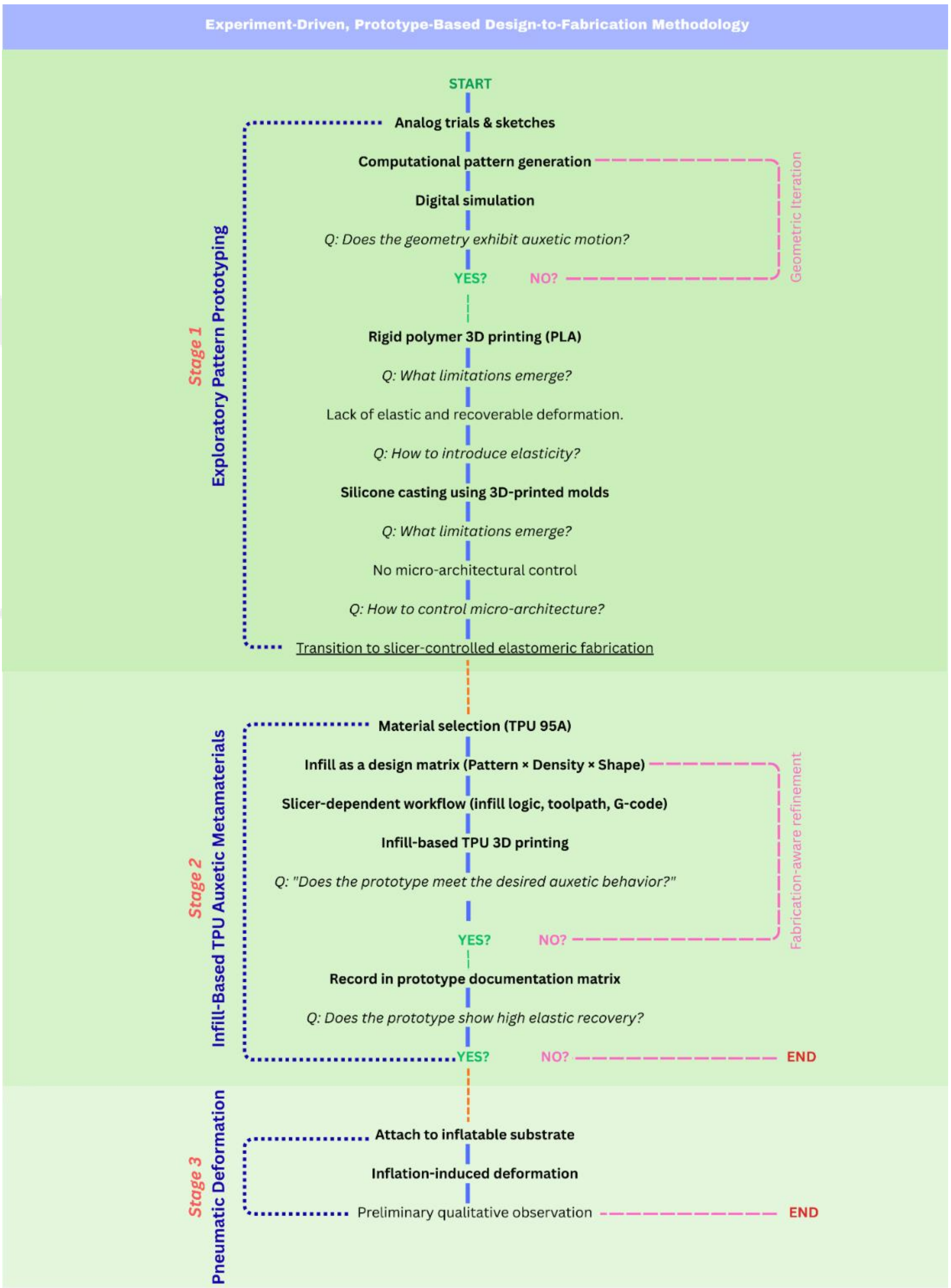

Figure 1.2: Methodology diagram showing 3 stages and workflow methods.

After preliminary hands-on pattern exploration, the study inspected how auxetic geometries could be qualitatively ordered through an exploratory prioritization process. Planar auxetic patterns, spanning numerous typologies and generated through parametric visual programming, were examined to hypothesize configurations that demonstrate clearer deformation potential. Patterns were sorted based on a visual assessment of their deformation behavior, particularly the extent to which internal voids or gaps visibly expand under expansion. This noticeable increase in open area, was treated as an indicator of qualities such as breathability, porosity, and deployability. Rather than operating as a predictive model, prioritization served to structure the design space and guide following decision-making. Within this exploratory framework, rotating auxetics consistently emerged as prominent candidates due to their apparent expansion mechanisms and frequent appearance in the reviewed literature. The process reinforces the premise that deformation can be predicted from geometric configuration prior to material testing or fabrication.

Contemporary research in architecture encompasses advances in 3D-printed façades (Pintos, 2023), textile-like assemblies (Souza, 2022), and auxetic deformation simulations (Su et al., 2020), forming a shared backdrop for fabrication-aware and material-driven research. By uniting these disciplines, this thesis builds on unexamined junctions between metamaterials, auxetic structures, and additive manufacturing. This synthesis reveals how auxetic permeability and deformation behavior can be governed through infill-based, slicer-controlled micro-architecture. Rather than treating porosity, auxetic response, and elasticity as separate features, the framework developed in this study integrates them straight into geometric definition and print logic. The thesis traces an evolution from basic planar grids to progressively intricate auxetic typologies, stressing how synchronized infill strategies, thickness control, and toolpath configuration could dictate deformation, which in this context is regarded as a documented and repeatable outcome of fabrication-aware geometric decisions, rather than a result of form-finding. Building on the work of Lakes and Alderson, as discussed in Kapsali's Biomimetics for Architecture, engineered auxetics exhibit high potential in programming deformation through geometry rather than material composition alone (Kapsali, 2021). This perspective supports the transition toward a workflow focused on encoding deformation behavior within planar micro-architectures.

The combination of triply periodic minimal surface (TPMS) geometries, functionally graded materials (FGMs), and infill-encoded actuation reflects a broader move toward the design of metamaterials. These design explorations were stored and exported using StereoLithography (STL) and 3D Manufacturing Format (3MF) files, which allowed for smooth iteration and fabrication. Though this study did not apply thermal-triggered shape memory polymers (SMPs), it draws theoretical parallels between SMP behaviors and TPU's elastic recovery.

Prior academic research has played an instrumental role in guiding this process. Ahlers (2018) designed a nonplanar 3D printing system that augmented surface quality by dynamically adjusting the extrusion head's height and angle, enabling smoother, textile-like surfaces with instilled deformation capabilities. His work defied the limitations of traditional slicers and introduced custom G-code scripting to expand geometric freedom. Similarly, Bakıcı (2023) inspected the mechanical resilience of 3D-printed TPU TPMS (triply periodic minimal surface) lattices under dynamic loading, revealing improved stress distribution and energy absorption compared to conventional infills. Meanwhile, architectural innovations by Naboni and Mirante (2015) set the stage for rethinking building envelopes as self-morphing, shape-shifting systems, concepts further explored in the initial thesis-related publication by Ayech & Akçay Kavakoğlu, (2024). The paper, merging computational knitting, ceramic textiles, and auxetic logic into a unified architectural metamaterial, laid theoretical and conceptual groundwork for subsequent stages in this thesis. It introduced an exploratory approach to deformable architectural envelopes by combining parametric modeling, algorithmic hypothesis, and tile fabrication to develop a 3D-printable rotating auxetic assemblies. In that work, future developments with thermoplastic polyurethane (TPU) and high-resolution infill programming were mentioned; these potentials are now realized in this thesis. The shift from PLA to TPU not only expands the material palette but also significantly boosts elasticity, surface recovery, and deformation control, extending the potential of auxetic metamaterials. The research investigates infill-based fabrication of stretchable TPU composites with auxetic behavior as a foundation for embedding more replicable intricate micro-architectures into the configurations. The research proposes a replicable framework for embedding deformation behavior within planar systems through geometry and print logic, supporting lightweight and fabrication-aware design methods.

Beyond academic discourse, real-world applications of auxetic structures accentuate their versatility across multiple design scales. At the product level, designers like Sung Ai Tsai (2023) have developed modular auxetic lighting systems such as *Prinx*, demonstrating how auxetic components can serve as both functional and aesthetic elements in 3D-printed lamps (Sadique, 2024). Correspondingly, fashion and footwear industries have begun to drawn on auxetic logic for adaptive fit and breathability as seen in Sruli Recht's self-fitting shoes that utilize auxetic mechanisms to conform to foot morphology (Concept Kicks, 2025). While at the research and industry junction, MIT engineers have 3D printed synthetic metamaterials with enhanced strength and stretchability, reflecting the ongoing shift toward structural functionality housed within materials (Chu, 2025). Within the intersection of computational design and experimental couture, a joint effort between fashion designer Iris van Herpen, and researchers at TU Delft explored how garments could be digitally scripted to achieve intricate forms and controlled deformation through computational fabrication for performance-integrated textiles (Doubrovski et al. 2018). While the focus was primarily on aesthetic and structural innovation, the framework presents a promising potential for the integration of breathable auxetic systems particularly in enhancing comfort, airflow, and adaptability in wearable design. This study identifies such collaborations as fertile ground for forthcoming implementation of auxetic logic, by which material intelligence could be embedded not just for visual complexity but also for purposeful response in dynamic environments. However, not all collaborative efforts between academia and industry have reached full potential. For instance, the partnership between Polymaker and Covestro, focusing on TPU, led to the realization of a 3D-printed fabric optimized for mass customization using flexible filaments and 2D print strategies, goals closely aligned with the efforts of this thesis, but the long-awaited collaborative initiative was later discontinued with no tangible outcomes

(Polymaker, 2020). This unfulfilled potential emphasizes the critical need for research that is fabrication-aware, performance-driven, and rooted in replicable methodologies.

Early rigid material experiments confirmed that geometry alone could manipulate surface behavior. However, PLA posed clear limitations in terms of elasticity and fabrication scalability, particularly under dynamic or repeated stress conditions. These challenges initiated a shift toward more flexible materials. Silicone introduced elasticity and multilayer adaptability into the research. In summary, the shift from rigid to elastomeric fabrication represents a logical progression of this interdisciplinary research. It synthesizes geometric expressiveness, elasticity, and digital precision into a metamaterial with programmable deformation. The resulting deformation is no longer a consequence of material choice alone, it is programmed into the system from the start, governed by structure, informed by material behavior, and triggered through actuation.

These prototypes revealed that functional behavior such as porosity or stretchability must emerge from a geometry-fabrication-material synergy. This realization guided the thesis's turn toward extrusion-based elastomeric systems that could support programmability at the infill level. The transition from silicone to thermoplastic polyurethane (TPU) marked a strategic and technical leap. TPU enabled desktop-scale additive manufacturing (AM) using fused deposition modeling (FDM), providing unprecedented control over internal geometry through slicer-directed infill logic. This made it possible to successfully embed customized micro-scale behavior within the print itself transforming infill from a passive structural filler into an active design mediator for the first time since the start of the research.

This perspective aligns with Severi's (2024a) research at the Bartlett School of Architecture, in which digital fabrication is redefined as a creative and structural design tool. Further inspiration stems from WASP's multi-nozzle silicone printing systems, which embed programmable deformation directly into fabrication routines (Severi, 2024b). In this thesis, the same logic is applied to TPU, using slicer software as a spatial scripting medium for structural intelligence. Revisiting structural mechanics within elastic materials reinforces the geometric basis of auxetic behavior. Plewa, Płońska, and Junak (2023) underscore the importance of joint configuration in defining how rigid square units deform, an insight directly relevant to the context of this research in which hinge zones, intercellular spacing, and junction geometries were manipulated to produce scalable, repeatable breathing effects. With deformation logic and print pathways fully embedded into design thinking, auxetic behavior swings from being experimental to being controllable. This also mirrors developments in programmable materials. Dong and Hu (2023) note the suitability of auxetic systems in sensor development due to their predictable mechanical response. Similarly, even without embedded electronics, 3D-printed auxetic surfaces show promising synclastic formations in both architectural and wearable scales. Although TPU is not a shape memory polymer (SMP) per se, its capacity for elastic recovery aligns with the behavior of SMPs described by Thakur (2017) and Brinson (1993). These parallels suggest that auxetic TPU systems could simulate passive mechanical adaptivity without thermal triggers, especially when designed with structurally intelligent geometries.

2. LITERATURE REVIEW

This part of the study tackles research on metamaterials and auxetics with an emphasis on geometry-driven material behavior, pattern-based design, fabrication processes, and application domains. After outlining the role of micro-architecture in defining metamaterial performance, the review is followed by a focused discussion on auxetic materials as a subclass of mechanical metamaterials distinguished by negative Poisson's ratio. Computational, pattern-based design methods are then observed, clarifying how auxetic behavior is purposefully encoded into the geometric logic. Additive manufacturing is addressed as a principal means for the physical realization of auxetic metamaterials, portraying the impact fabrication parameters have on actual performance. For further relevance, diverse applications in which auxetics and metamaterials display great value are discussed. Ranging from aerospace, to deployable systems, and soft robotics, application domains are selectively reviewed, demonstrating the practical worth of auxetic and metamaterial systems and positioning this research within this broader context. When industries as computational design and additive manufacturing synchronously come into play, an uprising in metamaterial fabrication is certainly foreseeable. A material's micro-architecture, its very core, could now be accurately programmable, and performance-oriented. This is where the integration of thermoplastic polyurethane (TPU), a polymer with great elastic potential, is unquestionable. Early research delivered the basis for deformation-aware material logics and auxetic pattern generation in architecture (Naboni & Mirante, 2015; Gatt et al., 2015), while more recent studies have expanded on these ideas through experimental analysis on hybrid textile polymer systems, and customized infill strategies (Lee, 2022; Yadavalli et al., 2024). In parallel, G-code scripting and slicer-targeting frameworks have proposed new methods for controlling print resolution, porosity, and mechanical responsiveness (Gokstorp, 2020; Lee, 2023). Literature discussed in the chapter reframes textile-like fabrication as a dynamic crossdisciplinary design domain. Every study adds to how material performance could be embedded through geometry and method rather than material composition alone. The resulting review synthesizes key contributions across computational design, material computation, and digital fabrication, with a particular focus on infill-based strategies for creating 3D-printed auxetic metamaterials.

2.1 Metamaterials: Geometry-driven Material Behavior

Metamaterials are architected systems of which the mechanical behavior is driven by internal geometry rather than by the inherent properties of the material itself. Within this context, material performance arises from the spatial arrangement, assembly, and deformation mechanisms of the units at the micro-architectural scale (Figure 2.1).

Figure 2.1: Parametrically designed auxetic pattern used for a shape-shifting wall at Hyperbody – Adapted from **Albag, O. E.** (2021).

Due to this distinction, metamaterials gained prominence as a geometry-driven domain, in which physical configuration becomes the core variable through which unconventional mechanical responses are realized (Albag, 2021; Zhao, 2025). It is important to remark that the geometric dominance in metamaterials allows for significantly various mechanical responses without any change in material composition. By modifying parameters such as unit-cell shape, orientation, and linkages, designers can tune stiffness, anisotropy, and deformation at the macroscopical scale. Zhao (2025) highlights that such micro-architectures shift material design from composition-based optimization to geometric control, reinforcing the role of mechanical logic as a leading design factor (Figure 2.2). Recent work has also proved that introducing hierarchy into micro-architectures results in lightweight assemblies of high functional performance. Hierarchical design considers how material is distributed across different scales, therefore reducing density while maintaining stiffness and load-bearing capacity (Figure 2.3).

Figure 2.2: Classical auxetic metamaterials – Adapted from **Zhao, C.** (2025).

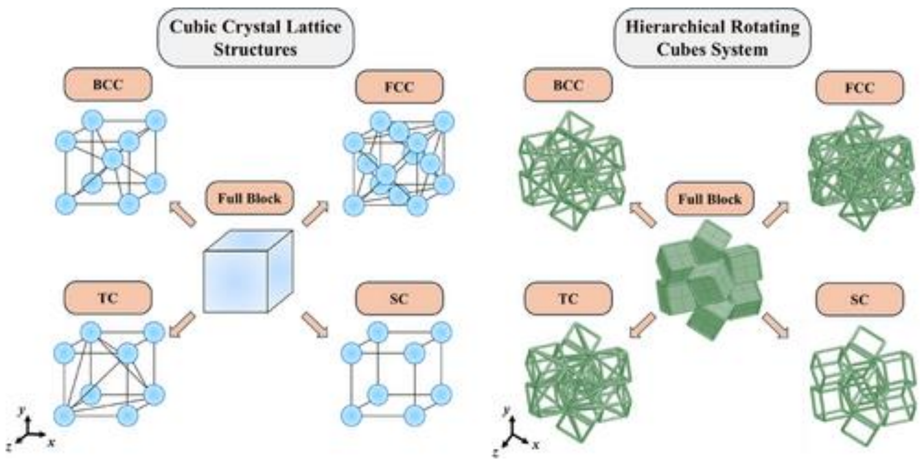

Figure 2.3: Schematic showing cubic crystal lattice arrangements and their implementation for the design of hierarchical rotating cube metamaterials – Adapted from **Mizzi et al.** (2025).

In their study, Mizzi et al. (2025) clearly illustrate this principle via three-dimensional hierarchical microlattices, showing how purposefully curated architectures can achieve high performance-to-weight ratios while featuring tunable Young's modulus values driven by structural density and micro-architectural configuration (Figure 2.4).

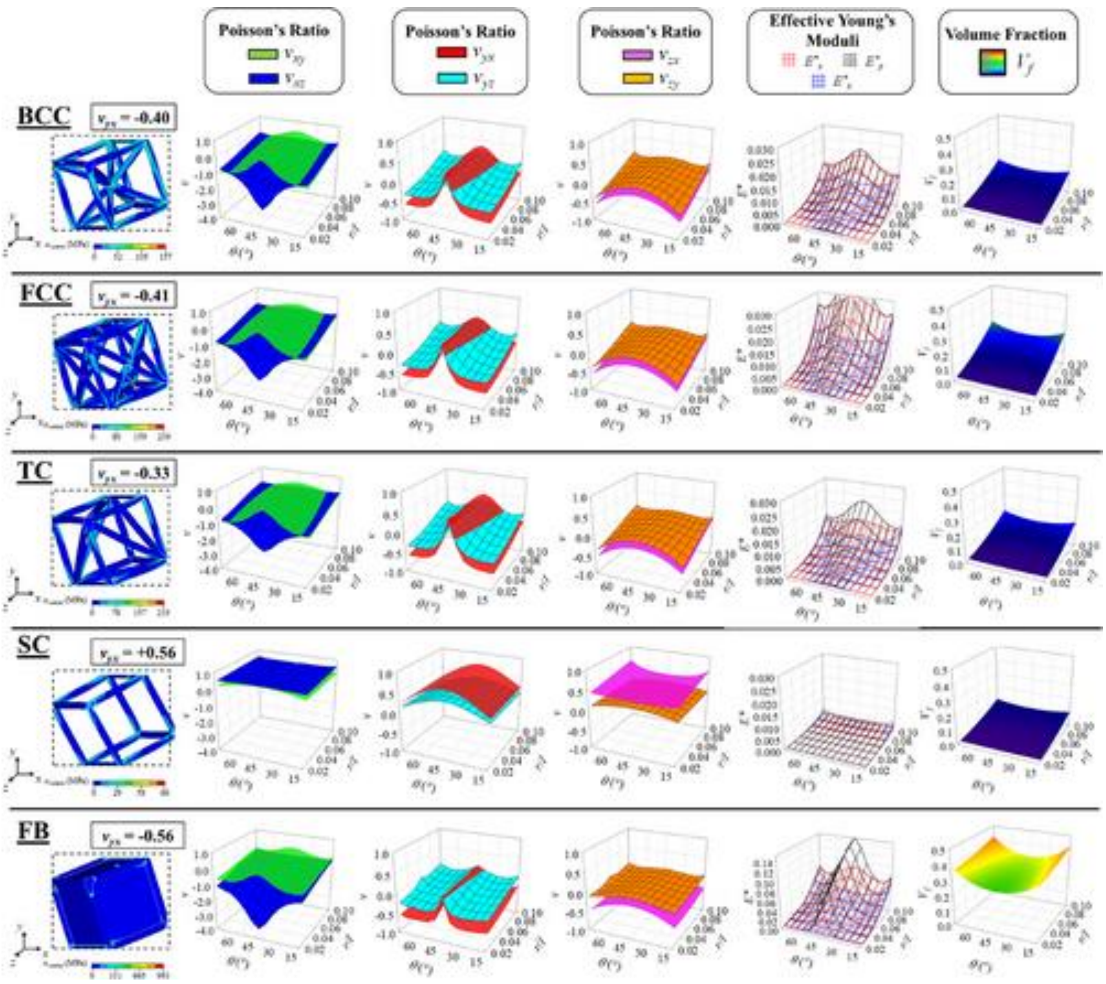

Figure 2.4: Deformed structures at 5% compressive strain in the *y*-direction showing how the effective Young's moduli vary based on hierarchy – Adapted from **Mizzi et al.** (2025).

Accompanied by parallel advances in additive manufacturing, reliance on complex micro-architectures has been increasing. Traditional methods of fabrication alone could be insufficient for producing the internal geometries seen in metamaterials, whereas technological advancements like 3D printing allow accurate control over micro-scale features, porosity, and three-dimensional variation (Duncan et al., 2018). Reviews constantly identify additive manufacturing as a chief technique for metamaterial research (Figure 2.5), as it allows intricate geometries to be physically realized and evaluated for use in diverse fields such as aerospace, defense, automotive, sports equipment, and biomedical devices. (Fan et al., 2021; Periyasamy & Srinivasan, 2025).

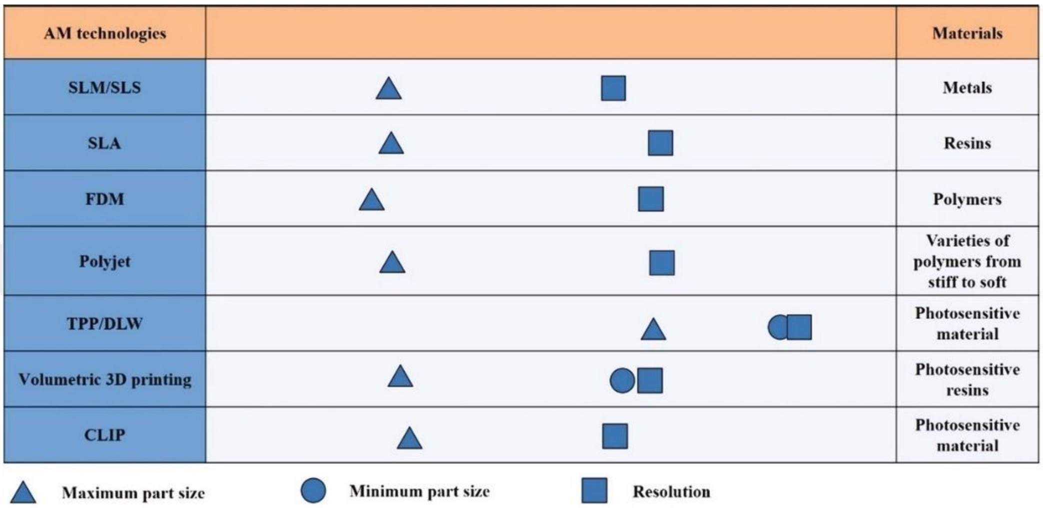

Figure 2.5: The manufacturing characteristics and applied materials of some typical additive manufacturing technologies. – Adapted from **Fan et al.** (2021).

Simultaneously, these studies note that fabrication procedures introduce other parameters that influence material behavior, emphasizing the importance of fabrication-aware design. Within mechanical metamaterials, auxetic materials count as a key subclass distinguished by their unusual deformation and curvature behavior (Figures 2.6 & 2.7).

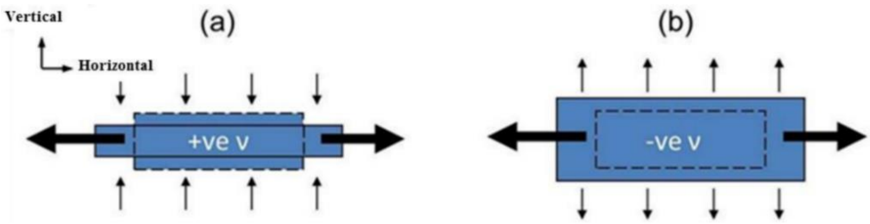

Figure 2.6: Distinction between conventional structures (left) and auxetic structures (right) under tensile loading – Adapted from **Duncan et al.** (2018).

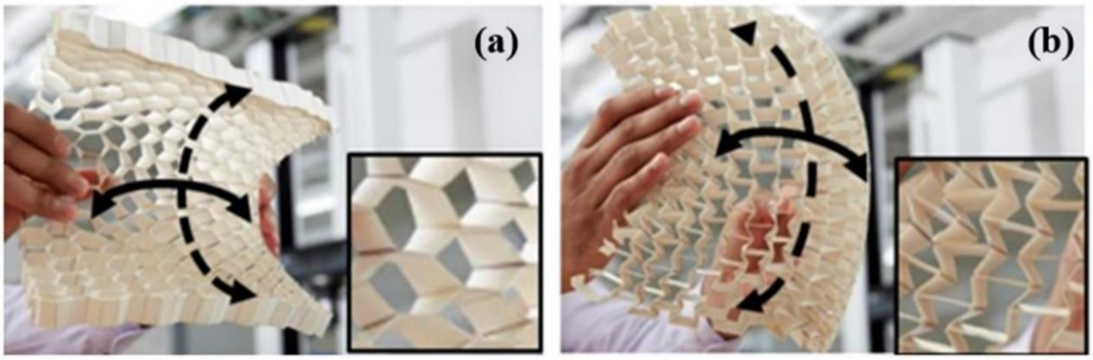

Figure 2.7: Anticlastic curvature of conventional honeycomb (left) vs synclastic curvature of re-entrant auxetic honeycomb (right) when bending – Adapted from **Duncan et al.** (2018).

2.2 Auxetics: Deformation Mechanisms

Auxetic materials are characterized by a negative Poisson's ratio, meaning they expand laterally when stretched and contract laterally when compressed. This counterintuitive behavior distinguishes auxetics and emerges directly from precise deformation mechanisms encrypted within the material's micro-architecture (Albag., 2021). The negative Poisson's ratio observed in auxetic systems is typically achieved through geometric mechanisms such as rotation, hinging, bending, and shearing of physical elements. These mechanisms allow core geometry to reorient or deform in a coordinated manner under load, producing macroscopic expansion rather than contraction. Lipton et al. (2018) demonstrate that subtle changes in handedness and geometric arrangement can lead to noticeably different mechanical responses, resulting in auxetic systems that display either rigid or compliant behavior based on their architectural configuration (Figure 2.8). This exposes how sensitive auxetic performance is to geometric design choices.

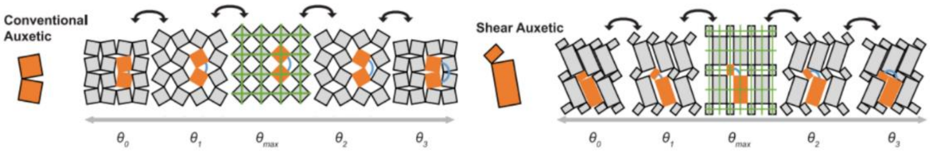

Figure 2.8: Conventional and shear auxetics made by changing the symmetries of the conventional auxetic patterns. – Adapted from **Lipton et al.** (2018).

Furthermore, auxetic behavior has been explored across a range of structural typologies, including lattices, cores, and membrane-like configurations. In lattices, deformation is mostly governed by rotational or hinging mechanisms at node connections, whereas in cores, auxetic response stimulates load distribution and energy absorption characteristics. Usta (2021) provides a detailed comparison between auxetic and non-auxetic core materials in his research (Figure 2.9), showing how alterations to internal geometry result in distinct deformation patterns and mechanical behavior under load. This work underlines the role of micro-architecture in defining auxetic response within metamaterials.

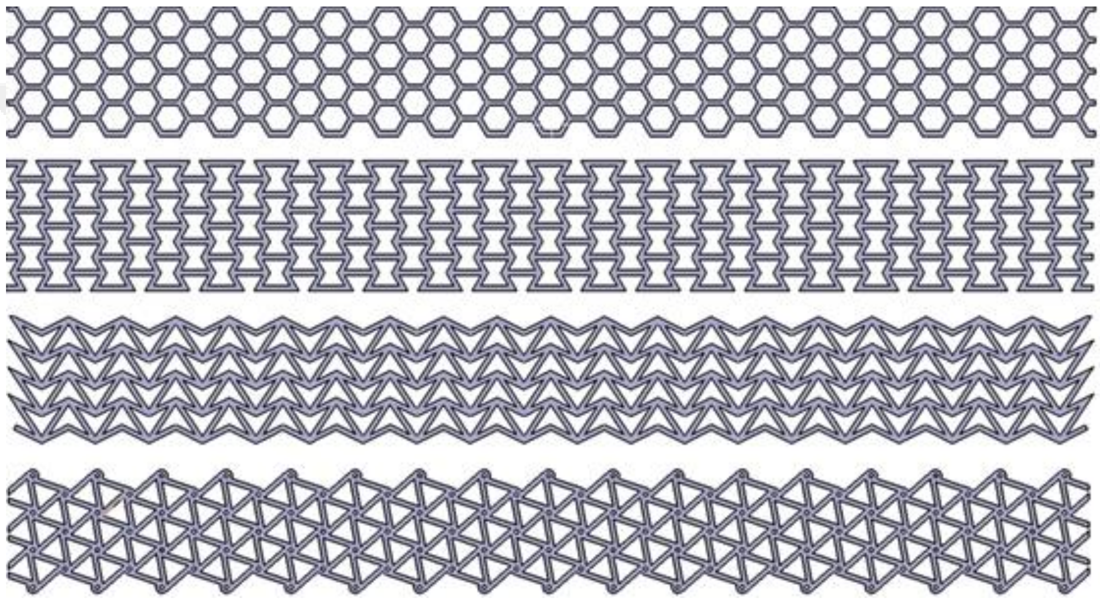

Figure 2.9: Topologies of auxetic and non-auxetic cellular structures. – Adapted from **Usta, F.** (2018).

Beyond lattice and core-based assemblies, auxetic behavior has also been inspected in membrane-like configurations subjected to inflation. Venkata et al. (2024) analyze inflated auxetic membranes and report deformation marked by the development of localized necking regions and wrinkling patterns, arising from the interaction between auxetic kinematics and surface constraints during inflation. These findings extend the understanding of auxetic response beyond rigid frameworks by demonstrating that geometry-driven deformation can also emerge in flexible, pressurized systems. The practical relevance of such deformation mechanisms has been established in application-driven contexts, particularly in biomedical engineering. In their study, Kim et al. (2021) show that auxetic structures used in tissue engineering scaffolds boost compliance and mechanical adaptability, allowing the scaffold to feature enhanced deformation while upholding physical integrity. This application explains how auxetic geometry can be leveraged to achieve responsive behavior tailored to precise requirements (Figure 2.10).

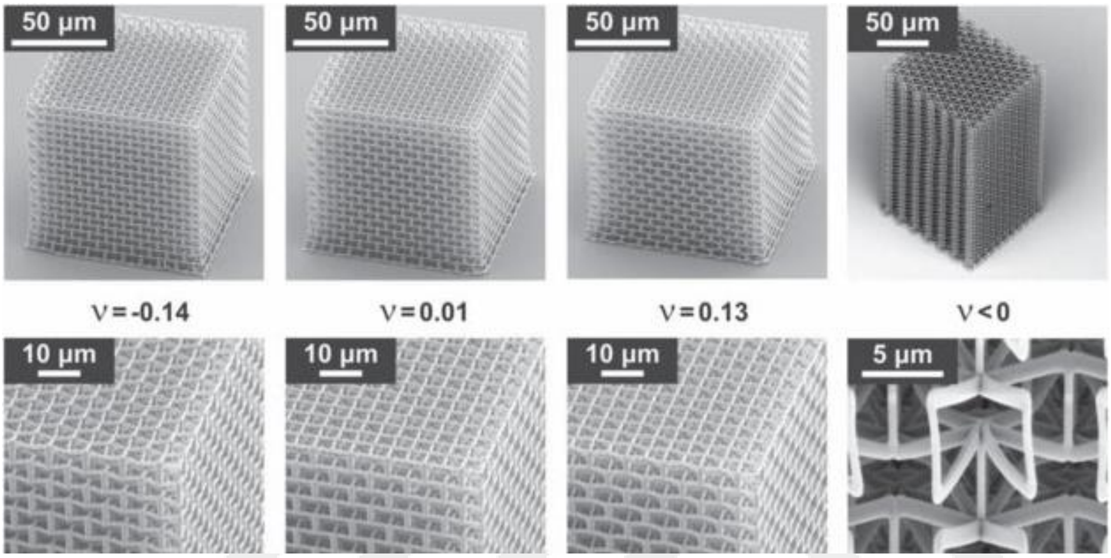

Figure 2.10: Fabrication results of the 3D meta-materials with auxetic unit cells. – Adapted from **Kim et al.** (2021).

These studies establish auxetic materials as a discrete subclass of metamaterials, defined by deformation that is fundamentally geometric. Across lattices, cores, and membranes, auxetic performance emerges from selectively planned micro-architectures that control how physical elements rotate, hinge, and reconfigure under load, reinforcing the central role of geometry in shaping mechanical response.

2.2.1 Pattern-based design of auxetic systems

Since auxetic systems are not naturally occurring materials, their behavior is encoded at the level of pattern, connectivity, and deformation logic, making design decisions central to their development. Pattern-based approaches provide a systematic means of embedding deformation by defining how elements move, rotate, or reconfigure.

Within this context, kirigami and tessellation-based strategies have emerged as effective methods for programming deformation through patterning. By presenting cuts, joints, or articulated regions into continuous surfaces, kirigami enables intricate shape changes to arise from simple planar geometries. Choi et al. (2019) validate how kirigami tessellations can be used to program shape and deformation in a predictable method, showing that shape-shifting can be encrypted through pattern logic (Figures 2.11 & 2.12).

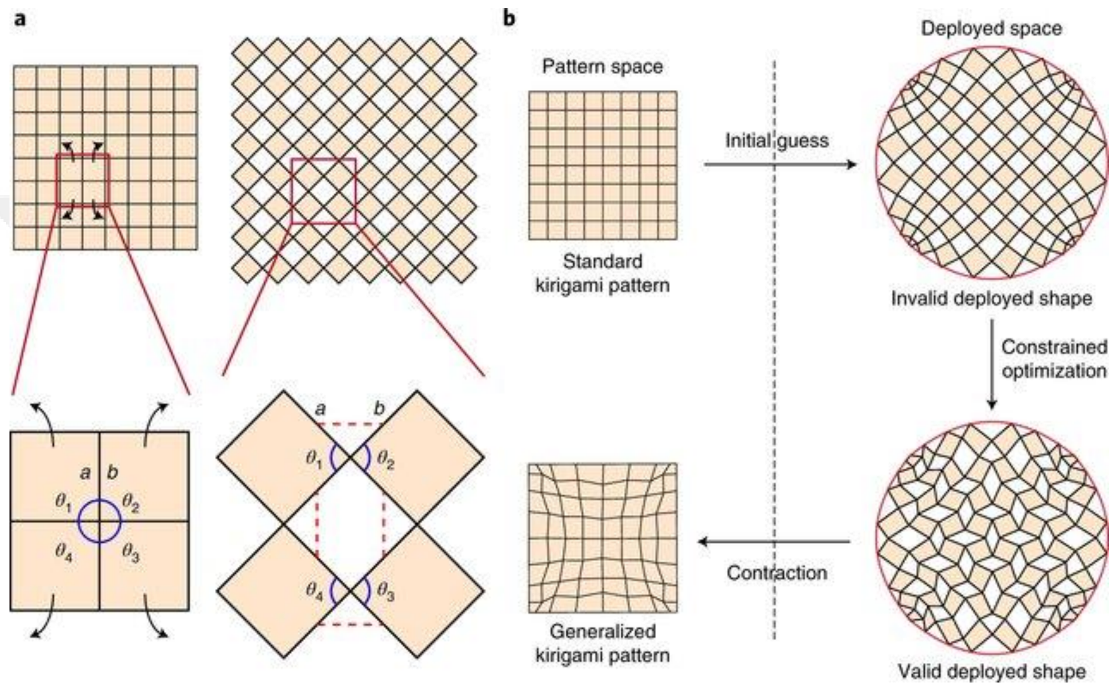

Figure 2.11: A quad kirigami tessellation and its deployed configuration – Adapted from **Choi et al.** (2019).

This work establishes kirigami as a foundational design method for geometry-driven deformation. Building on this knowledge, rule-based and additive frameworks have been proposed to structure the generation of kirigami patterns.

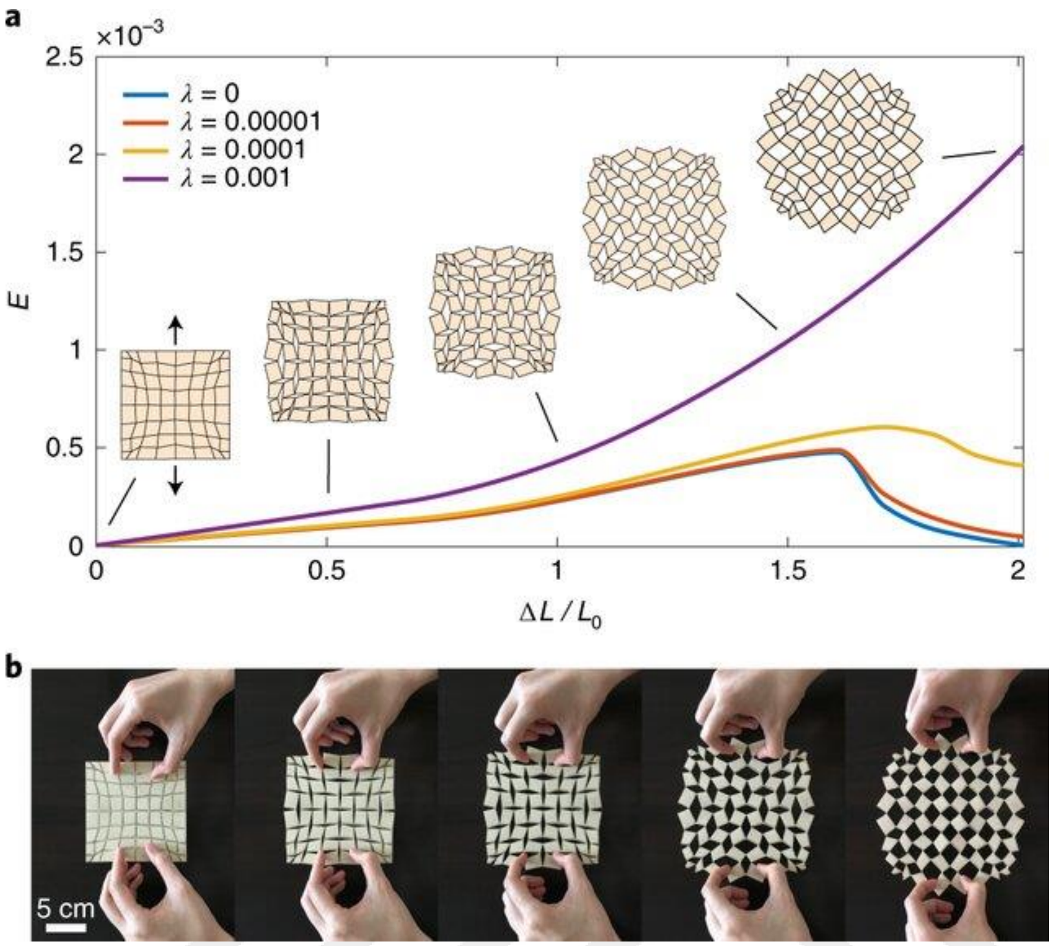

Figure 2.12: Energetics of the deployment simulations of the square to circle kirigami tessellation – Adapted from **Choi et al.** (2019).

Dudte et al. (2023) also introduce an additive design framework in which complicated kirigami assemblies are constructed by combining simple, detailed pattern elements. This method empowers scalable pattern generation while preserving predictable response, underpinning the idea that auxetic and deformable systems can be accomplished through modular geometric guidelines.

In parallel, computational methods have facilitated the design of auxetic assemblies. Physics-aware design approaches integrate mechanical simulation into the design process, optimizing geometric parameters with respect to desired deformation outcomes. Wang et al. (2023) reveal how computational frameworks that incorporate physical constraints can generate kirigami-based systems with meticulous shape morphing capacities, depicting the role of simulation-informed design in pattern-based assemblies (Figure 2.13).

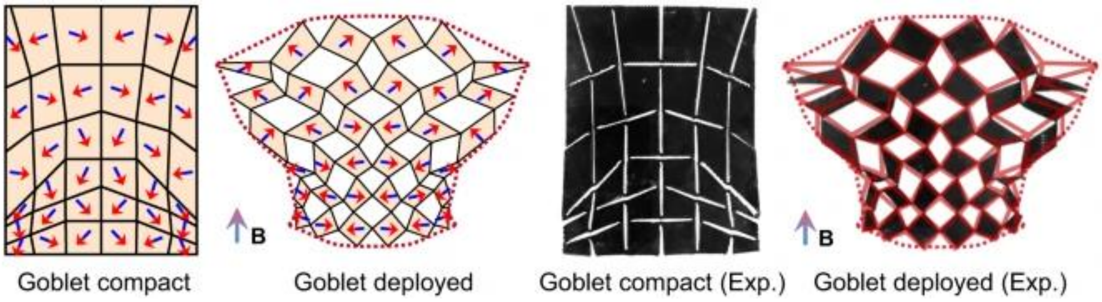

Figure 2.13: Compact and deployed simulation of optimized kirigami and its experimental verification – Adapted from **Wang et al.** (2023).

Moreover, inverse design methods have been used to automate the generation of auxetic geometries with target mechanical properties. Zheng et al. (2021) discuss how deep learning techniques can be used to map anticipated mechanical behavior, such as a specified Poisson's ratio, back to corresponding geometric configurations. This tactic further stresses that auxetic performance is a result of cautious design choices, in which geometry is optimized via data-driven processes rather than manual trial and error. Such efforts regard explicit design strategies that combine geometric patterning, computational reasoning, and optimization as an input for a predefined auxetic output (Figure 2.14).

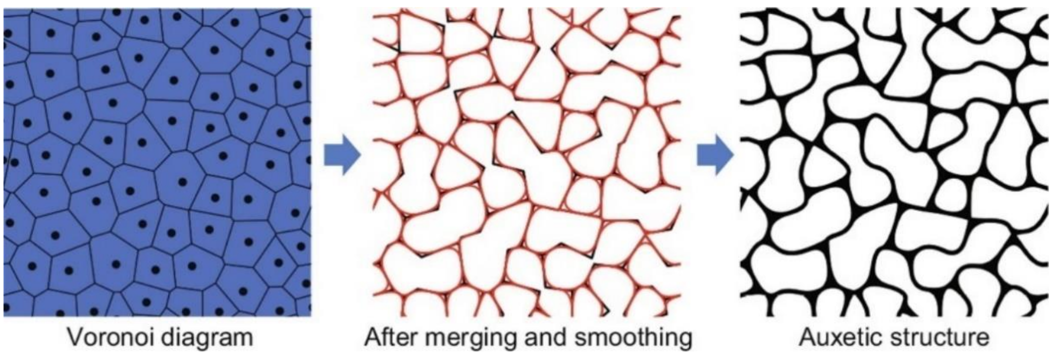

Figure 2.14: Computational generation of auxetic pattern using Voronoi tessellation – Adapted from **Zheng et al.** (2021).

2.2.2 Fabrication of auxetic metamaterials

The success of the final outcome of auxetic metamaterials is integrally tied to fabrication methods that provide sufficient accuracy and repeatability. While auxetic behavior is dictated by geometry, its physical manifestation depends on how that geometry is translated into material form. Here, additive manufacturing comes into play as the primary approach, as it enables the creation of intricate auxetic systems that are otherwise difficult to attain. Within additive manufacturing, fabrication constraints play a critical role in determining the mechanisms of auxetic structures. Parameters such as cell size, orientation, and topology cooperate with process-dependent factors, influencing stiffness, strength, and elastic recovery. Pehlivan (2024) declares that variations in unit-cell geometry and orientation significantly affect the tensile stiffness and elastic response of 3D-printed auxetic structures, highlighting that material behavior cannot be understood exclusively from geometry without considering fabrication conditions too. Beyond geometric configuration, orientation and toolpath-related decisions introduce anisotropy and variability into 3D-printed auxetic assemblies (Figure 2.15).

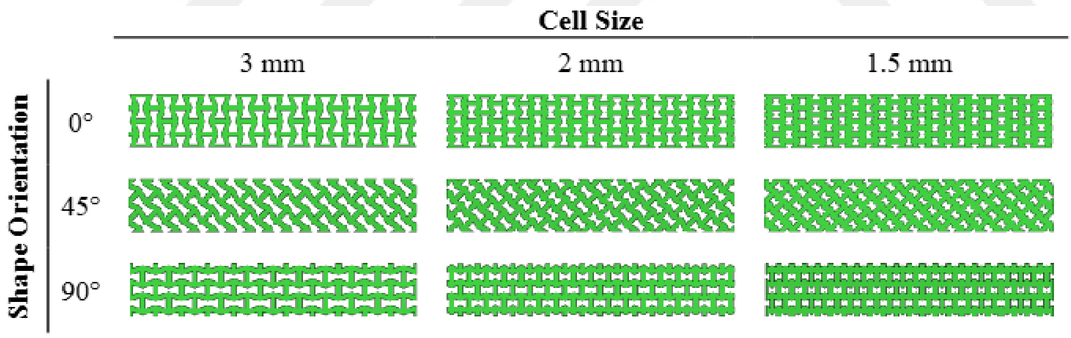

Figure 2.15: 9 tensile specimens with 3 different cell sizes and 3 different shape orientations based on Taguchi L9 orthogonal array – Adapted from **Pehlivan, F.** (2024).

Comprehensive reviews of metamaterial fabrication have shown that slicer-dependent parameters including direction, layer stacking, and toolpath strategy can significantly impact mechanical response, often mediating the correlation between design and actual behavior (Fan et al., 2021). These findings underscore the significance of fabrication-aware assessment when evaluating auxetic metamaterials produced through 3D printing. 3D-printed auxetics have also been explored in flexible and textile-like formats, where compliance and drapability become critical performance measures. In their study, Kabir et al. (2023) investigate the drapability of 3D-printed auxetic textiles and validate how geometric design affects deformation behavior in wearable contexts. This work proves that auxetic performance in flexible systems depends not only on lattice geometry but also on how 3D-printed structures interact with bending and surface stimulation (Figure 2.16).

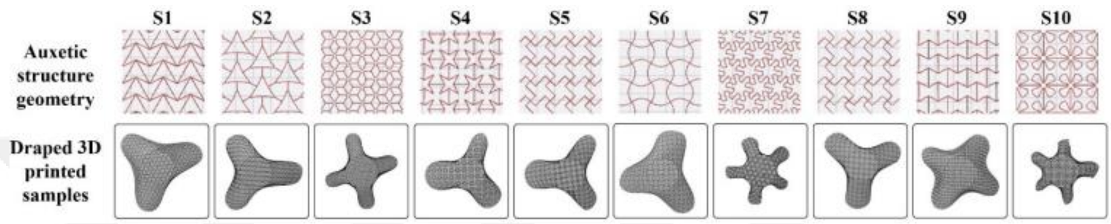

Figure 2.16: Geometries of auxetic structures and 3D draped samples of 10 3D printed textiles – Adapted from **Kabir et al.** (2023).

Related research on flexible lattice and isogrid structures further verifies the relevance of additive manufacturing in textile design and applications (Figure 2.17). In a similar investigation, Kalman et al. (2021) feature automated draping analysis of 3D-printed flexible isogrid systems, showing how additively manufactured architectures can be evaluated in terms of deformation and surface adaptation.

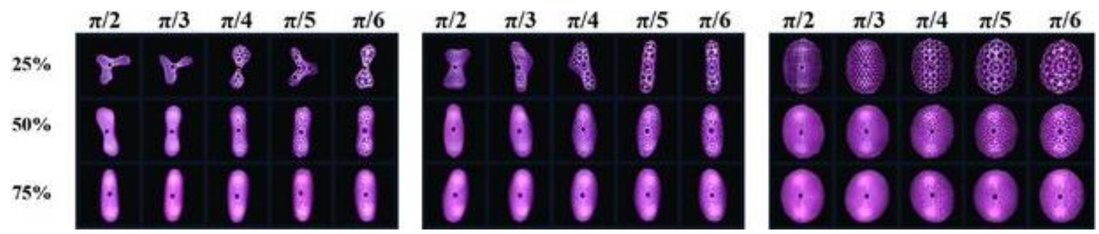

Figure 2.17: 5 infill patterns, 3 infill percentages, and 3 loading cases used for draping analysis resulting in 45 different test specimens – Adapted from **Kalman et al.** (2021).

Such studies underpin that systematic experimental methods that consider both geometry and fabrication parameters are crucial for interpreting and advancing auxetic metamaterials produced via additive manufacturing.

2.3 Application Domains of Auxetics & Metamaterials

Beyond theory, auxetics and metamaterials have been actively applied across a range of domains where lightweight structure, controlled deformation, and adaptive response are required. These applications clarify how geometry-driven material behavior can address performance demands that are difficult to attain otherwise.

In aerospace engineering, auxetics have gained huge interest given their potential to enhance energy absorption, impact resistance, and display unmatched physical efficiency. Institutional research initiatives have highlighted the relevance of auxetic designs for lightweight aerospace components, particularly in frameworks where enhanced mechanical performance must be achieved without increasing material usage. A highly related project by Istanbul Technical University Aviation Institute (2025) documents ongoing research into hybrid auxetic designs, accentuating their capacity for superior energy absorption and their competence for aerospace-related structural applications (Figure 2.18).

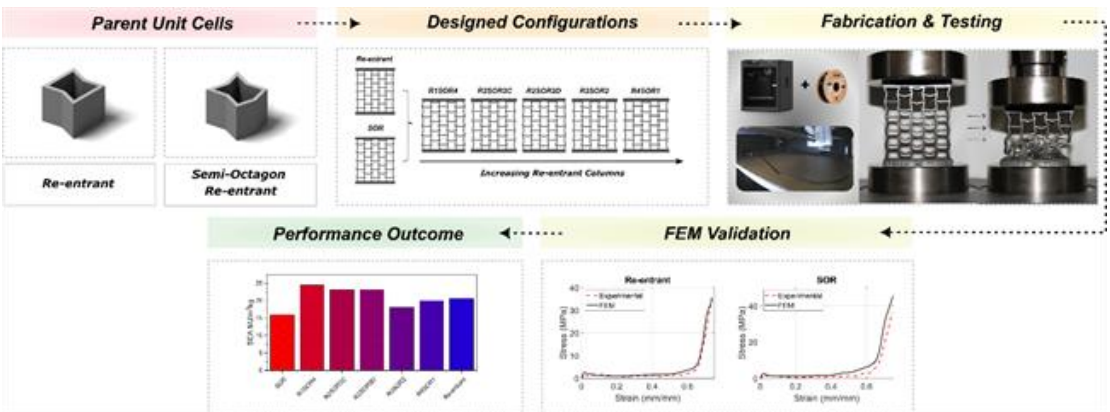

Figure 2.18: Hybrid auxetic metamaterial optimized for aerospace applications. – Adapted from **Istanbul Technical University Aviation Institute** (2025).

Complementary work within aerospace research has explored auxetic polymer systems in the context of deployable lightweight structures. Regarding this matter, Malakooti et al. (2021) present a NASA technical report on auxetic shape-memory polyurethane aerogels developed for deployable aerospace applications, indicating how auxetic geometry can be merged with advanced materials to achieve compact deployment and structural adaptability (Figure 2.19).

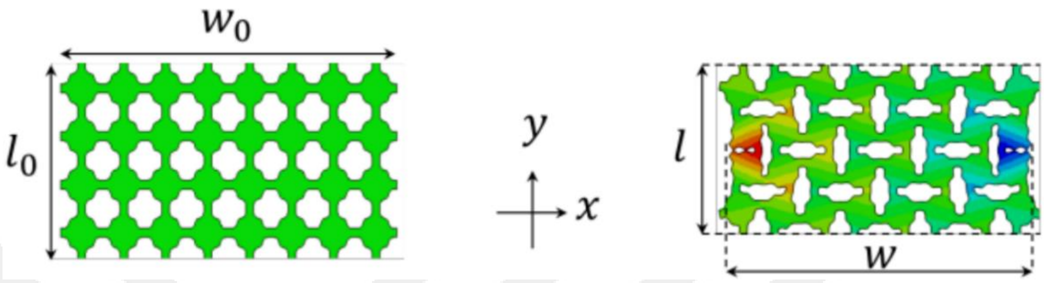

Figure 2.19: Reference and deformed configurations of the meta-aerogel developed by NASA – Adapted from **Malakooti et al.** (2021).

This effort illustrates the broader curiosity around auxetic metamaterials as candidates for space-related and aerospace systems in which weight reduction and deployability are critical. It's worth mentioning that auxetic and metamaterial principles have also been applied to transformable structures beyond aerospace contexts. Zaman et al. (2025) display how flat auxetic linkages can be rapidly deployed into curved structures through simple actuation strategies, highlighting the role of geometric linkage design in enabling efficient shape-shifting applicable in various industries ranging from product to furniture design (Figure 2.20).

In the field of soft robotics, metamaterial architectures have been used to achieve calculated motion and adaptability through structural design rather than complex actuation mechanisms. In her dissertation, Seyidoğlu (2025) demonstrates how bio-inspired metamaterial geometries can be encrypted into soft robotic systems to trigger rectilinear locomotion, showing the use of patterned surfaces as functional mechanical elements. This work positions auxetic and metamaterial logics as operative design tools for soft robotic locomotion and compliance (Figure 2.21).

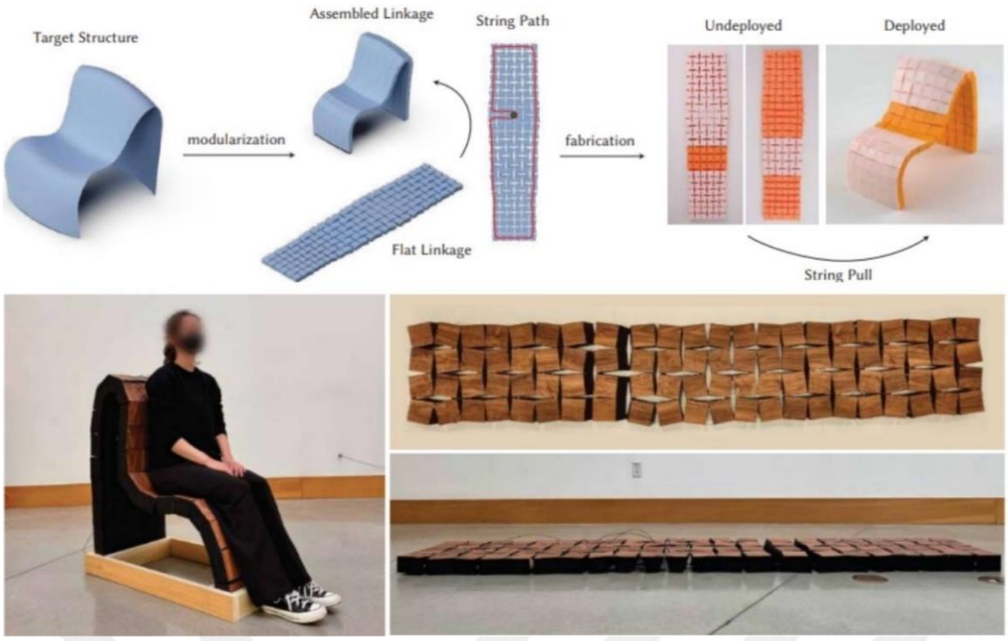

Figure 2.20: A target structure modularized into a flat auxetic linkage deploys into a human-scale chair by a single string pull using minimal friction – Adapted from **Zaman et al.** (2025).

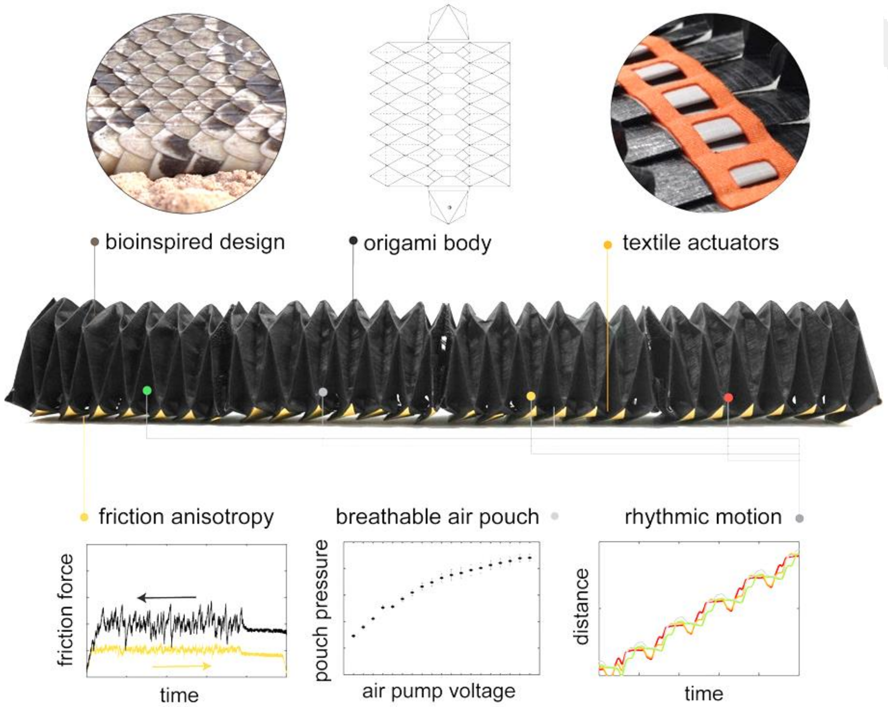

Figure 2.21: Snake-inspired soft robot for rectilinear locomotion – Adapted from **Seyidoğlu, B.** (2025).

A previous publication related to the same study has discussed the integration of metamaterial architectures into soft robotic platforms. Parvaresh et al. (2024) present a metamaterial-based soft snake robot, featuring origami and kirigami combined, in which structural geometry plays a fundamental role in attaining programmed movement (Figure 2.22). This reinforces the notion that mechanical behavior in soft robotics can be rooted within micro-architectural design, reducing reliance on complicated control schemes.

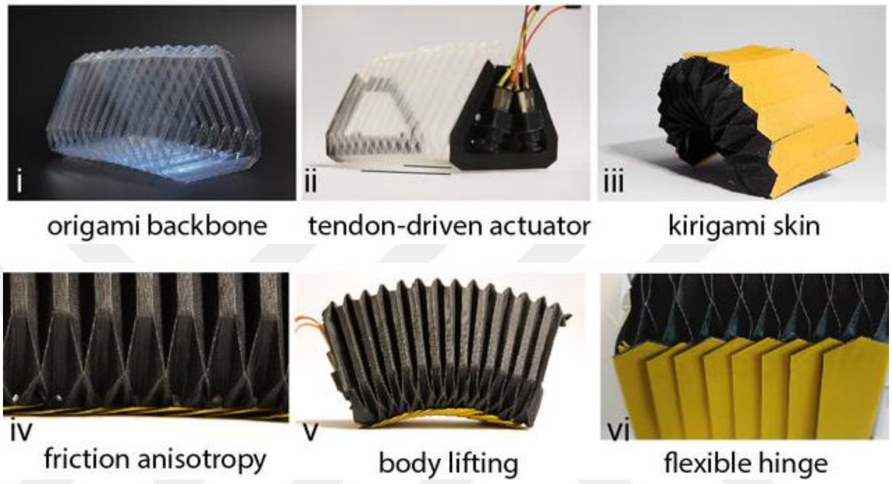

Figure 2.22: Bioinspired robot made of origami backbone & kirigami skin, and its behavioral features equivalent to those of a snake – Adapted from **Parvaresh et al.** (2024).

In an even older publication, Seyidoğlu et al. (2023) focus exclusively on integrating reconfigurable kirigami skins with soft robotic actuators for directional routing (Figure 2.23).

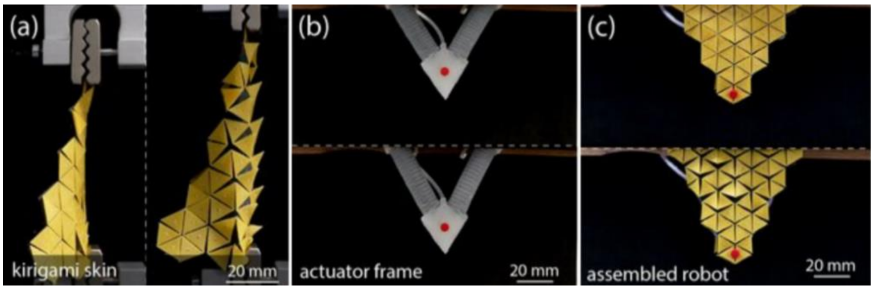

Figure 2.23: Tensile response of the compound skin, actuator, and assembled robot for a selected direction – Adapted from **Seyidoğlu et al.** (2023).

Lately, metamaterial concepts have been pushed beyond purely mechanical applications. AlAlawi et al. (2025) demonstrate metamaterial antennas whose operational properties can be tuned through physical deformation. This application illustrates how metamaterial design principles can be multifunctional, branching their relevance into domains such as communication and adaptive technologies (Figure 2.24).

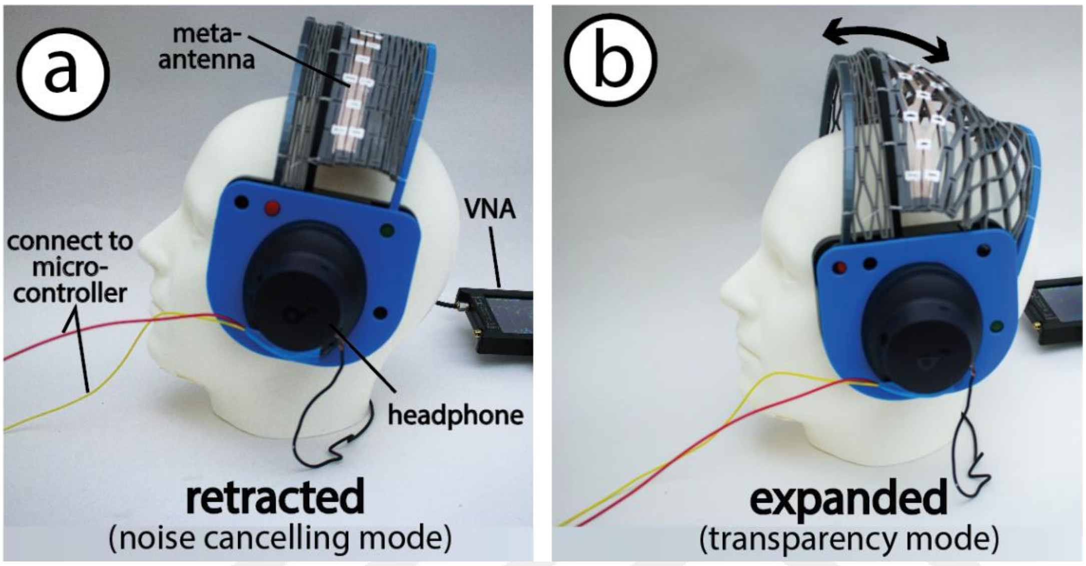

Figure 2.24: Metamaterial-based shape-adaptive noise-control headphone changes from noise canceling mode to transparency mode upon expanding – Adapted from **AlAlawi et al.** (2025).

Altogether, these applied projects serve as proof of concept, exposing how auxetic and metamaterial systems are not limited to abstract hypotheses but are dynamically employed across aerospace, soft robotics, and tech. The diversity of the domains underscores the scalability and pragmatism of this subclass of metamaterials especially with the fabrication tools and automation methods available within reach today.

2.4 Textile Fabrication: From Computation to 3D Printing

The evolution of textile fabrication with architecture demonstrates the shift from traditional weaving and tensile structures toward digitally informed, responsive systems. Historically, manual fabrication techniques, such as stitching, braiding, or mesh construction, came with constraints, often relying on steel reinforcements or synthetic fabrics for performance under environmental stress. The developments we witness every day in digital design tools and additive manufacturing adopt these very techniques to foster new design possibilities. As Naboni and Mirante (2015) articulate, computational methods enable the generation of auxetic patterns, establishing a framework for what they term "metamaterial computation" in architectural envelopes. This approach integrates material science and digital fabrication, allowing design iterations to be informed by material behavior simulations. Their study highlights the potential of auxetics in developing architectural membranes that go beyond stationary form by injecting responsiveness into the material logic.

When deformation-aware systems are discussed, Ou et al. (2018) stand out through their project KinetiX, which emphasizes both the spatial and perceptual transformation of materials. By leveraging auxetic geometries and embedded mechanical actuators, the study showcased how deformable units can be used to prototype responsive surfaces. Their method bridges a critical gap between physical interaction and architectural effectiveness in which auxetic patterns are presented as tools for enhancing user engagement and material expressiveness rather than being merely there for supporting the structure.

Academic investigations have further catalyzed textile innovation through explorations that hybridize textile surfaces with 3D-printed geometries. A compelling example is the master’s thesis by Lee (2022), where he introduces a process-based methodology for 3D-printing directly onto textiles using flexible filaments such as TPU (Figure 2.25). His study, based on a material-centric design philosophy, reveal how textiles and polymers could generate spatially complex yet materially continuous artifacts. By integrating roll-to-roll methods and layered geometries, Lee’s work opens new avenues for mass-customizable fabric-based products with programmable deformation and breathability. Complementing Lee’s work, Shajoo et al. (2021) conducted a technical and material analysis of hybrid textile structures embedded with auxetic behavior. Their study surveyed the interaction between pre-stretched jersey knit fabrics and 3D-printed polymer components specifically using PLA and ABS in dual-layer applications. The result was an auxetic hybrid capable of localized expansion through mechanical deformation, with the knit fabric serving as both a structural hinge and a membrane for durability and elasticity. The study proves how polymer-textile bonding methods, print parameters, and material selection can collectively generate dynamic behavior in otherwise flat textiles.

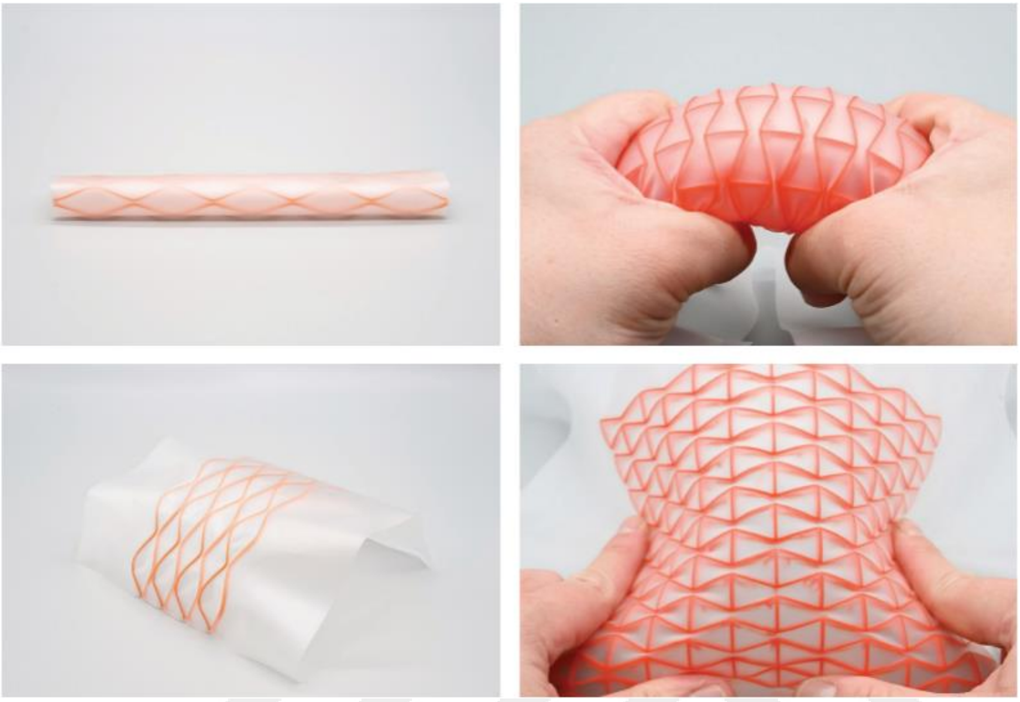

Figure 2.25: 3D print on TPU-coated nylon – Adapted from **Lee, E.-H. T.** (2022).

Notably, Shajoo et al. discuss how textile porosity and stretch-induced strain fields can store elastic energy during the printing process (Figure 2.26). This concept resonates with the principles of 4D textiles, materials that change form over time or in response to external stimuli. As the authors state, "In the process described here, an elastic knitted fabric was used as the textile substrate. This allows pre-stretching of the fabric prior to printing, in which case the textile is a repository of stored elastic energy." This shows how such textiles are a perfect medium for promoting auxetic structures.

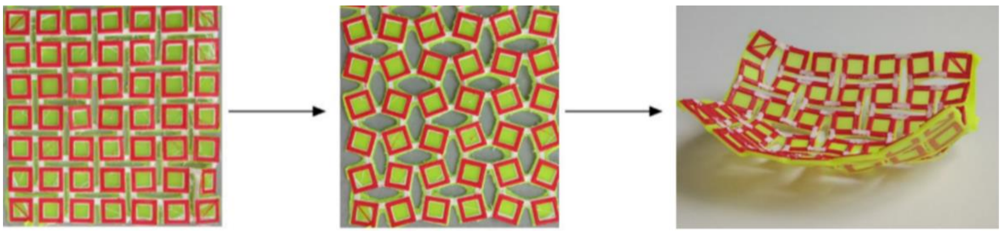

Figure 2.26: 3D printing of an auxetic pattern on jersey – Adapted from **Shajoo et al.** (2021).

Together, these works articulate a coherent trajectory from static, pre-determined textile forms to dynamic, performance-enhanced materials. Through parametric modeling, layered material integration, and programmable deformation, architectural textiles are being reconceptualized as active agents in design computation. These systems blur the borderline between architecture, fashion, and product design, paving the way for adaptable surfaces that respond to environmental or human input. Integrating additive manufacturing into textile innovation not only redefines form-making strategies but also introduces unprecedented modes of architectural expression. As demonstrated by both computational and experimental studies, the future of architectural textiles lies in creating reactive hybrid materials.

2.4.1 Programmable elasticity

Thermoplastic polyurethane (TPU) has become one of the most promising materials in additive manufacturing for soft, elastic, and highly deformable structures. Its unique mechanical profile, characterized by excellent elongation, energy absorption, and elasticity, makes it especially suitable for applications requiring both flexibility and strength. As Fuentes del Toro et al. (2025) demonstrated, TPU auxetic structures can sustain considerable mechanical strain while maintaining structural stability. Their study on gyroid and re-entrant geometries confirms that strain-dependent behavior in TPU is influenced by internal architecture as much as by material choice. Hu et al. (2024) expanded on this by investigating hybrid honeycomb-auxetic lattice systems fabricated with TPU. Their efforts emphasized that compressive and tensile tests revealed distinct anisotropic behaviors, with increased energy absorption and deformation control in multi-directional load scenarios.

The high compliance and deformation capabilities of TPU also make it ideal for soft robotics, wearable electronics, and biomedical applications. Pattinson et al. (2019) explored biomechanically tailored TPU meshes designed for wearable and implantable devices. Their approach utilized multi-scale design strategies to produce conformal meshes that balance stretchability with structural support. Similarly, Simarmata et al. (2025) used TPU in the design of 3D-printed orthotic insoles for flat foot treatment. Their findings demonstrated that auxetic-based TPU designs significantly enhance both comfort and adaptability when integrated into user-specific products. Beyond biomedical and product-scale applications, TPU gained huge significance in architectural material research. In his comprehensive master's thesis, Bakıcı (2023) evaluated the performance of TPU-based triply periodic minimal surface (TPMS) structures under impact loading. His findings suggest that TPU's elasticity allows for superior energy distribution across the lattice network, which is a valuable property for architectural systems exposed to dynamic stress, such as adaptive façades or impact-resistant panels. Addressing a very common challenge, printing with flexible filaments, Lee (2023) proposed a defect-controlled rapid printing system for TPU-based materials. His thesis details the technical modifications required for high-precision FDM printing, particularly in preventing filament buckling and ensuring dimensional consistency during extrusion. These innovations are essential for achieving repeatable and controllable material behaviors, particularly when developing auxetic systems where mechanical response is tightly linked to print fidelity. The discussed works illustrate TPU's remarkable potential as a 3D printing material in both experimental and practical domains. Its intrinsic elasticity, along with geometrically programmable behavior, positions TPU as a link between soft material science and structural design, making it ideal for architectural textile exploration, therefore, development of TPU-based lattices, hybrid systems, and bio-compliant surfaces will likely play a central role in the next generation of wearable, architectural, and responsive products.

2.4.2 Infill strategies

Infill strategy is a critical design parameter in fused deposition modeling (FDM) that influences mechanical performance, material usage, porosity, and structural behavior of 3D-printed components. One of the most extensively studied factors is infill density, which directly impacts load-bearing capacity and impact absorption. Dos Reis et al. (2024) demonstrated that mechanically graded infill densities significantly influence deformation profiles and energy dissipation under compression, particularly in impact attenuator applications. These findings highlight the role of density gradients in optimizing function-specific performance. Beyond density, the geometry of internal infill patterns plays a central role in defining the structure's performance envelope.

Yadavalli et al. (2024) compared gyroid and zigzag patterns and found that the gyroid configuration displayed superior flexibility and uniform strain distribution, making it more suitable for breathable and deformable TPU-based products. This kind of geometric optimization directly supports the development of auxetic materials, as seen in soft orthotics and wearable designs. Likewise, Zhang et al. (2023) presented an auxetic 3D lattice that enhanced energy absorption capabilities by fine-tuning the pattern topology at the mesoscale.

Surface continuity and layer articulation are equally important in infill-based fabrication. In his graduate research, Ahlers (2018) explored nonplanar printing techniques to generate smooth surfaces over complex geometries. By dynamically adjusting nozzle paths and layering sequences, his custom G-code framework eliminated layer stair-stepping while preserving material consistency. This approach proves useful in creating multi-surface, textile-like 3D forms where flow continuity is essential for mechanical reliability and visual quality. In a related thesis, Gokstorp (2020) introduced a Houdini-based platform for generating modular infill structures and custom toolpaths. His system employed a visual scripting workflow to simulate and compile G-code instructions based on part-specific infill logic; his method enabled precise pattern placement and density control, essential for printing adaptive infill systems in architectural and industrial contexts. Gokstorp's modular infill architecture showcases how computation and fabrication can be synchronized to optimize material behavior from the design phase onward.

The previous studies offer an in-depth understanding of how internal structure design ranging from infill density and pattern geometry to toolpath logic can be harnessed for responsive, lightweight, and functional 3D-printed materials. Infill-based design is no longer a secondary consideration but a driver of innovation in the fabrication of flexible, breathable, and programmable structures.

2.4.3 Slicer-based control

As 3D printing advances toward tailored fabrication, G-code customization is emerging as a critical method for controlling intricate fabrication strategies, particularly in the context of flexible materials like TPU. This section explores developments in open-source tools, language-based slicing strategies, and modular G-code scripting approaches for auxetic and textile geometries. Within this context, Gleadall (2021), in his work on FullControl GCode Designer, proposed a new methodology for additive manufacturing that replaces conventional slicing software with simplified full user control over toolpaths. By using an Excel-based interface to define every segment of the print path along with associated print parameters such as extrusion rate, direction, and speed Gleadall's system enables "unparalleled printing quality with precise control of the process" (Figure 2.27) and facilitates fabrication of structures that are otherwise impractical with slicer-based software (Gleadall, 2021).

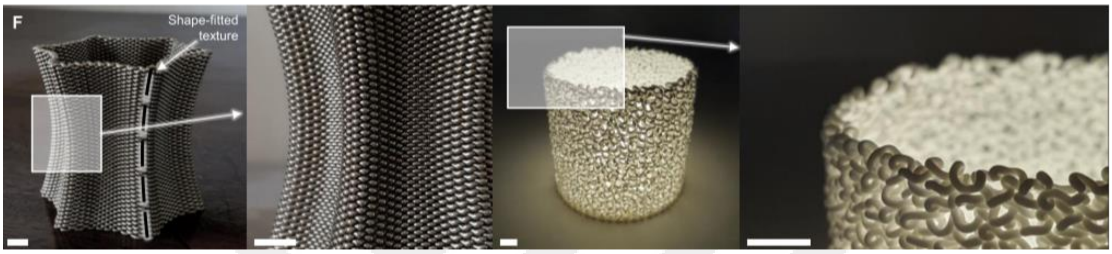

Figure 2.27: Mathematically defined structures via FullControl GCode Designer – Adapted from **Gleadall, A.** (2021).

Besides interface-driven tools, research has emerged advocating for programming language-driven slicing. Nandi et al. (2016) outlined a programming-centric agenda for desktop manufacturing, focusing on design synthesis, compiler optimization, and runtime error detection. They argue that slicing should be reframed as an optimizing compilation task, where custom tool paths are "analogous to optimizing compilation" and slicing logic can be written as programmatic transformations (Nandi et al., 2016). Koda and Tanaka (2017) further emphasized the potential of direct G-code manipulation for creative fabrication methods like material weaving. They proposed a system where path planning and material interaction were managed directly via G-code without intermediary modeling, facilitating unconventional strategies such as weaving-based infill designs and layered deposition schemes. Their technique reflects a move toward embedding design logic directly into the printing script, particularly useful for the design of woven or textile-like features (Koda & Tanaka, 2017). These studies reflect an expanding ecosystem of tools and methodologies where G-code becomes a creative and programmable medium for textile innovation. The reviewed works reinforce the importance of integrating computational scripting and modular toolpath design in advancing the field of infill-based auxetic textile fabrication.

Precision in 3D printing is not solely a function of hardware but heavily influenced by slicer algorithms and G-code configuration. Bryła & Martowicz (2021) analyzed how slicer choices significantly affect G-code output, noting that even with identical settings (e.g., infill density or layer height), variations between slicers like Cura and PrusaSlicer (Figure 2.28) lead to different toolpaths and extrusion behaviors, ultimately altering part geometry and strength.

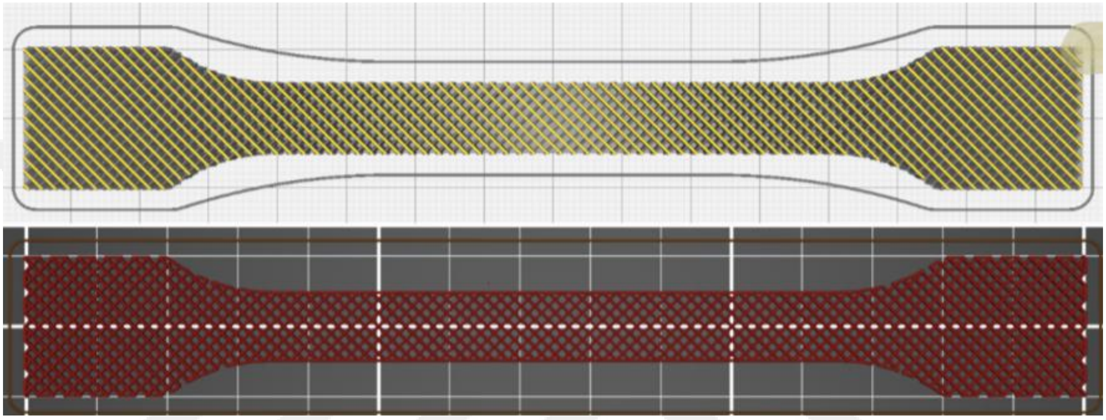

Figure 2.28: Visualizations of the structures generated in Cura (top) and PrusaSlicer (bottom) – Adapted from **Bryła & Martowicz** (2021).

Further expanding this, Steck et al. (2024) proposed a novel slicer algorithm generating sandwich-inspired infill patterns. These new patterns reduced material usage without compromising mechanical integrity, showing that G-code strategies can be engineered to support sustainable and efficient fabrication techniques. Such findings highlight the growing role of slicer customization as an essential element of digital fabrication control matching or exceeding traditional hardware-level optimizations in impact.

2.4.4 Programming Deformation

The exploration of multi-functional metamaterials has led to groundbreaking innovation in the field of auxetics, particularly where structure-driven deformation allows materials to exhibit negative Poisson's ratios. These unique behaviors, seen in materials that become thicker when stretched, are of critical importance for applications requiring enhanced mechanical response, energy absorption, and programmable adaptability. Hierarchical auxetic materials leverage multi-scale geometries to amplify deformation responses. Gatt et al. (2015) introduced hierarchical systems composed of rotating units and demonstrated how these designs can control the size, aperture, and mechanical behavior of the structure. They explain that hierarchical design enables precise control over auxetic behavior, aperture dimensions, and pore sizes within the system, making it well-suited for applications across biomedical and industrial domains. Tang and Yin (2017) further explored how hierarchical kirigami units can combine buckling, rotation, and cut shapes to achieve both maximum stretchability and/or compressibility highlighting the significance of geometrical manipulation for advanced mechanical functionality. Advancing from static auxetics, recent research has turned to kirigami-inspired systems that offer dynamic, programmable behaviors. Chen et al. (2021) presented bistable auxetic surface structures designed for rapid and reversible transformations, facilitated by patterned hinge mechanisms that enable snap-through deformation. Similarly, Qiao et al. (2025) employed inverse design principles to program kirigami units, enabling precise control over rotational morphing patterns. Kim and Park (2025) proposed a machine learning-driven optimization strategy for kirigami-based metamaterials, demonstrating how computational models can tailor multistability and shape-morphing by defining critical force thresholds for bistable transitions.

Staffová (2023) focused on polymeric metamaterials with advanced mechanical properties, specifically discussing how the mechanical response of thermoplastic structures can be enhanced by tailoring infill geometry, material blends, and post-processing. Her work provides evidence that polymer-based auxetics are increasingly suited for performance-critical fields like prosthetics, energy dissipation layers, and flexible enclosures.

Auxetic behavior is highly influenced by the geometry of its unit cells, particularly when designed for responsiveness. Lei et al. (2019) presented thermally activated systems with digitally reprogrammable forms that could shift their mechanical state when exposed to heat or force, showcasing a method for achieving tunable auxeticity through external stimuli. Similarly, Yousuf et al. (2020) explored 4D-printed auxetic structures that adapt over time, demonstrating how geometric programming combined with responsive materials can enable dynamic structural transformation. Both studies underscore the evolving potential of auxetic systems to transition from static to adaptable forms through material and design integration. Meanwhile, Meena and Singamneni (2019) demonstrated how variations in re-entrant cell geometry can reduce stress concentrations and maximize auxetic effects. Surjadi et al. (2025) expanded the mechanical tunability conversation by introducing double-network inspired lattice systems. Their design, composed of interpenetrating networks, allows for simultaneous enhancements in energy absorption and mechanical stiffness, key attributes for impact mitigation and shape memory systems.

Recent innovations in textile fabrication through additive manufacturing have introduced techniques that simulate woven behavior without requiring actual interlacing. This approach enables the production of highly flexible and responsive fabrics directly from 3D printers. One significant contribution in this field is DefeXtiles by Forman et al. (2020), which demonstrates quasi-woven fabric structures achieved through intentional under-extrusion. These defects are systematically controlled to create filament bridging and fabric-like pliability. The resulting textiles exhibit anisotropic stretchability and controllable porosity, providing a lightweight yet resilient alternative to traditional woven fabrics. Takahashi and Kim (2019) extended this framework by proposing programmable textile behaviors using FDM-based 3D printing. Their method utilized grid-based toolpath design to create fabric sheets that can fold and stretch depending on geometric modulation. The paper emphasizes the synergy between material selection and 3D-printing parameters to tune mechanical outcomes. The integration of bending, snapping, and coiling into a single print process blurs the line between textile design and mechanical actuation. Together, these studies redefine textile fabrication through additive manufacturing. By repurposing printer flaws (Forman et al.), manipulating toolpaths (Takahashi & Kim), researchers have achieved a level of control and creativity that mimics, and often surpasses, traditional weaving techniques. These methods mark a paradigm shift in how textiles can be digitally fabricated for architectural, fashion, and responsive design contexts. Kirigami-inspired auxetic systems leverage strategic cuts to induce complex deformation profiles and programmable surface behaviors. As noted by Kim and Park (2025), their optimization framework enables the design of kirigami structures with multistable responses, providing controllable expansion and folding sequences adaptable to varied geometric targets. The study emphasized the integration of surrogate models and evolutionary algorithms to fine-tune cell designs for scalable bistability and morphing efficiency. Conversely, Chen et al. (2021) introduced bistable auxetic surface structures that enable deployable 3D configurations from flat, elastic sheets. Their inverse design algorithm utilizes a precomputed library of bistable cells, indexed by expansion ratio and stiffness, allowing for highly stable deployments without external supports. Their prototypes validated the computational approach with physically demonstrable shape morphing driven purely by internal cell mechanics. Together, both strategies offer high-performance morphing, though kirigami systems offer more localized control over multistability, while bistable auxetics favor geometric global transformation through fewer material constraints.

Material-level comparisons between Triply Periodic Minimal Surface (TPMS) structures and infill-printed auxetic lattices are vital for tailoring energy absorption and deformation behavior. Fuentes del Toro et al. (2025) demonstrated that 3D-printed TPU lattices exhibit high energy absorption and fracture resistance due to auxetic geometries tailored for dynamic impact applications. Bakıcı (2023), examined the gyroid-based infill behavior of TPU structures under impact conditions. The study systematically compared infill densities and noted that while TPMS topologies offer consistent deformation profiles, customizable infill strategies provide greater adaptability and localized response under varying impact angles and forces. Thus, TPMS forms present robust continuous structures ideal for homogeneous applications, whereas infill-based strategies allow for greater customization in spatially varied stress zones, advantageous in architectural applications.

Finally, structural comparisons between polymeric metamaterials and textile-integrated lattices reveal distinctive advantages. Staffová (2023), in her thesis, explored the mechanical profiles of polymeric metamaterials and emphasized their stress-distribution potential in compact systems. Polymeric lattices offer high mechanical stiffness and durability, especially in load-bearing applications. In contrast, Zhang et al. (2023) developed textile-lattice hybrids demonstrating improved energy dissipation, breathability, and deformability under strain. Their work on auxetic 3D lattice structures proved useful for applications needing both flexibility and resilience, such as in protective wearables and breathable architectural panels. Therefore, while polymeric designs excel in precision and static strength, textile lattices are more adaptable, offering dynamic mechanical compliance for variable-load environments.

2.5 Auxetics and Fabrication (2015–2025)

The foundational years between 2015 and 2019 laid critical groundwork in the development of auxetic materials, digital fabrication methods, and programmable morphologies. These early contributions were pivotal in shaping today's multidomain applications of auxetics in architecture, soft robotics, and additive manufacturing.

One of the earliest influential works was by Gatt et al. (2015), who explored hierarchical auxetic mechanical metamaterials. Their study emphasized the scalable design of auxetic structures with enhanced deformation responses using hierarchical geometry. They demonstrated that such structures could be systematically tuned by manipulating their microstructural arrangement, thereby enhancing the strain field distribution during mechanical loading. Parallel to material innovations, architectural research on auxetics also emerged during this time. Naboni and Mirante (2015) investigated auxetic pattern computation for architectural applications. Their study developed a parametric design workflow to generate synclastic shells and adaptive grid shells using additive manufacturing. Notably, they leveraged variable infill strategies to tune the mechanical response of auxetic forms, indicating early crossovers between performance-oriented design and digital fabrication in architecture.

Ahlers (2018), in his thesis, explored nonplanar 3D printing methods for improving surface smoothness. His work presented one of the earliest open-source slicer implementations capable of generating nonplanar toolpaths. By combining planar and curved layers, the thesis showed significant improvements in surface quality without sacrificing print stability, thereby contributing to the ongoing evolution of 3D printer hardware and slicing algorithms. In a similarly fundamental study, Meena and

Singamneni (2019) introduced a novel auxetic configuration that reduced stress concentration effects, tackling a long-standing limitation of auxetic systems in performance-intensive scenarios. Their research employed a reentrant design strategy, showing improved load distribution and suggesting broader potential in engineering design. Another significant innovation during this period came from Lei et al. (2019), who introduced a reprogrammable auxetic lattice based on shape memory polymers. By embedding morphing behaviors directly into the material design, their research enabled post-fabrication reconfiguration of properties like Poisson's ratio and stiffness. This programmable behavior was controlled through geometric modifications and thermal cycles, providing a path toward adaptive and multifunctional materials. The domain of digital textile fabrication saw early integration with programmable material behavior. Takahashi and Kim (2019) introduced novel 3D printed fabric techniques, combining digital weaving and printed logic onto textile substrates. Their method allowed the construction of programmable textile surfaces, where the printhead movement was tailored to simulate fabric-level behavior. These early experiments highlighted the feasibility of embedding deformation logic in soft surfaces, anticipating later applications in soft robotics and wearable technology. These foundational contributions illustrate a period of prolific development across disciplines from mechanical engineering and materials science to computational design and architecture. They collectively demonstrate how early research not only established the theoretical underpinnings of auxetics but also introduced essential computational and fabrication tools that continue to shape the trajectory of programmable, stretchable, and multifunctional materials.

In recent years, significant developments in 3D printing, materials engineering, and computational design have expanded the capabilities of auxetic systems and textile fabrication. From custom slicer logic to biomimetic applications, research between 2020 and 2025 reflects a shift from foundational innovation to applied complexity and smart integration. On the academic front, slicing and infill experimentation has gained momentum. Gokstorp (2020) proposed a modular slicing strategy using Houdini to generate adaptable infill and toolpath logic, while Gleadall (2021) introduced the FullControl GCode Designer to provide researchers with an open-source platform for precise, rule-based path generation. Lee (2023), developed a defect-controlled printing workflow specifically for TPU filaments, showcasing improved reliability and consistency in soft material extrusion systems. Staffová (2023) examined polymeric auxetic lattices fabricated with masked stereolithography, underscoring the importance of internal geometry in defining performance characteristics for architectural and biomechanical scenarios. Steck et al. (2024) further advanced slicer control by proposing sandwich-pattern-based infills optimized for material efficiency. In parallel, the mechanical performance of auxetic TPU structures has been explored in biomechanical contexts. Fuentes del Toro et al. (2025) evaluated TPU lattices under dynamic conditions, highlighting their effectiveness in impact energy absorption. Simarmata et al. (2025) extended this to medical applications by designing auxetic insole orthotics for patients with flat feet, demonstrating the material's potential for personalized biomechanical support systems. Emerging work has also bridged auxetics and soft robotics. Oliveira et al. (2025) introduced a proprioceptive multistable metamaterial system using capacitive sensors to detect deformation states. Surjadi et al. (2025) further developed mechanical metamaterials inspired by double-network polymers to achieve both stretchability and robustness. These advancements mark a convergence of materials science, embedded sensing, and architectural design logics.

2.6 Research Positioning

Across the reviewed literature, Pattinson et al. (2019) identified limitations in mesh-based fabrication for wearable systems, emphasizing the need for compliant designs that balance breathability and mechanical strength. Similarly, Mojaver et al. (2024) noted the absence of parameterized control in pore distribution for 3D-printed TPU metastructure, which constrains both airflow management and stretchability. Real-time prediction and optimization of mechanical behavior based on infill geometry is also underexplored. Nandi et al. (2016) proposed treating slicing and toolpath generation as analogous to a compiler process, suggesting that print logic could be adapted in real time using language-level control. Gokstorp (2020), in his thesis, developed a slicing engine in Houdini that allows procedural generation of infill paths.

However, the proposed system lacked integration with mechanical feedback loops that could guide material deposition dynamically. Another critical limitation is the control of defects during extrusion, especially when working with flexible filaments like TPU. Lee (2023), presented a rapid defect-controlled system for 3D printing soft materials, yet emphasized that consistent layer adhesion and bridging remain issues in environments where retraction and low-pressure extrusion are involved. Integration of stretchable auxetic structures directly onto fabric substrates is also rarely studied. While Lee (2022) introduced a workflow for printing onto tensioned textile bases to produce responsive '2.5D' hybrids, this domain lacks systematic analysis in terms of fabric compatibility, stretching thresholds, and post-processing effects. These limitations, altogether, form the basis for the exploratory and documentation-driven investigation proposed in this thesis.

Despite growing interest in these fields, and while extensive studies have explored each of them across theory, computation, fabrication, and application domains (Figure 2.29), there still appears a lack of systematic, experiment-driven studies that document how slicer-controlled, infill-based 3D printing could impact the physical realization of auxetic metamaterials.

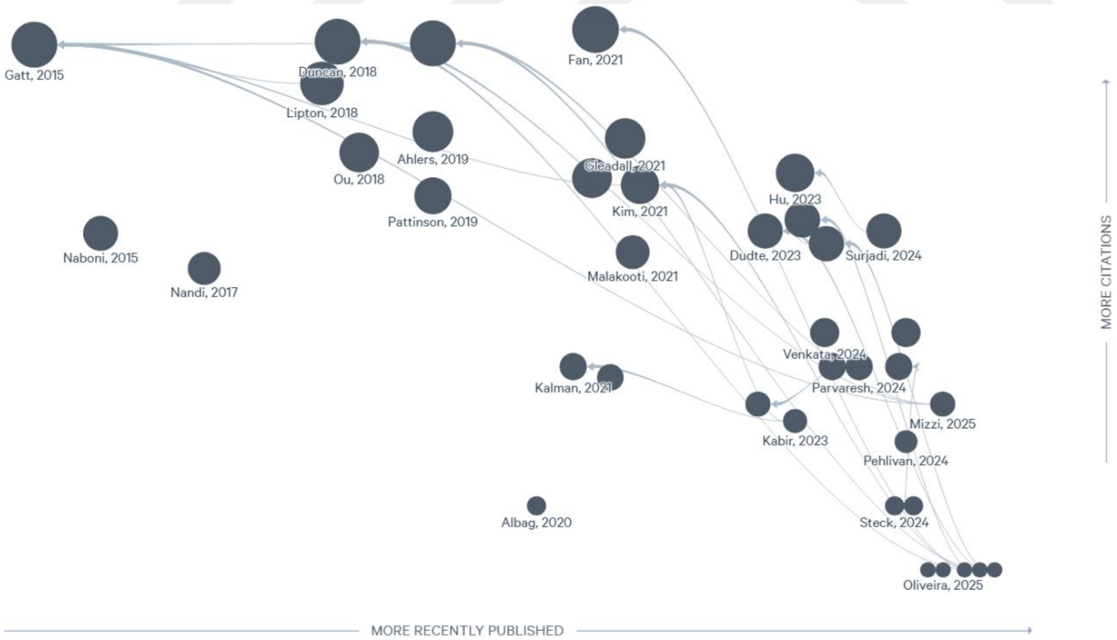

Figure 2.29: Literature map denoting publication year (x-axis), citation count (y-axis & node size) and citation connections (arrows).

Compared to its fully solid counterpart, infill-based additive manufacturing allows reduced material usage and print time, positioning it as a potentially more sustainable method in terms of resource efficiency. Nevertheless, how infill strategies mediate auxetic behavior across increasing scales of geometric intricacy, beginning at the micro-architectural level, remains limitedly documented, guiding the design-to-fabrication framework employed in this thesis.

3. EXPLORING AUXETIC PATTERNS

This chapter corresponds to the first stage of the methodology; it focuses on exploratory studies of auxetic patterns through computational design, digital simulation, and physical prototyping. The goal here is to form an understanding of geometry-driven deformation behavior rather than to assess material performance. Hands-on discovery begins with simple, tactile experiments: manually cutting and folding patterns from foam and paper to directly observe how auxetic geometries behave under stress. These early models informed a digital workflow that features parametric design. After 2D modeling some configurations, a qualitative prioritization was used to order a set of 9 auxetic patterns based on geometric clarity, applicability, continuity, and expected deformation behavior, replacing algorithmic evaluation with informed visual hypothesis. This codification of patterns acts as a supporting tool for design decision within the broader workflow rather than a performance validation mechanism. While studies on responsive and AI-assisted design have adapted data-driven methods, this work builds on preceding research by Ayech and Akçay Kavakoğlu (2024); the publication suggests reimagining static materials as breathable assemblies.

It is necessary to mention that this stage records the first trial of 3D printing with PLA for fabrication, and is concluded with a silicone casting experiment using inverse design of 3D-printed PLA molds for initial elastomeric testing. The method, however, proves that mold-based production has restrictions in terms of governing micro-scale architectural structures. This transition from rigid to elastomeric polymers stems from the desire to rethink how auxetic performance can be instilled within metamaterials using data-informed design and fabrication.

3.1 From Analog to Digital to Physical Prototyping

The first phase of the study employed an integrated approach for generating and evaluating PLA prototypes of the intended computational design of auxetic systems through crafting, digital modeling, and data-informed analysis. This sequence offered a systematic pathway from early geometric ideation to fabrication. Initially, exploration began with manual testing of auxetic geometries cut from soft materials such as foam and paper (Figure 3.1). This hands-on investigation allowed for a close reflection on deformation behaviors and intrinsic traits of auxetic materials, especially lateral expansion under tension (Evans & Alderson, 2000). These analog reproductions served as a tool for identifying digitally promising forms.

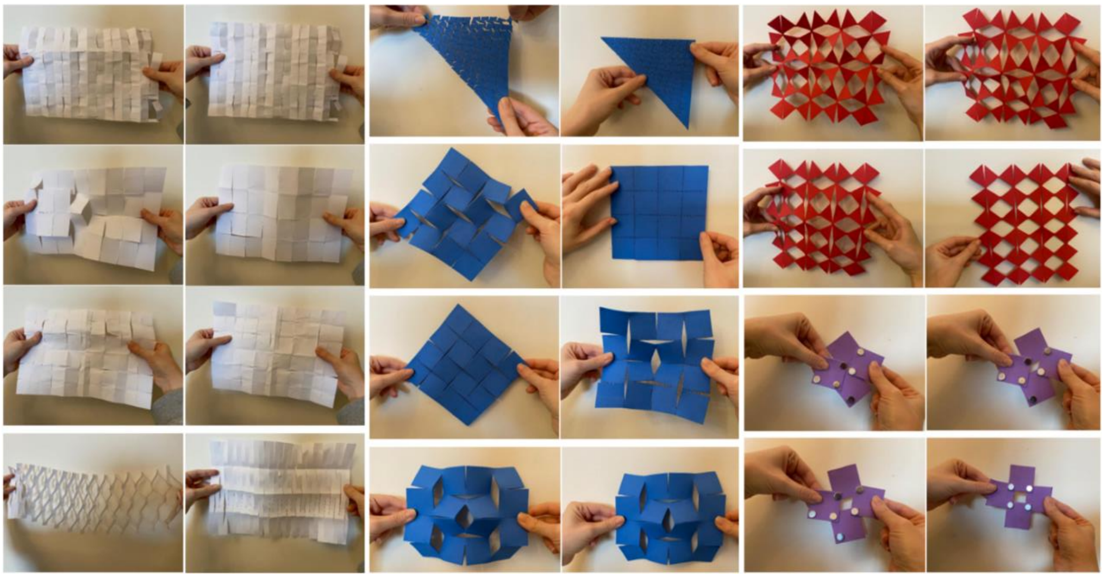

Figure 3.1: Hand-cut auxetic patterns using paper, foam, and magnets.

Moving from physical to digital exploration, parametric modeling served as the spine of design when it came to auxetic mechanisms. Using specialized plug-ins, diverse auxetic patterns were developed using parameters governing rotation, symmetry, and modularity. 9 patterns were compiled into a set of high-medium-low priority regarding testing. To establish a legible order among the patterns, prioritization was applied based on geometric criteria rather than optimization. This approach aligns with broader context in computational design where digital tools are used to guide research and decision-making without necessarily pursuing algorithmic optimization (Tamke et al., 2018). Through visual assessment of features such as openness, flexibility, and surface continuity, patterns were sorted and geometries with more vivid deformation potential and feasibility were set to higher priority. Prioritization remained intentionally simple and non-automated, reflecting emerging design workflows that incorporate computational generation with designer-led evaluation and judgment (O'Shea & Nash, 2015).

Rotating squares are listed as the patterns of highest priority due to their applicability by methods as simple as cutting and folding. The rotating auxetics logic guided design decisions in the next steps. To present surface tactility and potential deformation logic, parametric weaving informed geometric distinction and material enunciation through computational design (Liu et al., 2020). These features implemented visual and functional dynamics to otherwise motionless elements, enabling permeability and adaptability while retaining structural cohesion. Digital simulations of the tile arrays were conducted to assess their behavior under tension and rotation. These experiments informed design refinements ahead of physical production, in which prototypes were 3D-printed using FDM and later tested for deformation and assembly compatibility. This iterative phase emphasized feasibility and linkage accuracy . The full procedure of manual exploration, pattern prioritization, and fabrication outlines a framework that contributes to material computation in terms of examining how auxetic patterns can be integrated into surface-active systems. Originally proposed in an earlier publication by Ayech & Akçay Kavakoğlu (2024), this approach directly informed the development of TPU-based auxetic metamaterials discoursed later in this thesis. It also echoes computational design philosophy advocated by Kalantar and Borhani (2017), who highlighted the educational value of integrating material logic with algorithmic workflows early in the design process.

3.2 Computational Pattern Generation

The generation and evaluation of auxetic patterns in this phase served as a critical foundation for the development of metamaterials proposed in this study. Rather than treating auxetic behavior as a visual or formal novelty, this research focused on its material logic, behavioral adaptability, and data-optimized configurability. Together, these count as key criteria when aiming to translate rigid geometries into stretchable, breathable surfaces suitable for elastomeric additive manufacturing. Prototypes that explored prevalent auxetic mechanisms, such as rotating squares and re-entrant hexagons, provided tangible feedback on deformation, offering insights into how structures expand and compress. This is especially relevant to the present research, which requires controllable porosity and deformation for adaptive applications (Evans & Alderson, 2000). Following the analog phase, a parametric setting was established using visual programming. Parameters like unit size, rotation degree, and expansion axis offered rule-based auxetic configurations. These parameters were thoughtfully selected because of how direct of an influence they could have on breathability and elasticity in TPU-based metamaterials in the next stage. As demonstrated in research related to computational knitting and auxetic weaving, precise control over these elements is essential for producing specimens with selective permeability and retained tensile strength (Liu, Li, & Yuan, 2020). The parametric patterns generated via visual coding are compiled into a set for qualitative hypothesis rather than algorithm-driven evaluation (Figure 3.2).

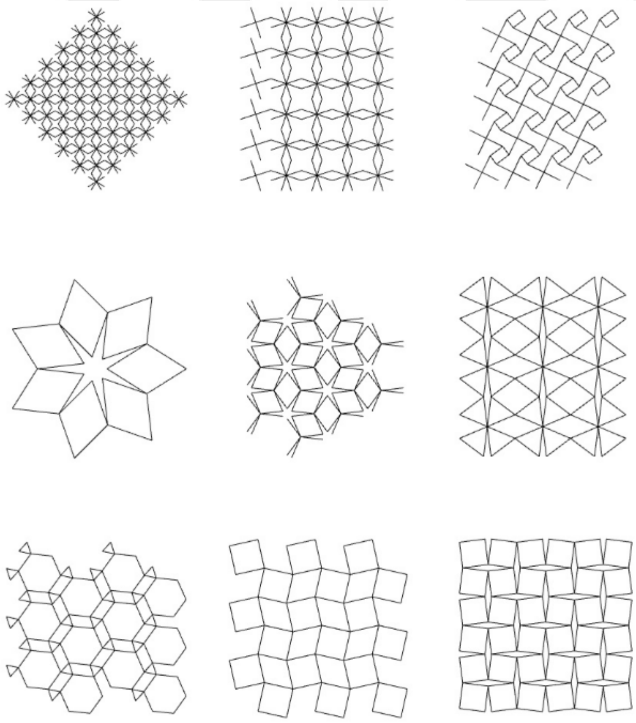

Figure 3.2: Visually programmed auxetic patterns.

The patterns are then assessed based on performance indicators such as openness, flexibility, and surface continuity. Broader discussions in computational design favor exploration and informed selection over random trial-and-error (Tamke et al., 2018). The pattern assessment is treated as an analytical identification method of geometries considered more suitable for fabrication, particularly in terms of balancing expressiveness with material efficiency and toolpath reliability. Comparable frameworks that merge computational generation with criteria-based filtering have been discoursed as means of navigating intricate design spaces while preserving design intent and material feasibility (Choudhry et al., 2023). Patterns of high priority function as a geometric foundation for the following stage of the research, guiding how cellular configuration triggers deformation under applied physical or environmental interaction. By prioritizing geometric assessment in early design stages, the research frames pattern assessment as an intentional design act rather than a consequence of automation. This method echoes inverse design strategies in which deep learning informs geometric reasoning while the designer's role in decision making is not dismissed (Zheng et al., 2021). In this sense, the approach contributes to fabrication-aware design strategies.

As apparent in Figure 3.3 and Table 3.1, 9 patterns achieved through visual programming are ordered according to geometric legibility, rotational continuity, and their anticipated capacity to physically express deformation.

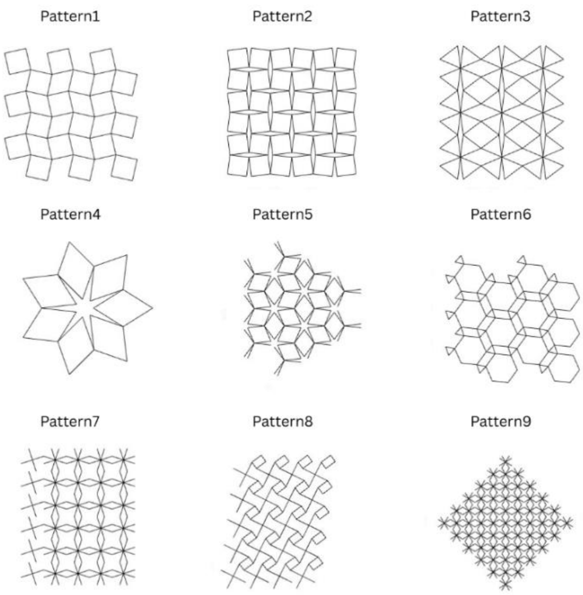

Figure 3.3: Exploratory prioritization of auxetic patterns based on geometric visual characteristics

Table 3.1: Patterns to be tested ranging from high to low priority.

Pattern Type	Representative Pattern	Exploratory Priority
Rotating Squares	Pattern1	High
Rotating Squares 2	Pattern2	High
Rotating Triangles	Pattern3	High
Multidirectional	Pattern4	High
Multidirectional 2	Pattern5	High
Hexagonal	Pattern6	Moderate
Quad Blade	Pattern7	Moderate
Quad Array	Pattern8	Moderate
Quad Blade Fractal	Pattern9	Low

Along the years, rotating auxetic configurations were consistently assigned high priority, reflecting their exceptional geometric properties and continuous recognition within literature related to auxetics as stable and interpretable mechanisms for negative Poisson's ratio behavior.

This order mirrors earlier work by Grima and Evans (2000), who showed that rotating square-based auxetic structures allow for a high degree of expansion under load, making them especially relevant for both architectural and textile applications requiring controlled deformation. This shapes an integral component of the methodology in broader context, serving both computational reasoning and design thinking as it allowed for the reduction of subjectivity in pattern nomination. Geometries with high priority formed the base units for material testing in subsequent stages, particularly influencing infill-based auxetic metamaterial generation.

3.3 Digital Simulation

Unit-cell and whole assembly design played a pivotal role in translating computational insights into tangible architectural modules. Following, priority was given to rotating squares. This pattern was transformed into a three-dimensional unit that began as plain surface but later on incorporated parametric weaving principles. Parametric design enabled the generation of detailed interwoven geometries, which were adapted to create rigid tiles with enhanced performance, flexibility, and visual depth (Ayech & Akçay Kavakoğlu, 2024). The design logic integrated two systems: a parametric weave base and a computational knitting-informed surface. The base functioned as a stable lattice informed by the geometry of the rotating squares pattern (Figure 3.4), while the surface skin borrowed logic from textile strategies, reminiscent of thatch layering in traditional knitting (Figure 3.5). These components were modeled using parametric plugins and custom nodes within a visual programming environment, in this case Grasshopper, enabling rotational symmetry and scalable repetition across the assembly. As Ayech and Akçay Kavakoğlu (2024) describe it: "The resulting design featured a complex, multi-layered structure that combined the functionality of auxetics with the aesthetics of computational knitting" (p. 1442).

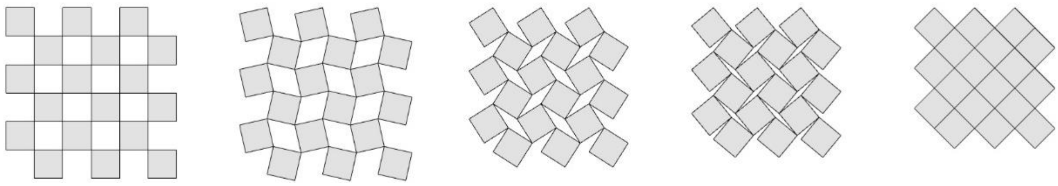

Figure 3.4: Visually programmed configurations of rotating squares

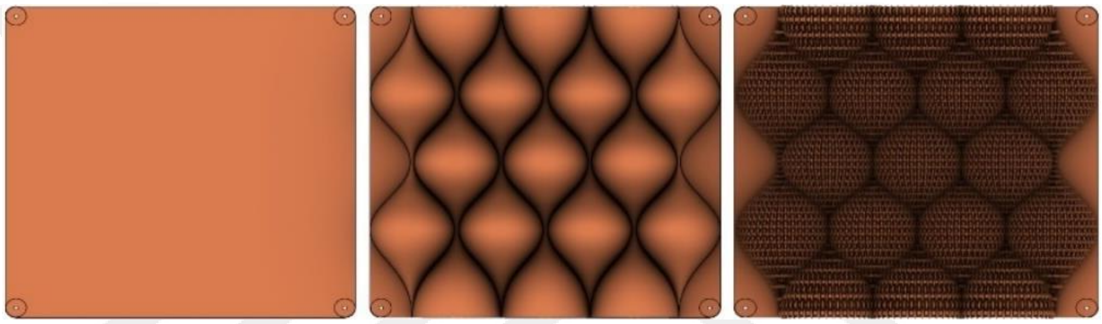

Figure 3.5: Computational knitting-informed tile texture

Knitting-informed design is especially relevant to upcoming stages in the study. While the SIGraDi paper first focused on rigid polymers, the thesis explores how parametric weaving strategies can be reinterpreted using flexible elastomers. The woven texture also draws conceptual support from architectural ceramics documented by Pintos (2023) and Pronina (2020), who highlight the potential for reimagining rigid surface textures as culturally resonant, structurally active components. Tovar (2023) further supports this direction, emphasizing that flexible, algorithm-driven ceramic bricks can dynamically wrap architectural spaces. In brief, this section of the research lays the groundwork for shifting from rigid woven envelopes to flexible architectural textiles. This aligns with Kalantar and Borhani's (2017) notion of "breathable walls" as interfaces that mediate between performance, material adaptability, and environmental feedback.

Through the fabrication phase, tiles derived from the rotating squares auxetic pattern were brought to life. This involved both virtual simulation and physical prototyping, ensuring that each stage contributed to refining the system's physical behavior and aesthetic value within architectural applications. The prototypes served as an initial testbed for the development of elastomeric auxetic metamaterials fabricated in subsequent phases of this study. Prior to physical fabrication, a detailed 3D simulation was conducted to visualize and verify the performance of the proposed assembly. The simulation focused on rotational configurations and tile linkages derived from the auxetic pattern of highest priority. Through visual programming, it became possible to optimize how tiles interact under varying deformation scenarios and stress conditions (Figure 3.6).

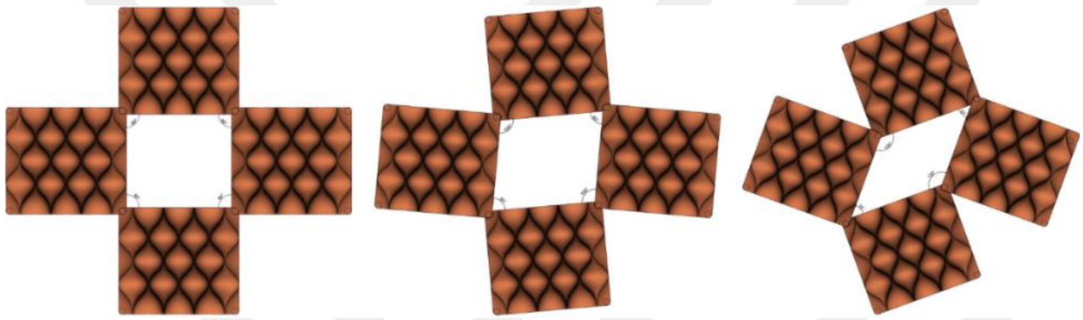

Figure 3.6: 3D simulation of ceramic textile assembly of 4 tiles.

According to Ayech and Akçay Kavakoğlu (2024), the simulation facilitated the investigation of various configuration and assembly methods aimed at enhancing the structural efficiency and performance of the designed assembly (p. 1443). This stage, fully dependent on the visual programming definition (Figure 3.7), ensured that final geometries would meet predefined mechanical and architectural criteria, and laid the groundwork for translating such design logic to soft-material implementations.

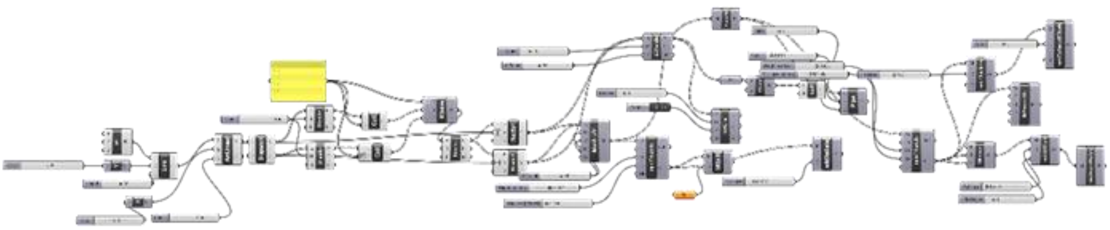

Figure 3.7: Visual programming definition.

3.4 Fabrication via 3D Printing

Following the simulation phase, a set of four identical 3D-printed PLA tiles was produced as the first physical manifestation of the 3D-printed assembly concept (Figure 3.8), which translated the digital model into fabricated tiles (Ayech and Akçay Kavakoğlu, 2024). The initial prototypes focused on producing the basic weaving structure, without the thatched surface, to validate the core mechanical behavior of the assembly.

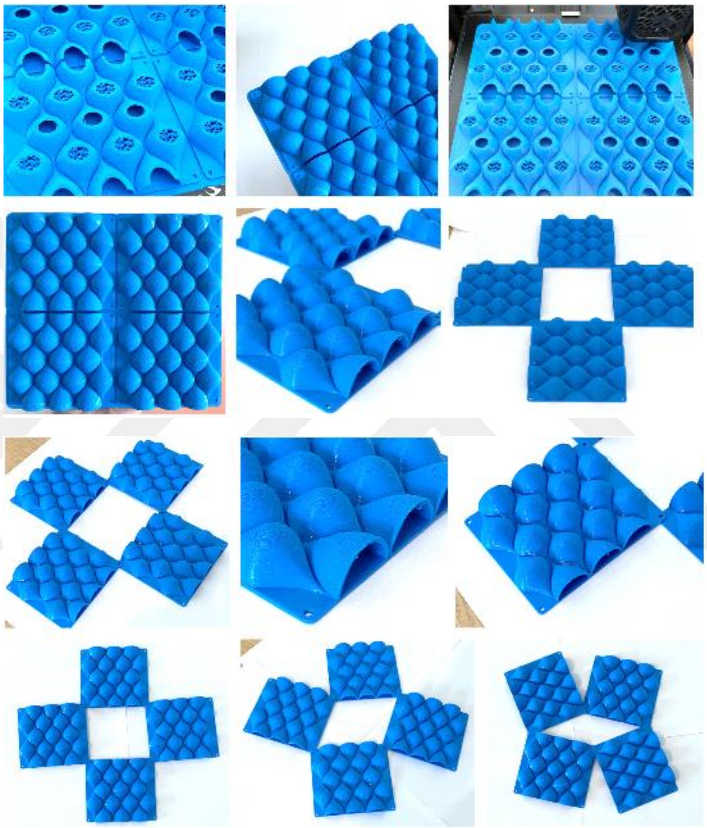

Figure 3.8: 3D-printed PLA prototype set composed of 4 tiles.

Screws were employed at pre-defined rotational joints, testing the auxetic response through parametric variation in joint angles (90°, 100°, 130°, etc.). This configurational flexibility significantly informed the tunable mechanical behaviors and variable connections in later developed elastomeric assemblies. While the fabrication involved standard PLA, the process suggests potential clay-based extrusion in future iterations.

3.5 From Rigid to Elastomeric Polymers

Following the outcomes explored in the initial phase of this chapter, a second phase extended the system's adaptability by employing elastomeric materials. The motivation for this transition stemmed from the desire to achieve deformability, resilience, and responsiveness within the same design logic. Rigid materials limited the capacity for real-time morphological changes, which are essential in systems manifesting such values. As a result, silicone was selected as the next material due to its elasticity and compatibility with 3D-printing fabrication workflows through inverse mold design and casting (Severi, 2024b). This transition marked a procedural departure from discretely assembled rigid tiles to elastomeric silicone units exhibiting auxetic expansion. The research introduced flexibility through the interplay between elastic materials and geometric transformation. This is in line with Thakur's (2017) discussion of shape memory polymers and smart textiles, which describes how tailored deformation properties enable fabrics to adapt to their environment. While silicone itself does not possess intrinsic shape recovery properties, its geometric programming within this prototype achieved a similar responsive behavior when subjected to expansion.

The new system (Figure 3.9) also proposed the use of functionally graded behavior across a dual-layered panel.

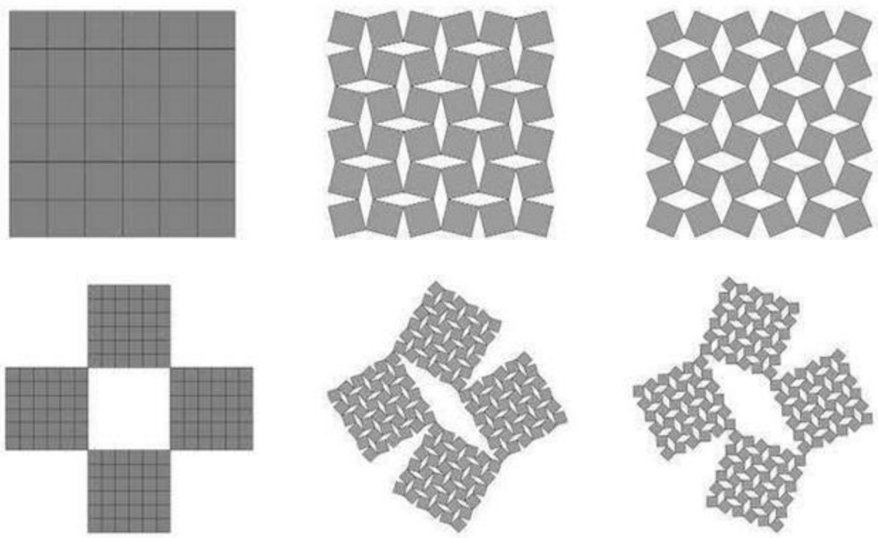

Figure 3.9: 1 unit vs 4 units FGM simulation.

This composite structure references the broader trend of using multi-material strategies for enhanced functional response in morphing systems (Karima, Habibi, & Laperrière, 2024). The graded performance was particularly important in tuning flexibility across surface zones, signifying the infill density and porosity modulations to be explored later.

The justification for selecting an auxetic pattern with multipart rotational joints was reinforced through existing research. Plewa, Płońska, and Junak (2023) demonstrated how auxetic behavior can be generated through rotating square arrangements, even in rigid connections. Translated into an elastomeric assembly, these joints allowed the silicone surface to dilate under pressure, yielding an effective increase in surface area without compromising enclosure. This was fundamental in establishing the architectural viability of a morphing system. In terms of fabrication, the silicone prototypes relied on layered mold casting (Figure 3.10). The inverse mold of the rotating square auxetic layer was 3D-printed, then silicone casting took place to accomplish the elastomeric version of the original pattern. This is an approach informed by advances in silicone printing and extrusion tooling, such as those documented by Severi (2024a) and WASP's academic collaborations. While additive silicone printing remains limited by resolution and equipment access, the conceptual implications of programmable deformation in soft-material architecture are significant. The mechanical expansion of silicone (Figure 3.11) parallels the intended performance of TPU-based auxetic metamaterials.

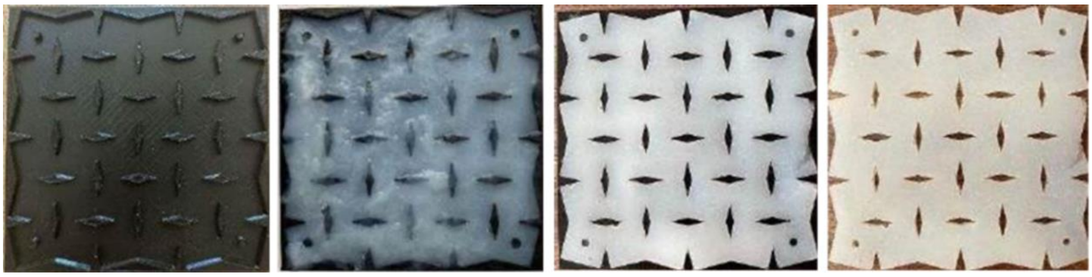

Figure 3.10: Silicone mold casting stages.

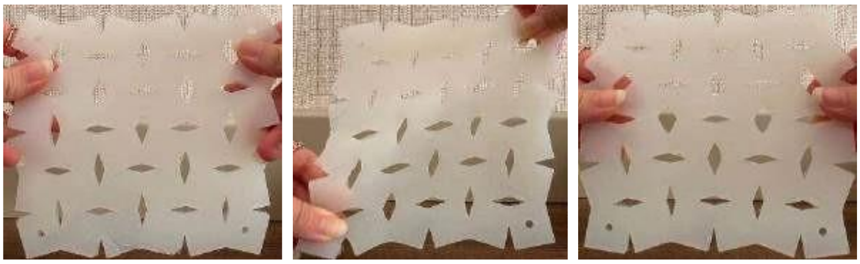

Figure 3.11: Silicone stretch test.

The introduction of this second elastomeric prototype phase sets the groundwork for the core focus of the thesis: creating an infill-driven auxetic metamaterial using elastomeric 3D printing. Silicone fabrication confirmed the necessity of programmable design tools and precision-driven geometry, especially for materials that combine elasticity with structural resilience. As Dong and Hu (2023) suggest, auxetic materials are treasured in developing sensor-integrated systems due to their responsive mechanical feedback, a property elastomeric 3D printing will further explore. Ultimately, the shift to elastomeric materials represents more than a change in medium; it reflects an expanded architectural ambition to integrate intelligence, deformation, and reactivity into carefully curated assemblies. As the research progressed, the transition from rigid PLA-based prototypes to elastomeric auxetic systems represented a noticeable fabrication leap. Silicone emerged in this phase as a promising candidate for its ability to embody flexibility, durability, and responsiveness, all while retaining predefined auxetic behavior. This shift aligns with the thesis objective of achieving adaptable auxetic metamaterials with embedded architectural potential.

The research introduced a functionally graded, multilayer silicone-based system, exploring dual-layer expansion patterns embedded in a tile assembly (Figure 3.12). FGM served distinct structural purposes, enabling varied deformation depending on the stimuli applied. Inspired by studies on pattern-dependent Poisson ratio control via mesh curvature, the system configured geometries that could actuate differentially across zones, forming a deformable metamaterial (Lei et al., 2019).

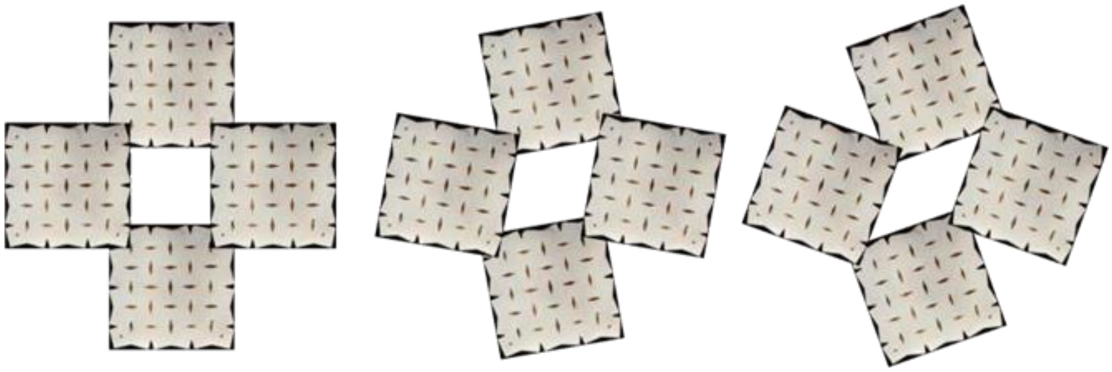

Figure 3.12: Silicone prototype visualized assembly of 4 tiles.

To place these developments within broader scientific context, the programmable nature of auxetic behavior in elastomeric materials, particularly silicone, can be understood through their role as tunable morphing systems. Such formations are ideal for architectural applications involving reconfigurability and passive response to applied changes. As Lei et al. (2019) describe, “the printed mesh can be programmed into different geometries by using the shape memory effect,” a principle that was adapted in the dual-layer design logic of this study. While silicone casting enables the conversion of rigid geometries into flexible material schemes, this method still imposes limitations in reaching accurate, repeatable control over internal architecture and deformation paths. Such limitations provoke the shift toward infill-based elastomeric 3D printing, where micro-architectural features can be explicitly programmed and analytically documented through slicer-dependent control. This conversion symbols the shift to fabrication-aware experiments, clearly explained in the next chapter.

4. INFILL-BASED TPU AUXETIC METAMATERIALS

This chapter forms the second, core experimental stage of the research methodology. Building upon the geometric and material insights developed in the previous chapter, this stage is meant to investigate infill-based auxetic metamaterials produced using thermoplastic polyurethane (TPU). Upon the transition from mold-based elastomer casting to slicer-controlled 3D printing, control over the micro-architectural scale is accomplished through infill logic, density, and toolpath configuration. Subsequent prototypes are systematically documented and synthesized within a prototype documentation matrix, which serves as the primary instrument for recording fabrication parameters and detected material response across each specimen in the experimental set. TPU was selected as the primary material due to its unique combination of elasticity, mechanical durability, and compatibility with precision 3D printing. In particular, TPU Flex 95A provided an ideal balance. Its firm enough to ensure consistent flow and print fidelity, yet flexible enough to support dynamic deformation, making it especially effective for applications requiring both responsiveness and resilience (Fuentes del Toro et al., 2025; Lee, 2022). Beyond its mechanical advantages, TPU also offers sustainable fabrication potential as a recyclable thermoplastic elastomer (Lee, 2022), aligning with broader environmental considerations of this thesis. Crucially, this material supported the core design value, which is using infill not as a secondary setting, but as a generative system that encodes performance directly into the structure. Pattern, density gradients and localized variations allowed the material to perform differently across specimens and specimen zones, enabling support where needed and openness where porosity or stretch was prioritized. This design logic marks a departure from traditional solid to infill-based 3D printing and reinforces a central thesis claim: Mechanical behavior, tactile quality, and environmental responsiveness can be programmed from the inside out through the interplay of material selection and computational geometry. Through systematic testing, infill patterns such as grid, gyroid, cross hatch, and 3D honeycomb (Figure 4.1) were evaluated for their impact on permeability, flexibility, and structural stability (dos Reis et al., 2024; Wevolver, 2024; Steck et al., 2024).

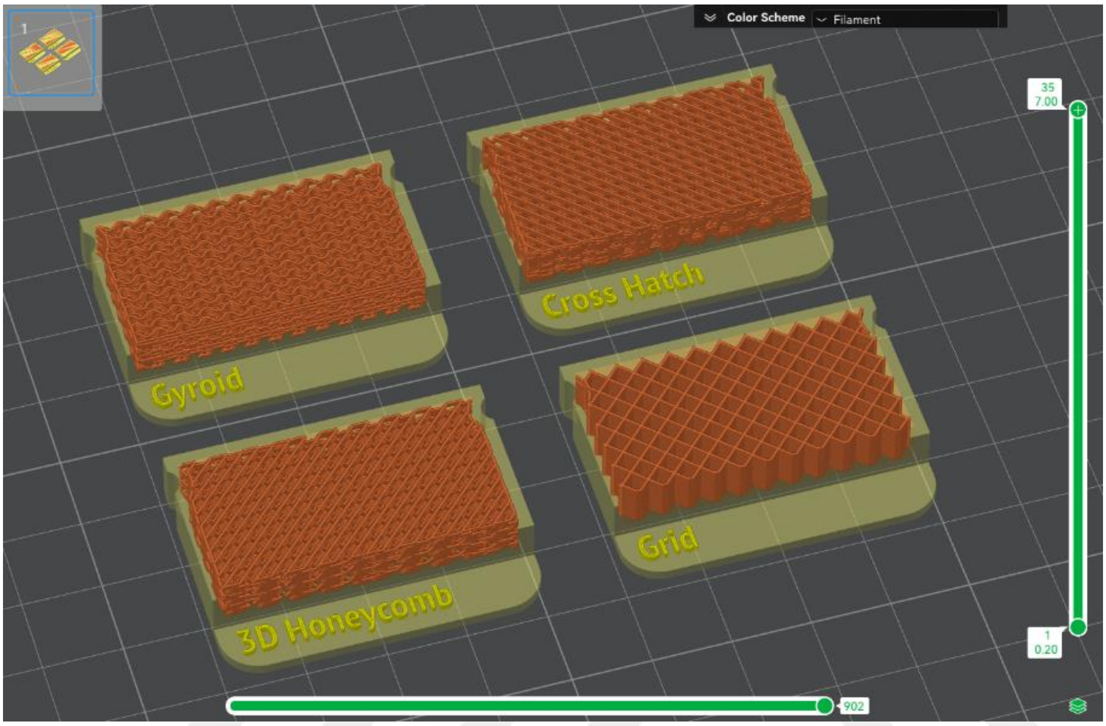

Figure 4.1: Bambu Studio infill patterns tested in the study.

4.1 Filament Type and Hardness Justification

Building on the shift toward elastic, programmable materials, this section articulates why TPU was selected as the core medium for fabricating infill-based auxetic metamaterials. Unlike previous materials explored in earlier phases of the research, it offers a unique combination of elasticity, printability, and mechanical resilience, properties that make it well-suited for dynamic, stretchable applications. One of TPU's key advantages lies in its ability to withstand large deformations while maintaining dimensional stability. According to Yadavalli, Myadam, and Telu (2024), this filament exhibits excellent tensile and compressive behavior under varying infill patterns, supporting controlled expansion and contraction essential for auxetic response. This makes it particularly appropriate for applications where repeated mechanical stress is expected, such as breathable surfaces or adaptive systems. Its high tear resistance and significant elongation at break enhance durability without demanding embedded reinforcement, while its compatibility with more sustainable fabrication practices was a key consideration. As a thermoplastic elastomer, TPU can be remelted and reshaped with minimal degradation, offering recyclability benefits not available in thermoset elastomers or silicone-based materials. Lee (2022) highlights the material's potential for producing mono-material assemblies that simplify dismantling and repurposing, two key considerations in sustainable design. Additionally, TPU's consistent flow characteristics during extrusion enable high-resolution printing of complex geometries, like gyroid or zigzag infills, which are central to the design logic developed in this thesis. As Fuentes del Toro et al. (2025) note, such infill strategies not only influence mechanical properties but also allow for porosity control, enabling lightweight, permeable structures without compromising strength. This aligns with the focus of the study, where materiality and performance intersect. Lastly, the use of TPU builds on findings by Pattinson et al. (2019), who demonstrated its suitability for biomechanically tailored meshes in wearable and implantable devices. Their work supports broader assertion of this thesis: Auxetic behavior can be programmed not only through geometry, but also through strategic material selection, enabling textiles to breathe, flex, and endure in real-world contexts. In this stage, Porima TPU Flex 95A (1.75 mm) is employed as the primary filament due to its optimal suitability especially for fabricating infill-based auxetic metamaterials. According to Bambu Lab's technical guide, 95A is positioned among the softest TPUs that can ve reliably printed using consumer-grade systems, within a hardness hierarchy ordered as follows: 77D > 70D > 55D > 95A > 85A > 83A > 80A > 75A > 70A (Bambu Lab, n.d.). Materials softer than 80A are generally avoided due to their tendency to deform under extrusion force, often leading to under-extrusion or clogging. By contrast, 95A retains enough structural stiffness to flow consistently, while remaining flexible enough for applications requiring mechanical response and deformation.

The selection of this filament stems from its successful deployment in recent experimental research too. For example, Fuentes del Toro et al. (2025) conducted a detailed mechanical assessment of auxetic structures fabricated from TPU 95A under compressive loading. Their findings confirmed the material's ability to absorb energy while maintaining structural coherence, validating its suitability for high-performance metamaterials. Similarly, Oliveira et al. (2025) fabricated proprioceptive multistable metamaterials using NinjaTek Cheetah 95A. The study emphasized the filament's effectiveness in producing mechanically resilient and sensor-integrated geometries, traits aligning with the fabrication objectives of this thesis.

Complementing these technical studies, Lee (2022) provided a design-oriented investigation into the tactile behavior of TPU 95A within 3D-printed textiles. At MIT, Lee explored 3D printing directly onto stretchable fabrics using various TPU suppliers, including filaments with 95A Shore hardness. His work demonstrated how even high-durometer TPU could exhibit textile-like softness when distributed strategically. As Lee explains, "Despite being executed with a harder TPU (Shore 95A), the translucent, line-based design actually forms a softer volume when the garment is reconfigured" (p. 32). This insight underscores that computational geometry, especially infill architecture, can outweigh material hardness in defining tactile behavior, adaptivity, and deformation capacity.

To ensure print fidelity and repeatability across prototypes, several TPU-based trials were conducted on the Bambu Lab P1S, culminating in a tuned profile that enabled consistent, defect-free prints. Fabrication parameters such as extrusion temperature, print speed, layer height, and retraction settings were carefully calibrated and standardized across all prototypes after a course of trial-and-error. The finalized settings included a 0.4 mm nozzle, 0.2 mm layer height, extrusion temperature of 240°C, bed temperature of 35°C, and a print speed of 30 mm/s, printed on a textured PEI build surface. Early attempts included multiple failed prints due to stringing, surface delamination, and warping, issues commonly encountered in elastomeric printing, particularly at the infill level. These challenges were gradually mitigated by adjusting extrusion flow, wall settings, and retraction parameters. Iterative tuning of material and print behavior was essential to achieving the anticipated design outcome. The consistent use of Porima TPU 95A throughout this phase contributed to the accurate fabrication of controlled, lightweight, and adaptive auxetic metamaterial prototypes. As the study progressed, it became evident that the success of the specimens depended not only on selecting the right filament, but also on pairing it with carefully curated geometric intelligence, fabrication constraints, and tactile intent, shaping a material logic that is both computation-driven and deeply empirical.

4.2 Infill as a Design Matrix: Pattern × Density × Shape

Infill design has evolved from a passive unrecognized element into a fundamental design tool, an internal geometry that accentuates structural resilience, visual rhythm, and material efficiency. In the context of TPU-based metamaterials, infill operates as a programmable tool for performance driven design, encoding mechanical behavior and spatial texture directly into the material's geometry rather than serving merely as structural support. Physically, infill patterns dictate how force is absorbed, transmitted, or released. Dos Reis, Carbas, Marques, and da Silva (2024) highlight that infill density plays a crucial role in 3D printing, influencing the mechanical performance, material consumption, and overall print quality of the fabricated object. Their research on geometrically graded impact attenuators reveals how strategic infill modulation can induce localized behavior by concentrating or dispersing deformation within specific regions based on the functional role of each zone. This is particularly relevant to textile-related applications, where both softness and support must coexist. Moreover, efficiency and sustainability have become integral to performance. Steck et al. (2024) developed a slicer-based infill strategy inspired by sandwich-core geometry, optimized for reduced waste. Simulations on a 10 cm^3 part showed up to 77% less material use and 78% faster print time, while preserving stiffness comparable to full grid infill. This reconceptualization of internal material logic proves that high structural performance does not intrinsically conflict with sustainability objectives, particularly within iterative, materially demanding domains such as prototyping. For TPU, infill plays a particularly nuanced role, governing not only structural response but also the material's adaptivity, stretchability, and visual expression. Yadavalli, Myadam, and Telu (2024) highlight that mechanical performance in 3D-printed samples is highly influenced by the choice of infill pattern and key process parameters, including nozzle temperature, print speed, and bed temperature, as confirmed through systematic experimentation and testing. This interplay between design logic and fabrication settings establishes the core strategy of this thesis, leveraging both geometric and machine control to achieve targeted performance.

Aesthetically, the semi-transparency of TPU means that infill patterns are no longer hidden. They become part of the object's perceptual articulation, turning microstructures into surface rhythms. This work takes advantage of the duality, designing infill to act as both skeleton and skin, uniting function and ornament within a single material system. Patterns such as gyroid, zigzag, and honey comb not only augment deformation but also outline visual texture and permeability. This geometric approach aligns with a broader architectural logic in which performance emerges from layered micro architecture. It reframes 3D printing not as shell construction, but as the deliberate cultivation of surface logic from the inside out. Through this lens, the thesis proposes a shift in perspective: from external form to internal intelligence, from outer layer to embedded behavior. Infill in this case is the origin point of performance and design intention. The structural and aesthetic performance of TPU-based auxetic metamaterials is inherently tied to the interdependent parameters of infill pattern, density, and surface geometry. This section describes the use of a design matrix to explore and compare these parameters, empowering the evaluation of resulting metamaterial behaviors through visual and mechanical performance.

To begin, infill pattern selection plays a decisive role in the mechanical performance and sustainability of a print. A test study by Autodesk (Stock, 2021) compared material consumption and print time for different infill patterns by printing identical 25×25×25 mm cubes at 20% infill, 0.2 mm layer height, and with no shells or perimeters. The results highlighted gyroid infill as the most efficient in both material use and speed (Figure 4.2). According to the study, switching to gyroid infill not only reduces filament waste but also accelerates print time, making it one of the most sustainable options available for prototyping.

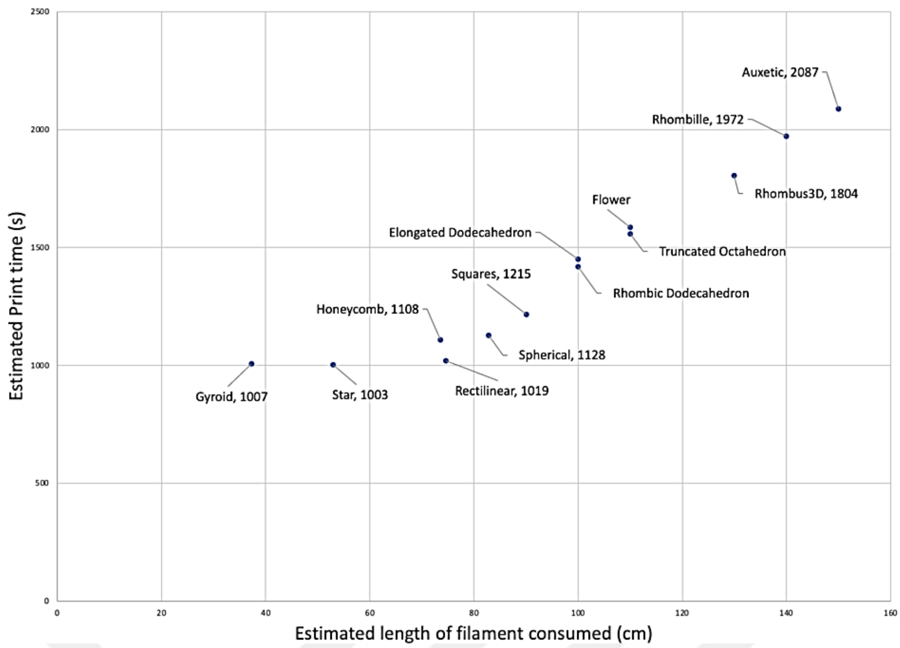

Figure 4.2: Infill pattern sustainability – Adapted from **Stock, T.** (2021).

These outcomes were directly considered in the development of the prototypes for this study. Given its durability and sustainable printing performance, gyroid was nominated as the primary infill strategy. The gyroid structure consists of continuous, undulating lines forming complex yet smoothly interconnected geometry, providing high isoptropic strength and notable shear resistance. As Wevolver (2024) explains, this pattern "requires less material to achieve greater strength than many infill patterns and can be printed rapidly due to its curvy lines." For the auxetic metamaterials systems proposed here, this pattern is ideal since it balances stretchability with structural support and maximizes permeability through its periodic voids, which is crucial for the adaptivity of the final designs. Beyond the infill pattern itself, density gradients allow for fine-tuning the mechanical response within a single part. As reported by Wevolver (2024), the technique of variable infill density or infill gradient offers advanced control over localized flexibility, stiffness, and porosity. This enables a hybrid strategy in which certain zones of a of a specimen may be rigid to provide support, while others remain open to maximize permeability and stretchability. To evaluate these parameters, a structured design matrix was developed, pairing a selection of infill patterns (grid, gyroid, crosshatch, 3d honeycomb) with a range of densities (between 5% and 100%), as well as variable infill densities within a single print. This logic was applied to repeatable textile units with diverse shapes and mechanisms. Each unit was 3D-printed in TPU and assessed for tactile flexibility, expansion potential, porosity, and print efficiency. This process allowed for cross-comparisons and guided the selection of optimal pattern-density combinations based on the intended field of application.

This parametric exploration was not limited to slicer presets. Drawing from the methodology of Gokstorp (2020), who developed a custom slicer in Houdini for modular infill and toolpath control, this thesis also explored manual infill parameterization. While not fully re-coded in a new slicing environment, the study borrows from his logic of thinking about infill as a modular and computational element rather than a pre-baked print setting. This foundation enables the possibility of future adaptive workflows that could auto-generate infill rules based on deformation intent, breathability requirements, or external stimuli.

The research path further builds on earlier findings by Ayech and Akçay Kavakoğlu (2024), highlighting the role of computational logic in generating performative systems. Their publication involving 3d-printed auxetic systems framed visual programming as a mediator between material behavior and responsiveness. By extending this logic to TPU and adopting a layered matrix of pattern, density, and geometry, the research pushes this vision into the realm of lightweight, stretchable, and structurally active metamaterials. The structured design matrix developed facilitate creating a fabrication-aware, performance-optimized, and material-efficient auxetic metamaterial. Guided by a computational understanding of infill mechanics, the matrix becomes a framework for organizing and predicting material behavior, tuning performance from the inside out.

4.3 Slicer-dependent Design Workflow

The manual toolpath workflow developed for this approach is centered on integrating parametric modeling tools and slicer-based controls to optimize the fabrication of auxetic TPU-based metamaterials. The design process began in Grasshopper, where auxetic geometries, particularly rotating square modules, were generated and analyzed

(Figure 4.3). These forms were selected for their predictable deformation, rotational properties, and porosity potential, making them ideal candidates for metamaterials.

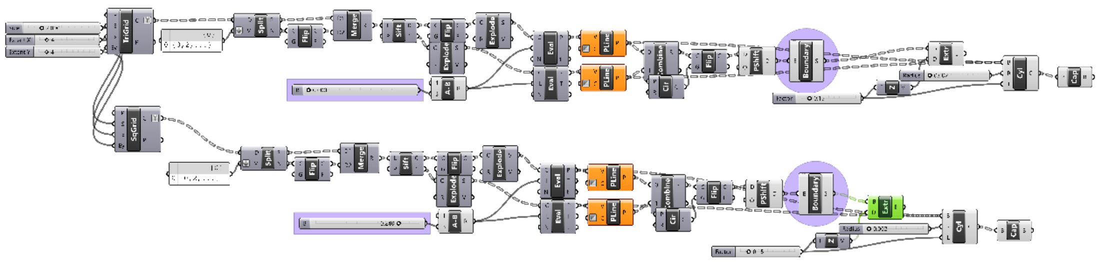

Figure 4.3: Visual programming definition for rotating auxetics.

To explore the functional and visual effects of these patterns, early experiments involved printing simple grid geometries with default slicer settings. These initial models included all walls and top and bottom layers, which were incrementally stripped back in subsequent iterations. Wall counts were tested at three, two, one, and zero, while layer configurations progressed from full enclosure to infill-only constructs with no top or bottom surfaces. This strategy exposed the internal infill structure and allowed for direct evaluation of porosity, expansion behavior, and tactile quality. Across all experiments, a consistent layer height of 0.2 mm was maintained to ensure comparability of results.

All prototypes were printed on a Bambu Lab P1S equipped with a 0.4 mm nozzle and textured PEI build plate, which offered enhanced bed adhesion for TPU. Unlike rigid materials like PLA, TPU's elastomeric properties often caused issues such as stringing, under-extrusion, or failed adhesion. Several early prints were unsuccessful, which led to a refinement of slicer settings and the creation of a custom profile suited for flexible filament behavior. These failures served as critical back-and-forth dialogues that later informed precise print configuration settings. In Grasshopper, the approach employed programmable deformation modules via rule-based pattern generation (Figure 4.4). The goal was to create scalable, textile-like geometries that show auxetic response under tension or compression. The generated patterns were digitally simulated and then exported as STL files for slicing. Although Bambu Studio, the native slicing software of the Bambu Lab ecosystem, was used in this case, the workflow remains adaptable to any visual programming environment and slicing software offering equivalent control.

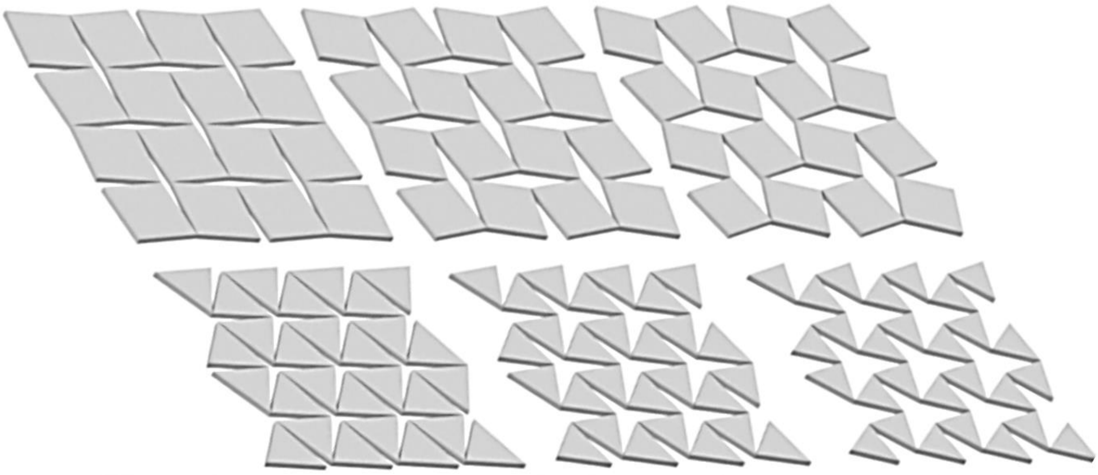

Figure 4.4: Visual programming configurations of rotating auxetics.

Exporting from Grasshopper to Bambu Studio allowed precise control of the geometry subject to slicing and 3D-printing. Once imported to the slicer, the geometry would be scaled, rotated, and optimized for shell configuration and infill exposure. This workflow ensured that every exported model could be rapidly tested for mechanical behavior while preserving the integrity of its computational logic. The visual programming logic maintained parametric control over pattern density and scalability, facilitating rapid iteration of design variants without the need for remodeling.

4.3.1 G-code configuration for TPU

Following geometric design, slicing parameters played a critical role in achieving the desired balance of high mechanical resilience and low material density. The slicer profile was developed through multiple test prints and iterative fine-tuning. The final configuration stabilized at a print speed of 30 mm/s, nozzle temperature of 240°C, and bed temperature of 35°C. This combination was selected for its ability to reduce stringing while maintaining filament flexibility. The textured PEI plate offered reliable adhesion at low bed temperatures, crucial for preventing warping in open infill structures. A custom print profile was generated in Bambu Studio, in which the TPU preset was further tailored to reflect the unique needs of auxetic metamaterial design. The profile involved adjusting wall count, extrusion width, and retraction values to reduce filament tension. Key parameters such as feedrate (M220), flowrate (M221), and fan speed (M106) were optimized to suit elastomeric behavior. These configurations were saved and reused across all prototypes to maintain printing consistency. The print profile leveraged the slicer's internal logic to generate a performance-tuned G-code that aligns with the research objectives of creating lightweight, durable, and deformation-aware specimens. Final outcomes of slicer-controlled iteration (Figure 4.5) highlight the progress.

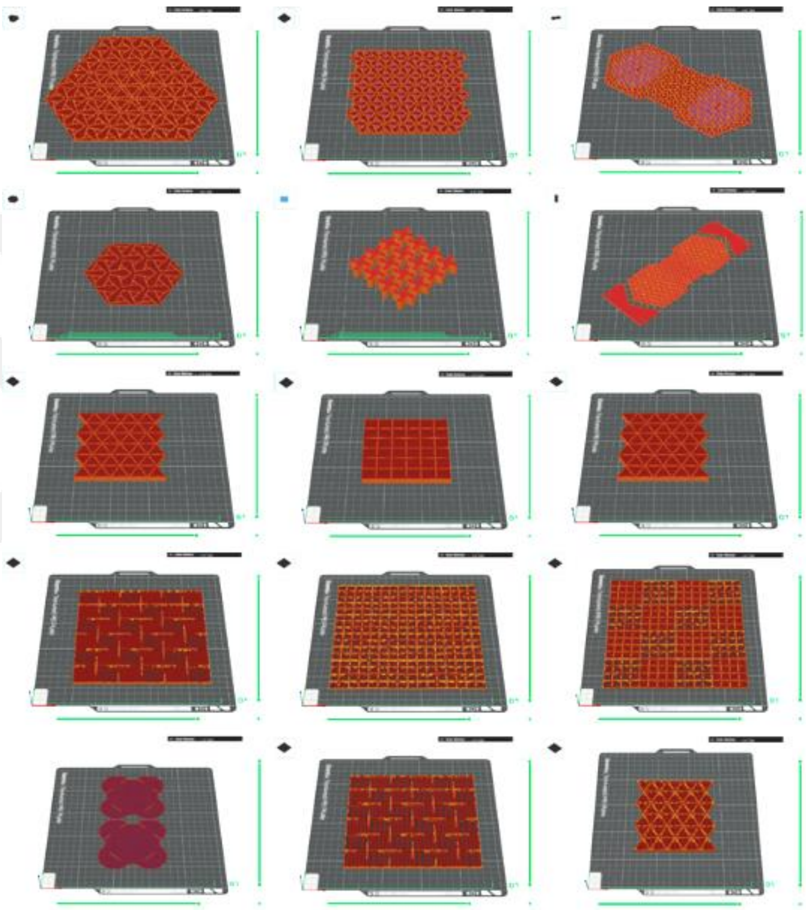

Figure 4.5: Infill-based STLs preview in slicer.

4.4 Prototype Documentation

As mentioned earlier, the prototypes presented in this stage are systematically documented in an effort to capture the geometric configuration, material response, fabrication parameters, and observed mechanical behavior. This stands out as the basis of the prototype documentation matrix, through which experimental observations from each specimen act as datasets informing the next. This structure reflects the design-to-fabrication logic adopted in the research in which non-auxetic prototypes serve as a baseline for the consecutive investigation of increasingly intricate auxetic typologies (Table 4.1).

Table 4.1: Expected differences between non-auxetic vs. auxetic prototypes.

Feature	Normal (non-auxetic)	Auxetic
Lateral reaction	Contracts (edges pull inward)	Expands (edges push outward)
Resulting curvature	Anticlastic (saddle-like)	Synclastic (dome-like)
Deformation uniformity	Uneven (buckling, folds)	Smooth (distributed strain)
Area change	Nearly constant or reduced	Increases significantly

Figure 4.6 clearly shows the two categories when stretched, although the core of the experiment-driven methodology in this case lies in the specimens' synthesis rather than their comparison or optimization.

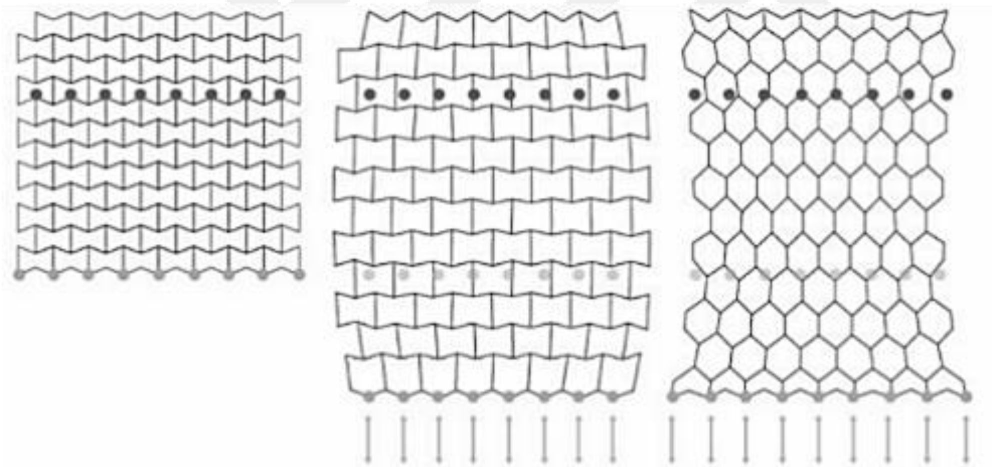

Figure 4.6 : Auxetic structure in relaxed state, auxetic structure in extension, non-auxetic structure in extension (Ordered left to right) – Adapted from Naboni and Mirante (2015).

The prototypes were intentionally set to include various categories (Figure 4.7) to explore not only aesthetic and structural behaviors, but also the practical limitations of 3D printing auxetic metamaterials. Across all trials, the behavior of each prototype under manual tension was analyzed to assess stretchability, return memory, structural response, and porosity. This phase emphasized the relationship between computational intent and physical product, particularly how toolpath settings and infill configurations translate into lightweight, stretchable, and mechanically resilient metamaterials.

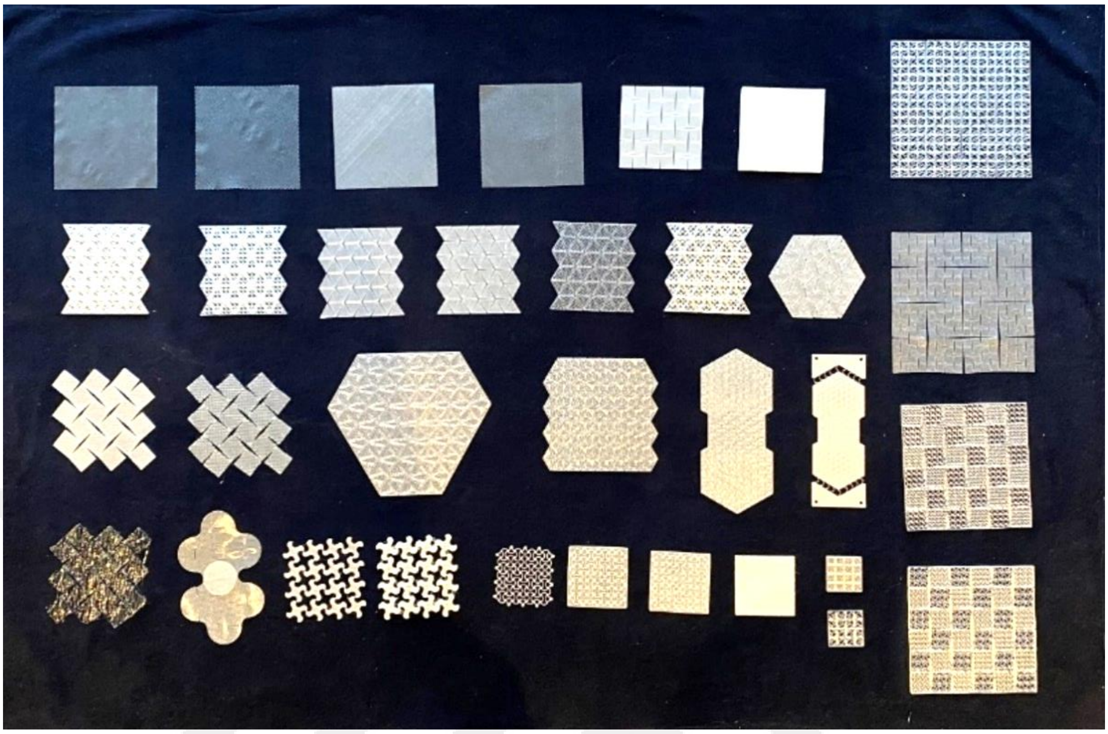

Figure 4.7: Final prototypes of infill-based auxetic TPU textiles.

The tested prototypes were organized into a branching structure that groups configurations by typology while highlighting their instantly observable advantages and limitations during handling and deformation. Rather than offering a performance comparison, this structure functions as a qualitative reading instrument, capturing how different geometric tactics reveal distinct trade-offs in terms of stretchability, stability, print reliability, and porosity. The transition from non-auxetic to more complex auxetic specimens observed across the prototypes reflects established experimental approaches in which internal geometry is regarded as the primary driver of deformation behavior (Usta, 2021). In parallel, the use of typological grouping and hands-on evaluation aligns with fabrication-oriented studies that rely on prototype-based reflection to expose geometric and process-related constraints in 3D-printed auxetic systems (Pehlivan, 2024). This visual structuring supports the broader documentation effort by clarifying how geometric and infill decisions manifest during physical interaction with the 3D-printed specimens (Figure 4.8).

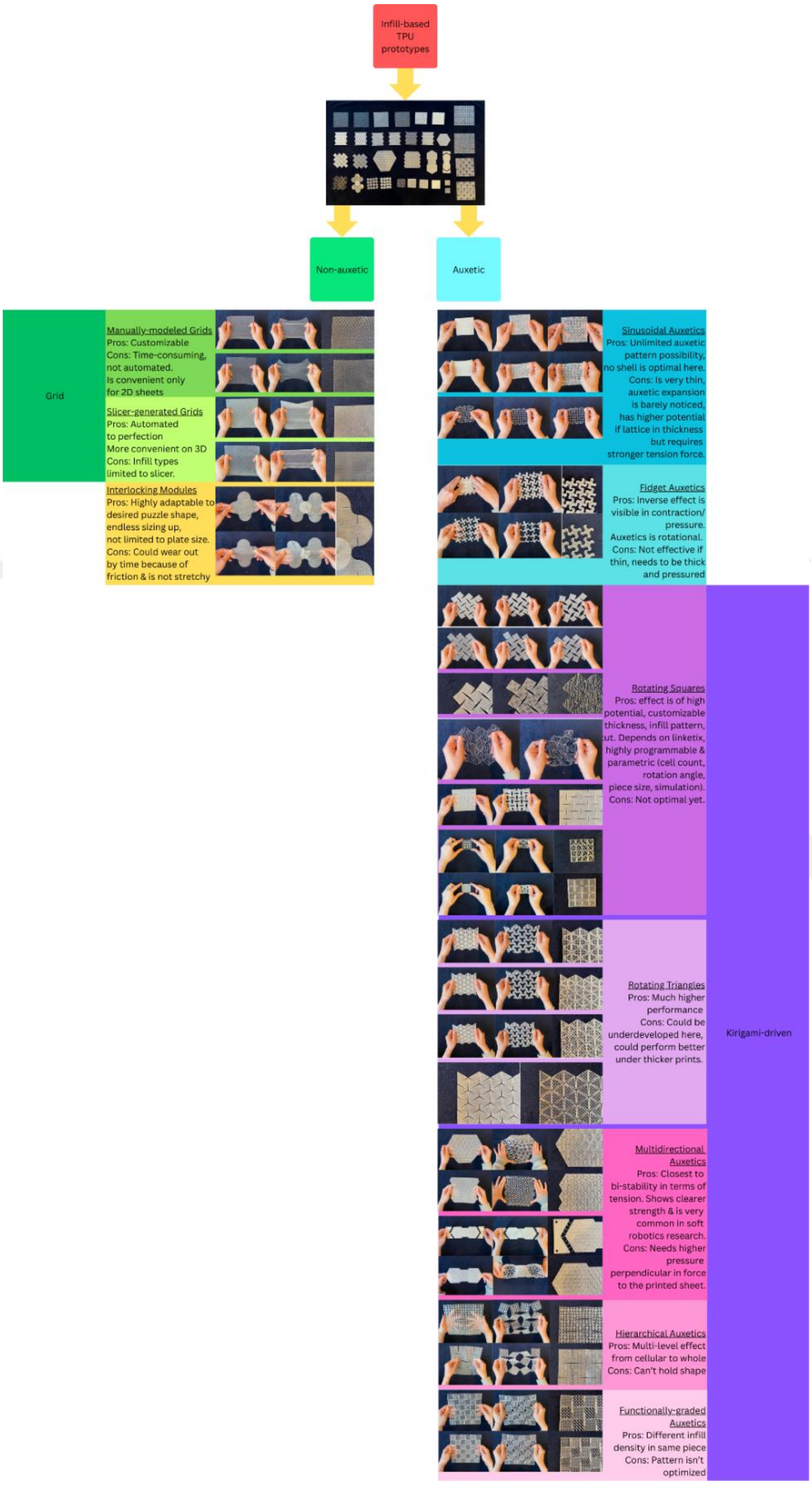

Figure 4.8: Branching of prototype categories and their instantly spotted pros and cons.

4.4.1 Non-auxetic prototypes

Non-auxetic prototypes serve as a baseline for experimenting with TPU and establish the transition from manual modeling to a slicer-dependent workflow. The sequence begins with manually modeled grids, which offer initial reference for evaluating elastomeric printability. Then slicer-generated grids follow, in a shift to parametric slicing logic, automation and toolpath-driven variation. Lastly, interlocking module prototypes are presented to test modularity and assembly logic. Non-auxetic specimens are frequently employed in experimental research to isolate the effects of geometric parameters and fabrication settings before introducing auxetic behavior. This section marks the transition from solid to infill-based printing, providing space for infill logic to be tested independently of auxetic configuration.

4.4.1.1 Manually modeled grids

Manually modeled grids formed the first iteration of the prototype series (Figure 4.9). These grids were constructed as simple square lattices composed of overlapping 45°-line arrays, mirrored and extruded to approximate an infill-like structure. The models were exported as STL files and fabricated directly through the slicer without settings modification. This established a baseline for elastic response through basic deformation, informing early observations on material resilience. This approach allowed direct geometric customization, but it was time-consuming, non-automated, and primarily applicable to flat, two-dimensional sheets.

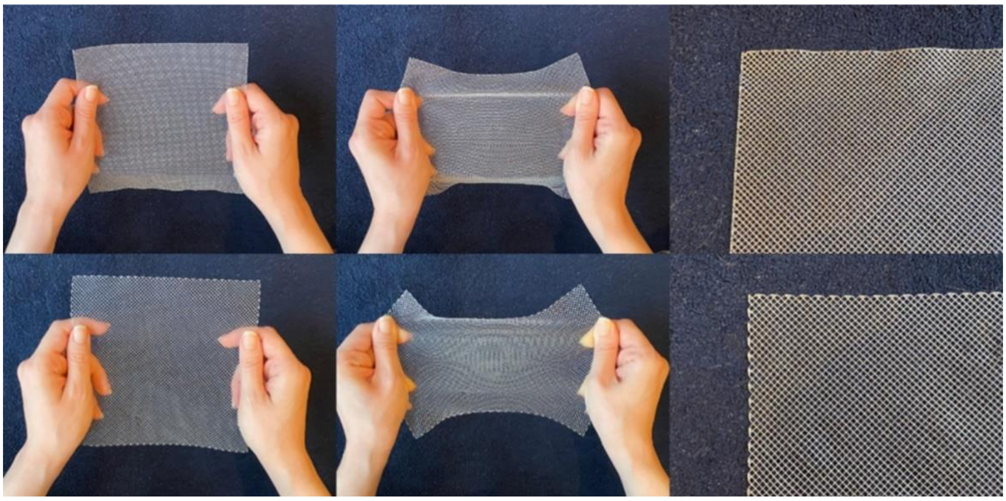

Figure 4.9: Manually modeled textile grid prototype**.**

4.4.1.2 Slicer-generated grids

The second category employed slicer-generated infill patterns, specifically grid and gyroid (Figure 4.10), within solid cube models imported from Rhino. Using Bambu Studio, shells were progressively removed: first the top, then the bottom, followed by wall count variations (3, 2, 1, 0). This experimental setup enabled the conversion of a 100% solid geometry into a porous and breathable mesh using only slicer parameters. Gyroid infill outperformed grid patterns by offering superior shear resistance, faster print times, and lower filament use, which are the same advantages observed by Steck et al. (2024). Dos Reis et al. (2024) noted that infill-driven structural variations influence energy absorption capacities. This transition marked the adoption of gyroid as the study's default infill due to its strength-to-weight ratio, fluidity of deformation, and sustainability profile.

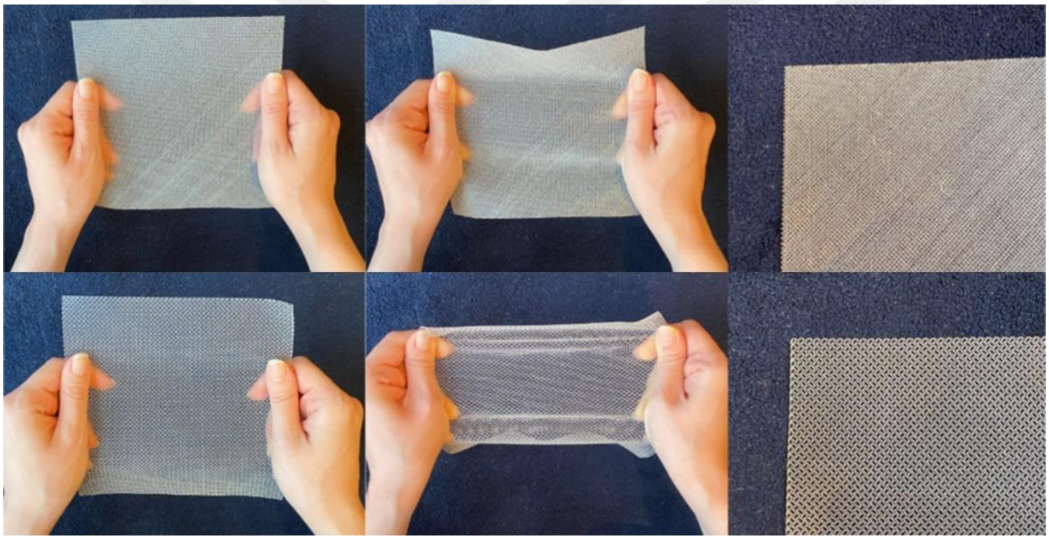

Figure 4.10: Slicer-generated textile 80 % grid density & 50% gyroid density.

These grids introduce a highly automated fabrication logic, allowing the fabrication of complex 3D porous lattices with high consistency and precision. Compared to manually modeled grids, they are significantly more convenient for volumetric geometries, as infill patterns are generated directly from slicing parameters rather than explicit geometric modeling. This method is efficient for repeatability, but the range of micro-architectures is constrained by the toolpath logics of each slicing environment and its predefined native infill pattern library.

4.4.1.3 Interlocking modules

Inspired by wearable 3D-printed fashion, this category examines interlocking lace modules sourced from open-source library Printables (Variable Seams, 2024). These flat, interlocking geometries were altered using gyroid infill, both with and without bottom layers (Figure 4.11). While prints with no bottom shell proved fragile, those retaining a base exhibited structural coherence and retained breathability due to the woven nature of the module. Lee (2022) explored similar TPU systems on fabric substrates, noting that Shore 95A TPU, when printed in translucent line-based configurations, resulted in a “softer volume when the garment is reconfigured” (p. 32). These findings come in parellel with the fabricated fashion module's capacity to form scalable, reconfigurable assemblies driven by geometric compliance. Such assemblies can extend beyond fixed plate dimensions; however, their deformation relies primarily on mechanical linkage rather than material articulation, with potential wear arising from joint friction over time.

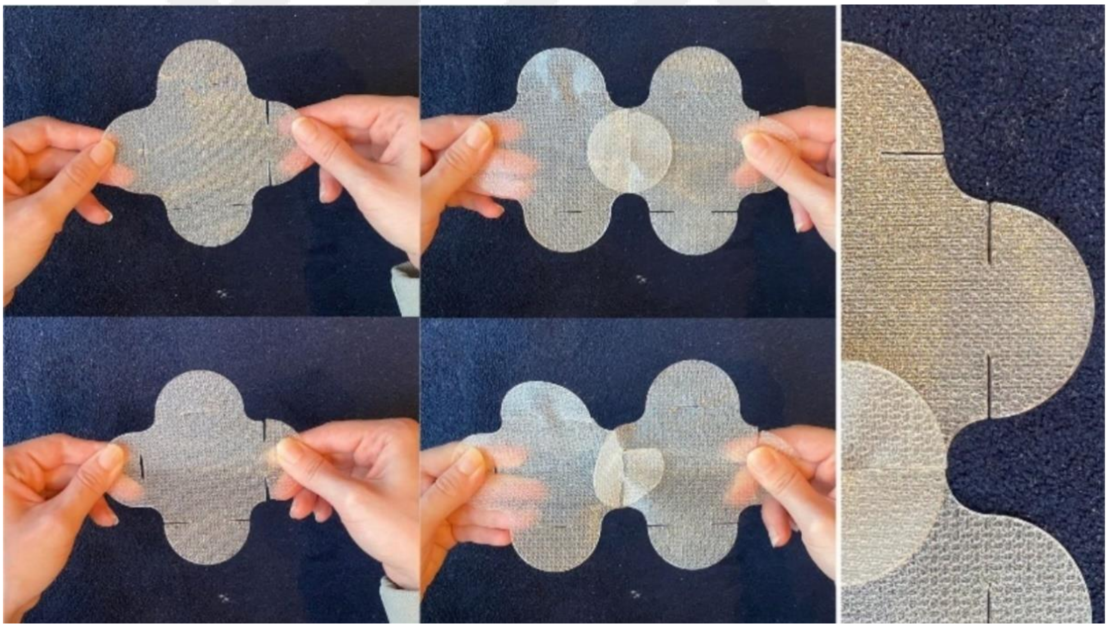

Figure 4.11: Interlocking lace modules with bottom shell & 50% gyroid infill.

4.4.2 Auxetic prototypes

Beyond sinusoidal and fidget auxetics, other categories inspected in this section, including rotating auxetics, multidirectional auxetics, hierarchical auxetics, and functionally graded auxetics, are primarily informed by kirigami design logic. Kirigami-inspired tactics underscore how cut patterns, unit relations, and topological variation can be employed to encode deformation within planar schemes. This perspective aligns with computational kirigami workflows (Figure 4.12) that treat geometry as an additive, rule-based system capable of producing prescribed target mechanisms (Dudte et al., 2023).

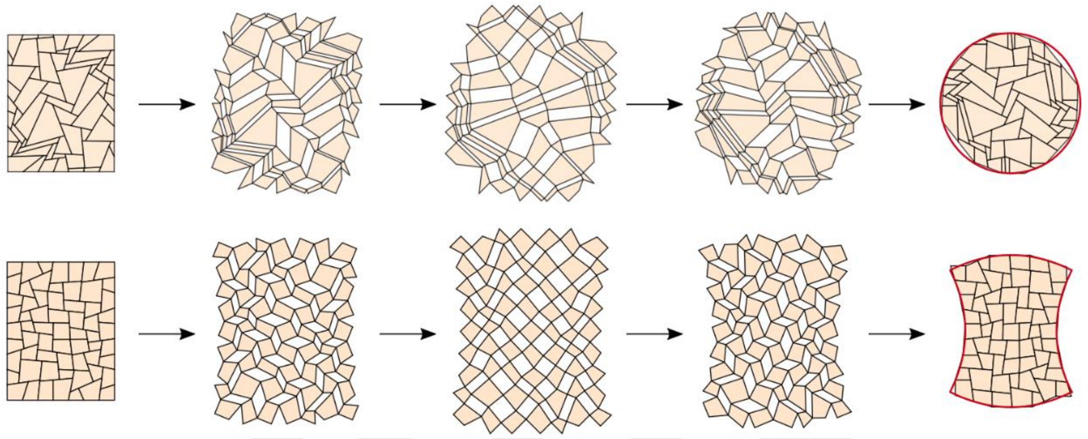

Figure 4.12: Rigid-deployable, compact reconfigurable kirigami patterns that morph from a rectangle to a prescribed target shape – Adapted from **Dudte et al.** (2023).

4.4.2.1 Sinusoidal auxetics

This category explored sinusoidal patterns, avoiding sharp pivot points and using continuous wave geometries instead (Figure 4.13). The concept aligns with Su et al. (2020), who developed auxetic systems that deform uniformly through structured sinusoidal motion. Though the geometry was not yet optimized for infill-based fabrication, the print showed excellent elasticity and mechanical integrity under tension. There is huge potential for designing this type of curvature as an infill for slicer-controlled fabrication. As a hypothesis, it is expected to result in noticeable auxetic expansion if it acts as microarchitecture for any flexible geometry. While these patterns offer extensive geometric flexibility and are adapted for shell-free fabrication, their thin, continuous ligaments tend to limit the perceptibility of auxetic expansion under low tension, suggesting greater deformation potential when implemented as a thicker lattice micro-architecture capable of enduring stronger applied forces.

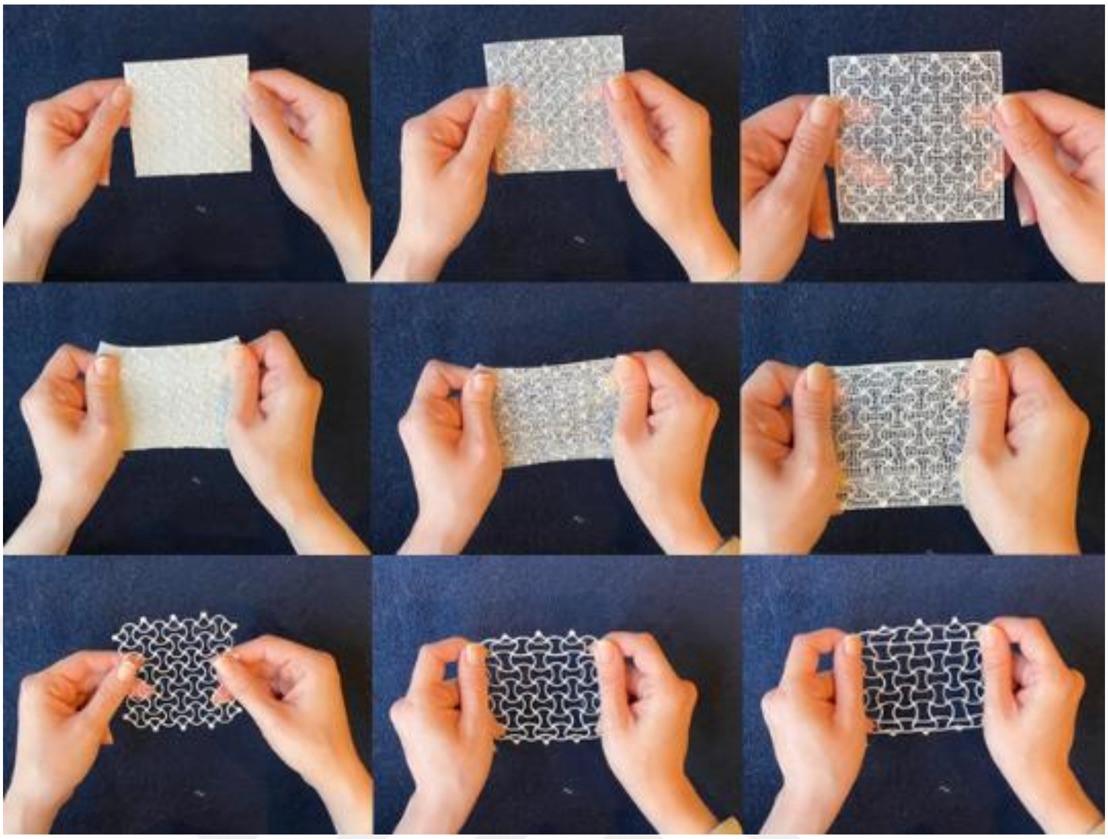

Figure 4.13: Sinusoidal auxetics with shell and infill density variables.

4.4.2.2 Fidget auxetics

This configuration is distinguished from others by its discrete, hinge-driven deformation mechanism, which introduces snap-through behavior and potential bistability. Its auxetic behavior is observable under contraction or pressure, where inverse deformation becomes visually pronounced through discrete rotation. Such behavior is sensitive to thickness and confinement, as thin specimens tend to suppress stability, demanding increased material thickness or applied pressure to activate the envisioned deformation mode. This situates the fidget auxetics (Figure 4.14) within a class of auxetic systems in which deformation arises from geometric restriction and fixed energy barriers (Chen et al., 2021). These configurations are thrive in applications requiring discrete state changes, rather than continuous deformation.

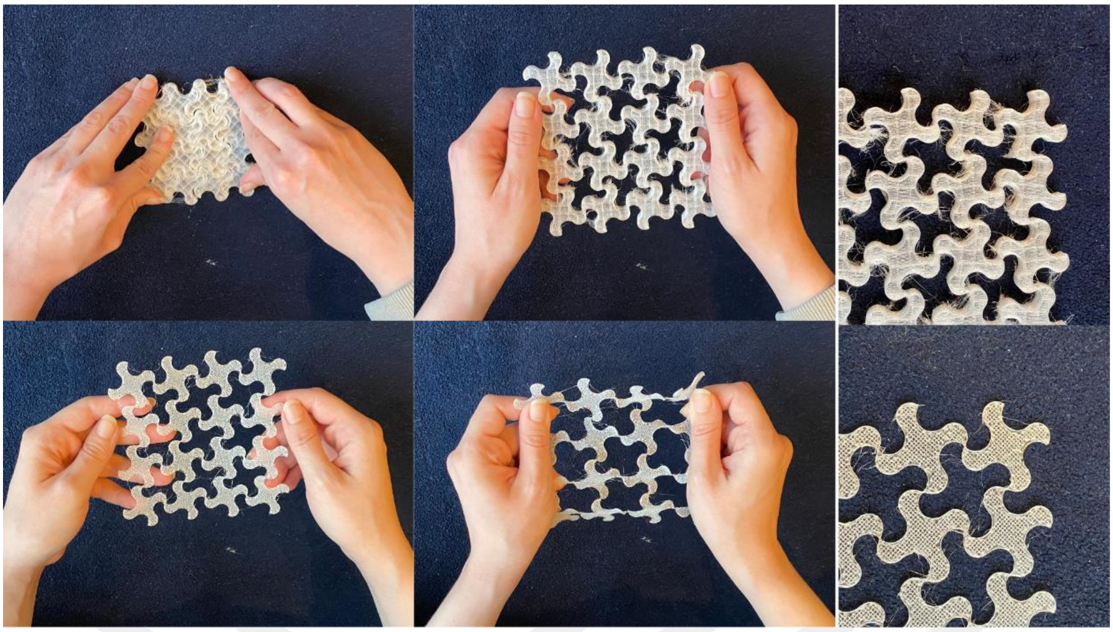

Figure 4.14: Fidget auxetics trial and error.

4.4.2.3 Rotating auxetics

Rotating auxetic patterns were developed parametrically using Linketix plugin within Grasshopper, drawing on pattern families previously acknowledged through exploratory geometric prioritization (Figure 4.15) (Ayech & Akçay Kavakoğlu, 2024). The two top-priority patterns in the list were selected and translated into multiple fabrication variants by systematically adjusting infill density, thickness, and shell conditions. Prototypes were produced both with and without bottom shells to inspect the role of geometric continuity in upholding structural coherence during fabrication and deformation. While specimens without a bottom shell lacked structural stability, configurations with a thin shell exhibited continuity while still enabling bidirectional breathability through a combination of lateral auxetic expansion and internal porosity generated by the infill structure. Among the tested variations, the most coherent response was observed in specimens combining a single bottom shell with 50% gyroid infill, balancing structural integrity with intermediate permeability. Across this set, thickness, infill density, infill type, and shell configuration were treated as interdependent parameters, considering rotating auxetics as infill-based elastomeric micro-architecture.

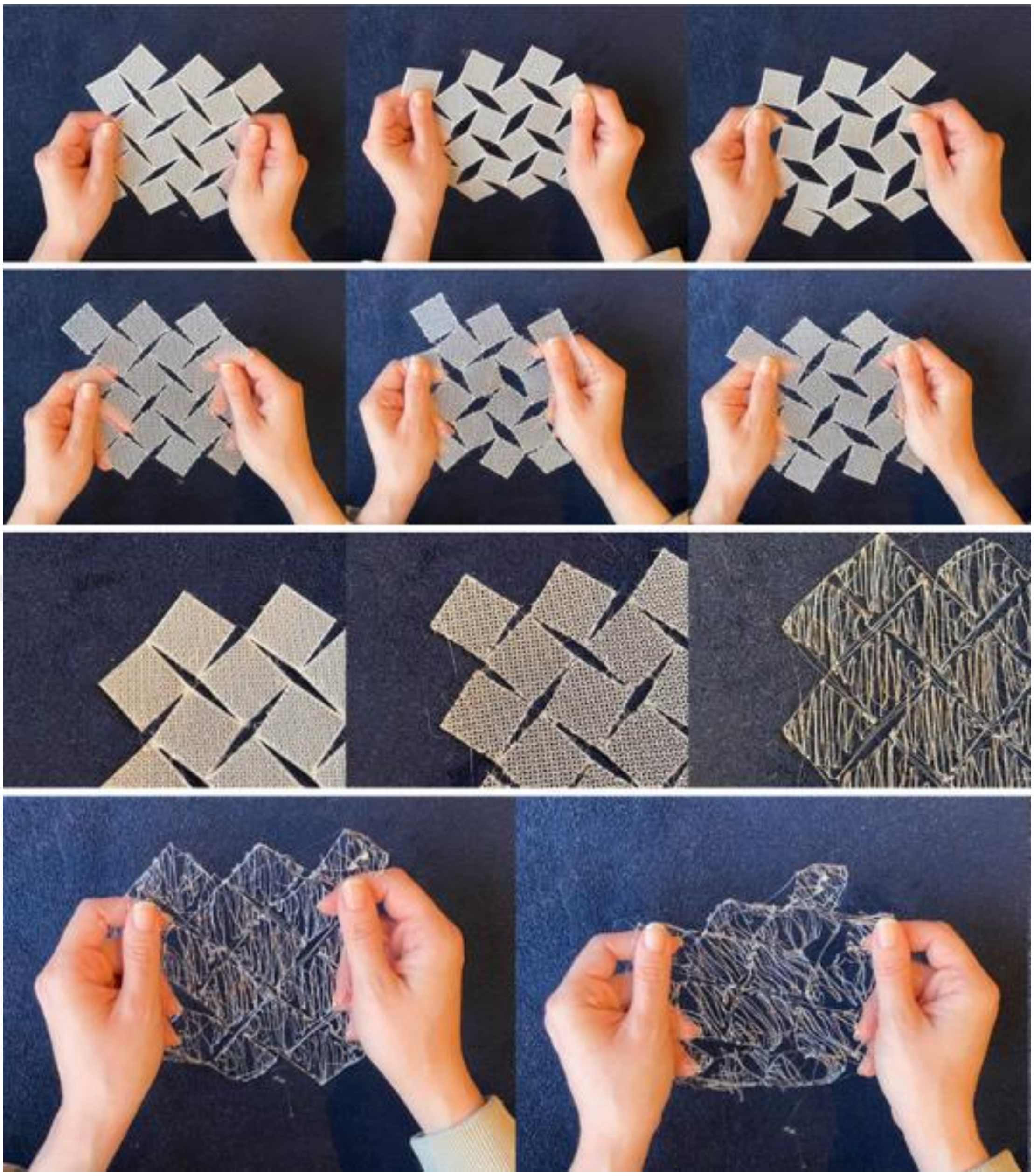

Figure 4.15: Rotating squares – highest priority pattern trial and error.

Rotating squares display high potential due to their strong, visually comprehensible auxetic response, combined with extensive parametric control over cell count, rotation angle, unit size, thickness, and infill logic. Although the parametric definition is highly adjustable, which enables rapid customization and simulation-driven adjustment, the current implementations remain exploratory and are not yet optimized for precise fabrication conditions.

To improve on the structural resistance, custom auxetic definitions were programmed in Grasshopper using mirror array logic. These designs simulated rotating triangle (Figure 4.16) and rotating square geometries (Figure 4.17), controllable in rotation angle and hinge width. Once exported and printed with gyroid infill at densities as low as 15%, these prototypes showed enhanced shear resistance and aesthetic expression. The parametric flexibility of the design matrix allowed the geometry to adapt to structural demands while remaining breathable.

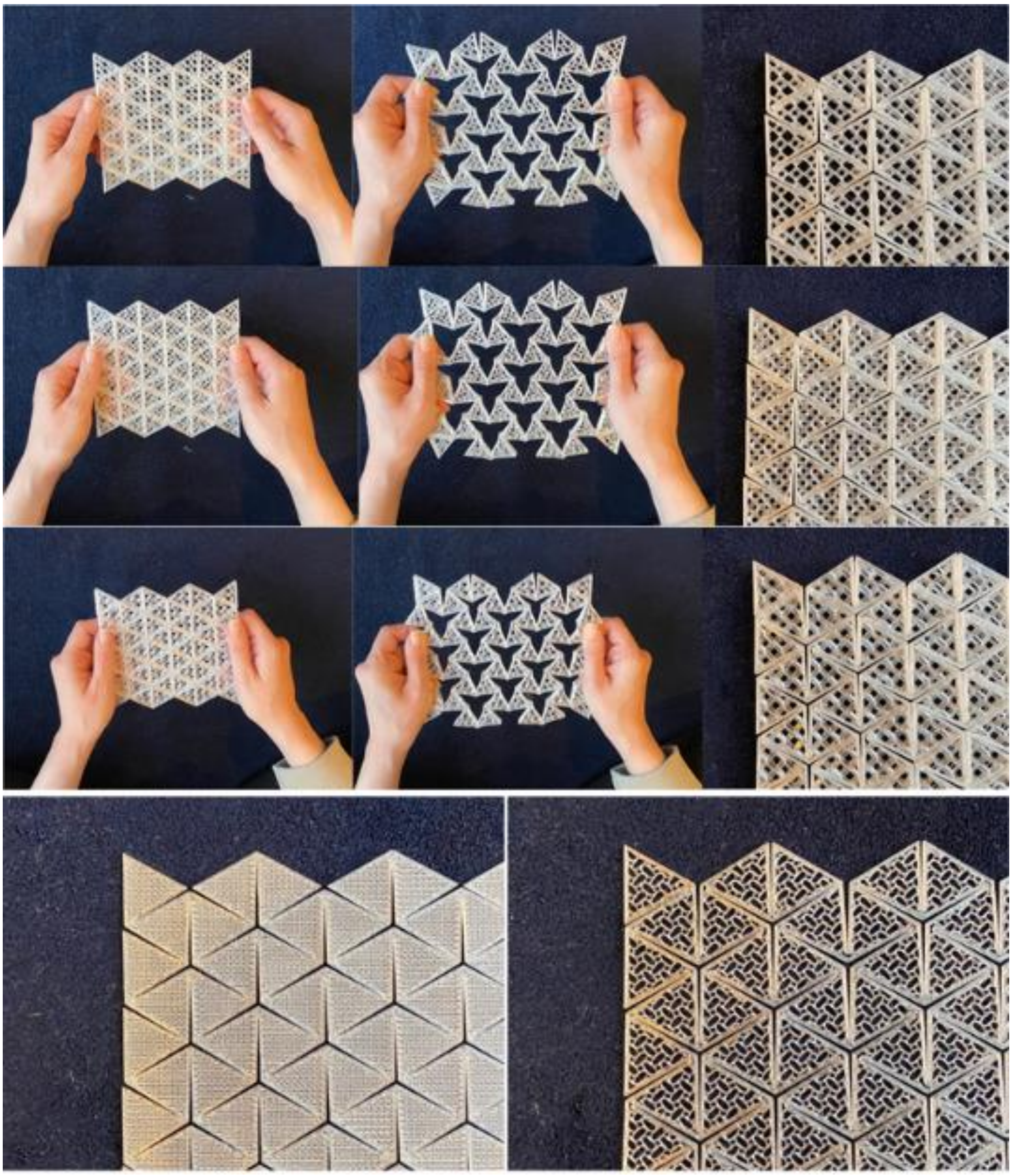

Figure 4.16: Rotating triangles with various infill density and infill pattern.

Rotating triangles exhibit higher deformation responsiveness and structural stability, but their auxetic behavior could be further improved by increased thickness and refined infill settings.

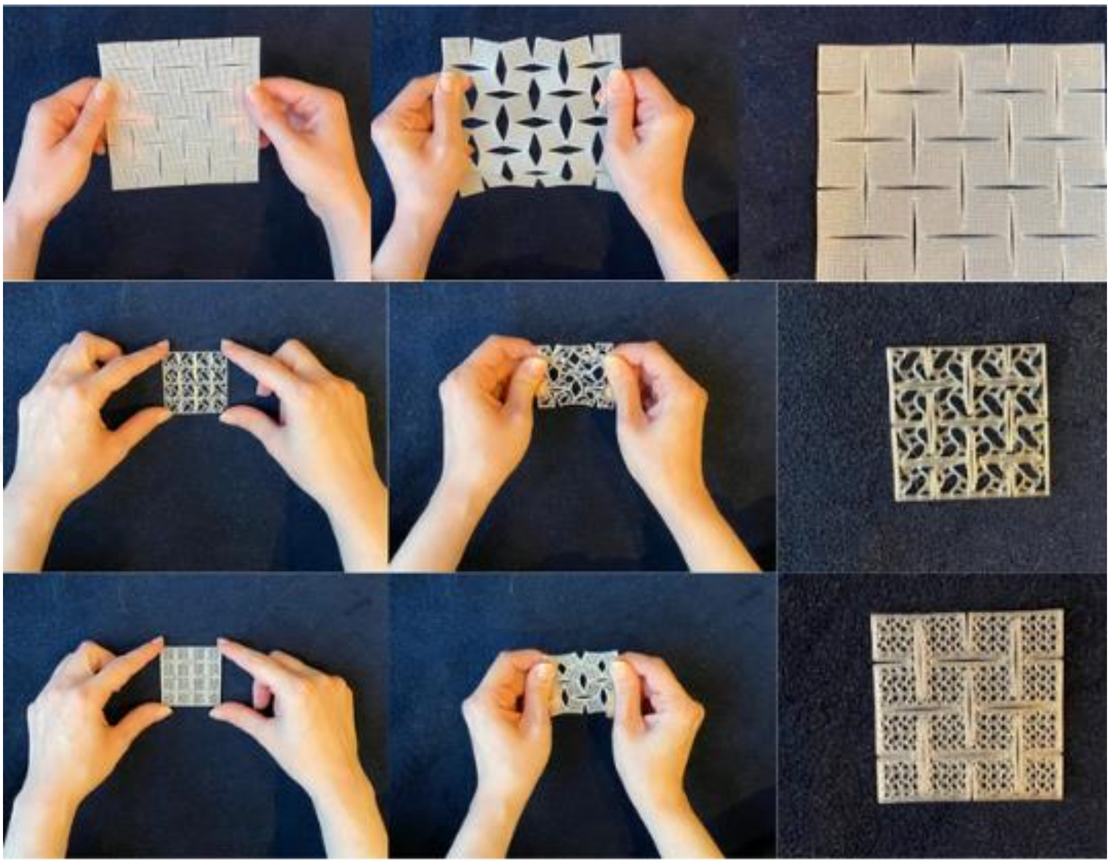

Figure 4.17: Rotating squares including micro-scale.

The second rotating squares configuration focused on closely observing the behavior of the system at the micro-architectural level, as illustrated in the above close-up of the printed specimen. The magnified scale revealed that auxetic expansion is governed not only by the rotation of individual units but also by the continuity and resolution of their linkages. Zooming in on the micro-scale emphasized fabrication-sensitive effects, such as local stiffening at joints and variations in pore opening, underpinning the role of infill-based control in shaping the emergent behavior of rotating auxetic metamaterials. As described by Grima and Evans (2000), rotating-square auxetics are mechanically efficient due to their negative Poisson's ratio, a quality effectively demonstrated in these prints. This category mimicked the grasshopper simulation very accurately (Figure 4.18), suggesting mechanical behavior of highest potential.

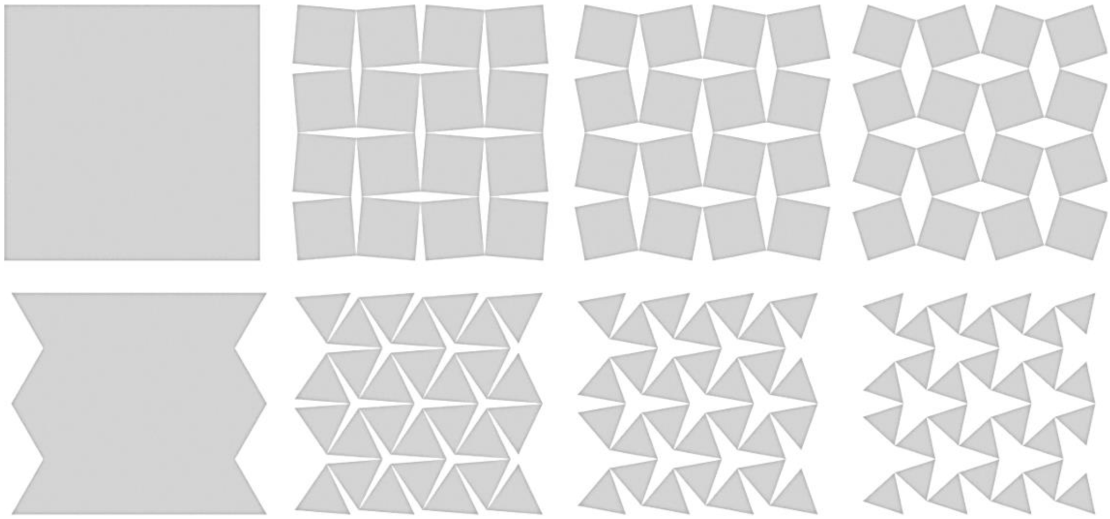

Figure 4.18: Visual programming simulation of rotating auxetics.

4.4.2.4 Multidirectional auxetics

These prototypes were developed as kirigami-inspired polygonal systems designed to endure large, multidirectional deformation through rotational, snap-through motion, replicating cut-pattern logics similar to those studied by Chen et al. (2021). While prior studies verified bistability using laser-cut rubber or rigid sheet materials, this version adapts corresponding geometries to TPU through additive manufacturing. Specimens unveiled metastable deformation behavior, in which temporary shape preservation occurred under applied tension or pressure without achieving fully stable alternate states, reflecting the influence of material elasticity rather than geometric lockup. Multidirectional auxetics established higher apparent strength under tension and clearer deformation, a behavior frequently utilized in soft robotics research. Effective stimulation required relatively higher pressure perpendicular to the specimen, highlighting a constraint in sensitivity to lower forces. Regardless, this category yielded the most architecturally robust prototypes in the study, illustrating how kirigami-inspired auxetic logics can be decoded into TPU-based infill assemblies while maintaining controlled, repeatable deformation behavior (Figures 4.19 & 4.20).

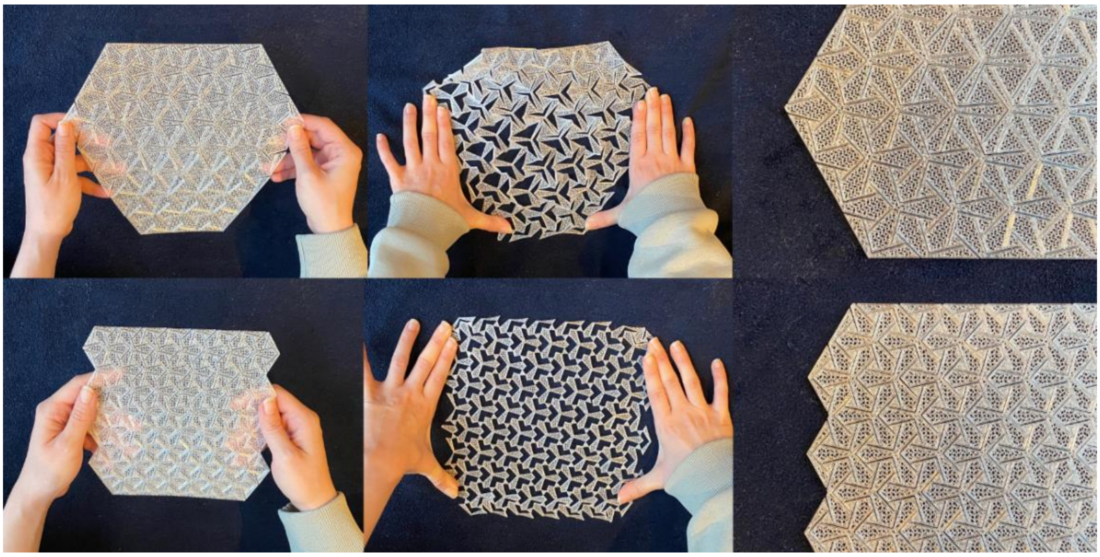

Figure 4.19: Multidirectional auxetic dome.

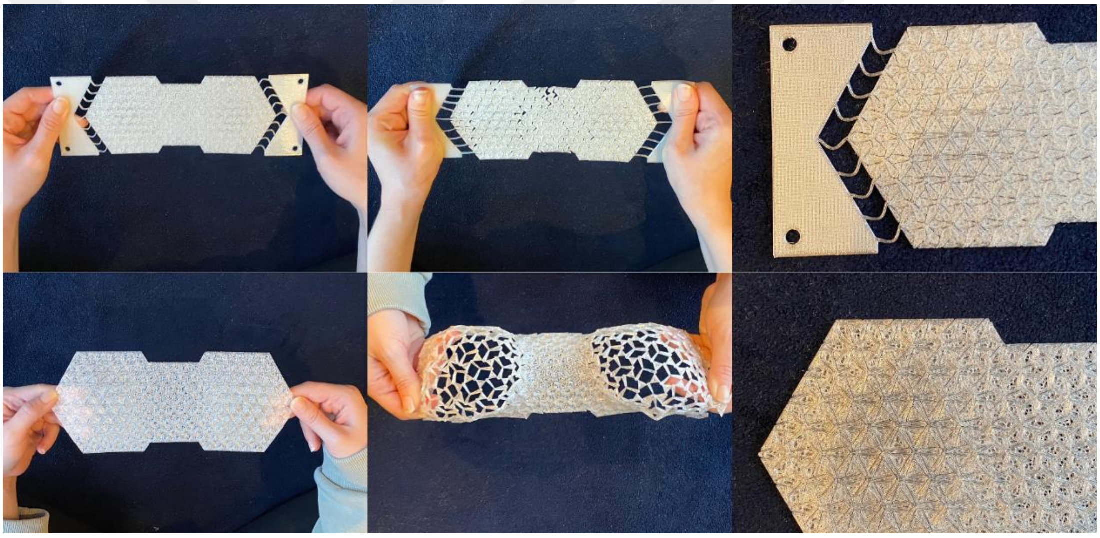

Figure 4.20: Multidirectional auxetic double dome.

4.4.2.5 Hierarchical auxetics

This category introduced deformation across multiple geometric scales by nesting auxetic units within larger surfaces, maintaining a uniform infill density across the whole system (Figure 4.21). This strategy enabled coordinated cellular-to-global deformation and improved shear resistance. Observations indicate that effective deformation distribution in this category depends on fabrication thickness sufficient to sustain the deformed configuration.

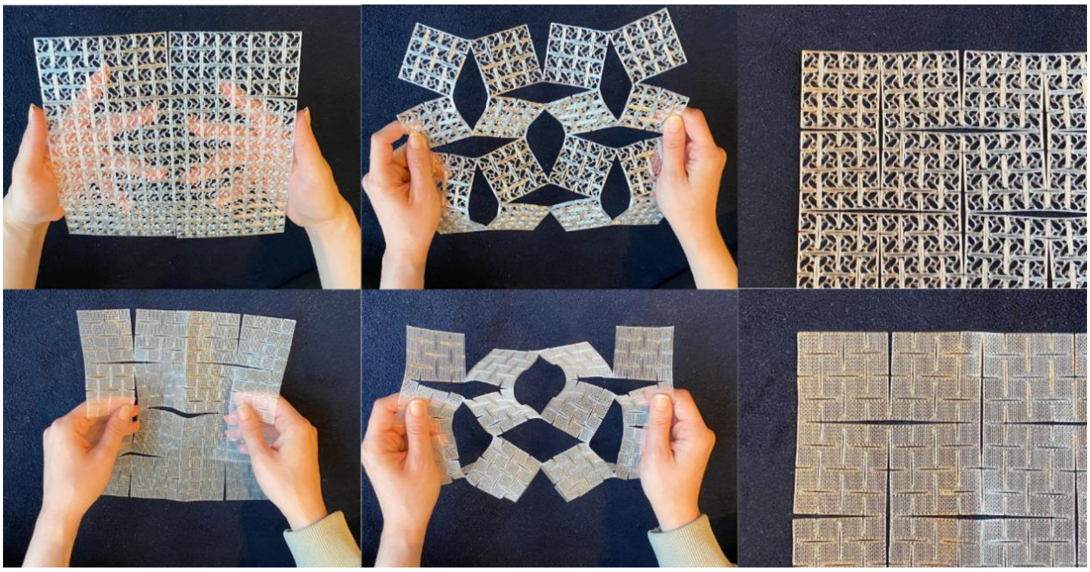

Figure 4.21: Hierarchical auxetics with uniform infill density.

4.4.2.6 Functionally-graded auxetics

This category considered how spatial variation in infill density affects deformation within a single auxetic specimen (Figure 4.22). Inspired by FGM strategies (Stock, 2021; Wevolver, 2024), configurations revealed trade-offs between strength, porosity, and fabrication efficiency.

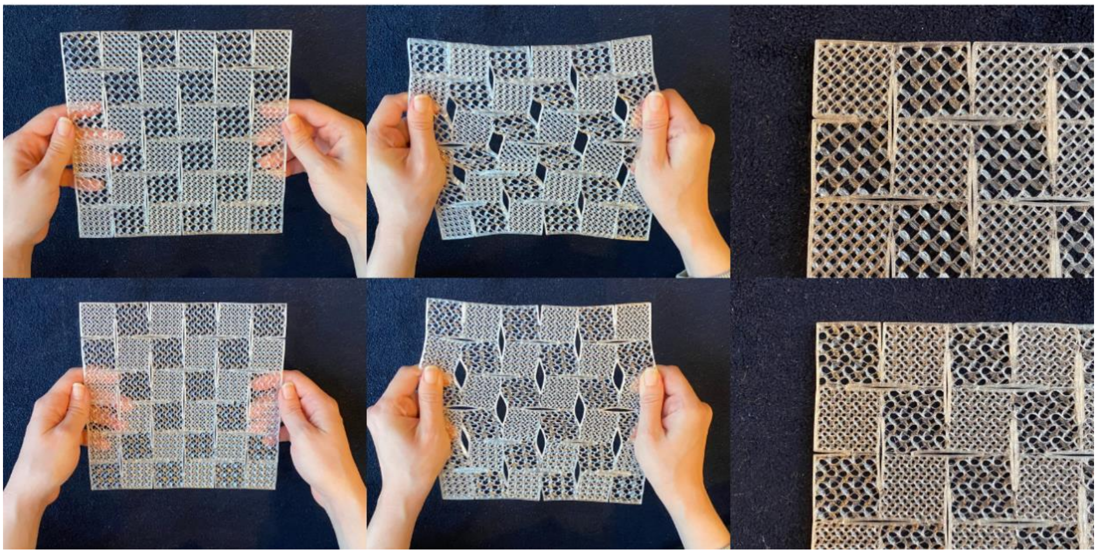

Figure 4.22: Functionally graded auxetics with hierarchical infill density.

While graded infill density improved shear resistance and held shape better than hierarchical auxetics, performance remained dependent on overall material distribution, and the auxetic pattern itself was not yet optimized for graded deployment. Experiments with different patterns, including 3D honeycomb, cross-hatch, and gyroid, showed variation in print time and stretchability, with gyroid still yielding the best balance between curvature, deformation range, and resilience. The ones where infill density varied revealed stronger shear resistance, but the thickness was also a variable. An interesting finding worth mentioning was noticed when switching infills: 3D honey comb infill surpasses gyroid's cost effectiveness when it is used as a 3D infill; it requires less print time and less filament. This results in an urge to discover and design more sustainable infill patterns.

Towards the end of this stage, all of the fabricated specimens are listed within a prototype documentation matrix (Figure 4.23). The matrix functions as a synthesis tool that validates the experimental knowledge produced throughout this chapter by recording geometric typologies, infill strategies, material parameters, and perceived deformation behavior. Rather than ranking or evaluating performance, this matrix provides a well-structured overview of constants as well as variables in the geometry and fabrication strategy used in the process, revealing how slight variations could redirect auxetic behavior. Beyond cataloging separate prototypes, this documentation matrix shapes the core of a comparative framework that makes associations between design intent, fabrication strategy, and observed behavior readable across the entire prototype set. By aligning non-auxetic baselines with progressively complex auxetic typologies, it enables cross-reading between categories and reveals how shifts in infill logic, thickness, and shell configuration convey deformation behavior independently of geometry alone. In doing so, the matrix reports a wider gap in auxetic metamaterials research, where experimental results are often reported in isolation without a unified structure for comparison. Its replicable format combines geometric, fabrication, and behavioral parameters into a transparent reference that supports collective interpretation, permitting future studies to adopt, extend, or recalibrate the method while preserving evaluation and design-to-fabrication reasoning.

Category & Factor	Manually-modeled Grid	Slicer-generated Grid	Interlocking Module	Sinusoidal Auxetic	Fidget Auxetic	Rotating Squares	Rotating Triangles	Multidirectional	Hierarchical	Functionally-graded
Auxetic behavior	Non-auxetic	Non-auxetic	Non-auxetic	Auxetic	Auxetic	Auxetic	Auxetic	Auxetic	Auxetic	Auxetic
Kirigami-inspired	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes
Infill type	None	Grid/Gyroid	Gyroid	Grid/None	Grid	Gyroid	Gyroid/ Crosshatch/ 3D Honeycomb	Gyroid	Gyroid	Gyroid/ Crosshatch/ 3D Honeycomb
Infill density	None	80%/50%	50%	15%	50%	25%/50%	25%	25%/50%	10%	15% & 10%
Infill direction	45º	45º	45º	45º	45º	45º	45º	45º	45º	45º
Dimensions x,y,z (mm)	85,85,1.5	85,85,1.5	100, 100, 0.6	85.25.85.25,2.5	150, 150, 0.3 150, 150, 0.9	120,120,1.5	125.130,1.5	160, 140, 2 210,210,0.9	200,200,3	180,180,4.5
Top:Bottom Shell	0:0	0:0	0:1	0:5 0:2 0:1 0:0	0:1	0:0	0:0	0:0 0:1	0:0	0:0
Print Time	8m	12m/23m	16m	25m	10m	1h11m/ 1h38m	50m 53m 46m	2h32m 1h45m	4h39m	3h14m/ 3h18m/ 3h11m
Stability	Monostable	Monostable	Monostable	Monostable	Monostable / Potential Bistability	Monostable	Monostable	Monostable / Potential Bistability	Monostable	Monostable
Elastic Recovery	High	High	Low	High	Thick: Fast self-recovery Thin: Fail	Thick: High Thin: Fail	High	High	Fail	High
Stiffness	Low	High/Low	Medium	High/Medium/ Low	High/Low	High/Medium/ Low	High	Very high	Low	Very high
Anisotropy/ Isotropy	Isotropy	Isotropy	Anisotropy	Weak anisotropy	Isotropy	Near isotropy	Near isotropy	Symmetry-dependent	Direction-dependent	Direction-dependent
Deformation mechanism	Strut bending	Toolpath-driven bending	Mechanical interlock	Elastic curvature inversion	Snap-through rotation	Rigid-unit rotation	Rigid-unit rotation	Multi-axis rigid-unit rotation	Multi-scale hinging	Gradient-controlled hinging
Motion type	Continuous	Continuous	Semi-discrete	Continuous	Discrete	Continuous	Continuous	Continuous	Continuous	Direction-dependent
Energy behavior	Elastic	Elastic	Elastic + friction	Elastic	Energy barrier	Elastic	Elastic	Elastic	Elastic (multi-stage)	Elastic (graded)
Geometric logic	Orthogonal grid	Directional grid	Locking modules	Continuous ligaments	Hinges / locks	Rotating rigid cells	Rotating rigid cells	Rotating polygons	Nested unit cells	Density / scale gradient
Role in research	Baseline reference	Fabrication control	Transition system	First auxetic case	Adaptive / interactive	Canonical auxetic	Canonical auxetic	Geometric exploration	Performance tuning	Optimization strategy
Primary visual cue	Rectilinear ribs	Toolpath lines	Locked joints	Wavy ligaments	Snap hinges	Square cells	Triangular cells	Polygonal cells	Nested cells	Gradient density
	Non-auxetic			Auxetic						
	Grid					Kirigami-driven				

Figure 4.23: Prototype documentation matrix.

4.5 Pneumatic Deformation: An Experimental Observation

Earlier research has observed auxetic membranes under inflation; compared to their conventional counterparts, auxetic patches exhibited larger deformation ranges. This property has been vastly linked to biomedical applications such as enhanced compliance during bladder tissue healing (Venkata et al., 2024). Building on this knowledge (Figure 4.24), the final stage of this thesis introduces a preliminary inflation-based deformation study using nominated TPU auxetic specimens attached to inflatable substrates.

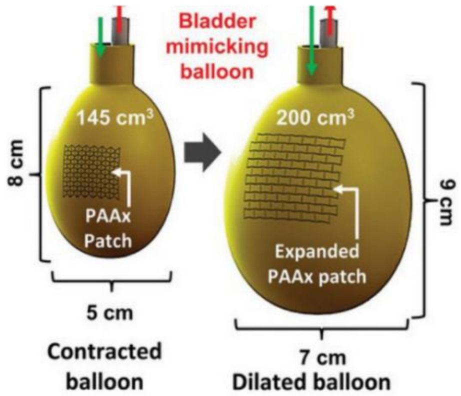

Figure 4.24: Inflated auxetic membrane patch attached to a balloon substrate, illustrating large deformation capacity – Adapted from Venkata et al., (2024).

The experiments presented in this section serve as an observational extension of the prototypes documented previously in the matrix rather than as a performance-based assessment. By subjecting selected specimens to pressure, this stage of the methodology explores deformation modes and out-of-plane behavior that cannot be comprehended exclusively via tension (Figure 4.25 & Table 4.2).

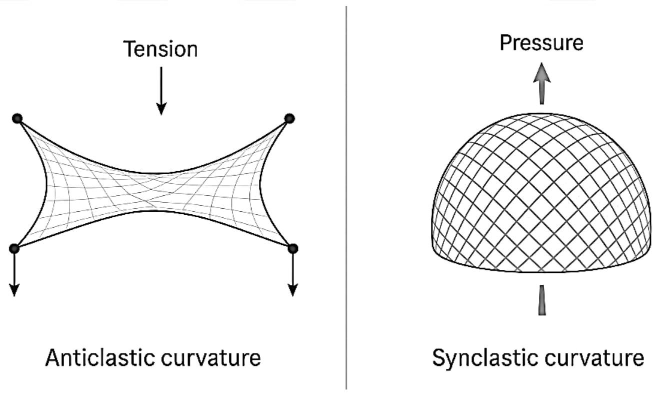

Figure 4.25: Tension vs pressure curvature.

Table 4.2: Tension vs. pressure logic.

Aspect	(Tension)	(Pressure)
Driving Force	External Tension (pulling)	Internal Pressure (pushing)
Curvature Type	Anticlastic ($K < 0$)	Synclastic ($K > 0$)
Structural Logic	Surface Minimization	Volume Expansion
Material Behavior	Contracts laterally under stress	Expands laterally (auxetic)

To conclude this chapter with a qualitative assessment, three prototypes that stood out, multidirectional auxetics, rotating square auxetics, and rotating triangle auxetics, were selected for a basic pneumatic deformation observation through simply inflating a balloon. These specimens exhibited promising behavior during earlier manual tension trials and were therefore identified as demonstrative configurations for stretchable, lightweight, and structurally resilient auxetic metamaterials. Their combined mechanical performance, print integrity, and deformation response set them apart as the strongest candidates among all prototyped categories. Correspondingly, the nominated specimens match the highest-priority categories within the exploratory prioritization list based on geometric and visual characteristics.

For the observation, the nominated prototypes were adhesively attached to the surface of balloons and subjected to incremental inflation (Figure 4.26).

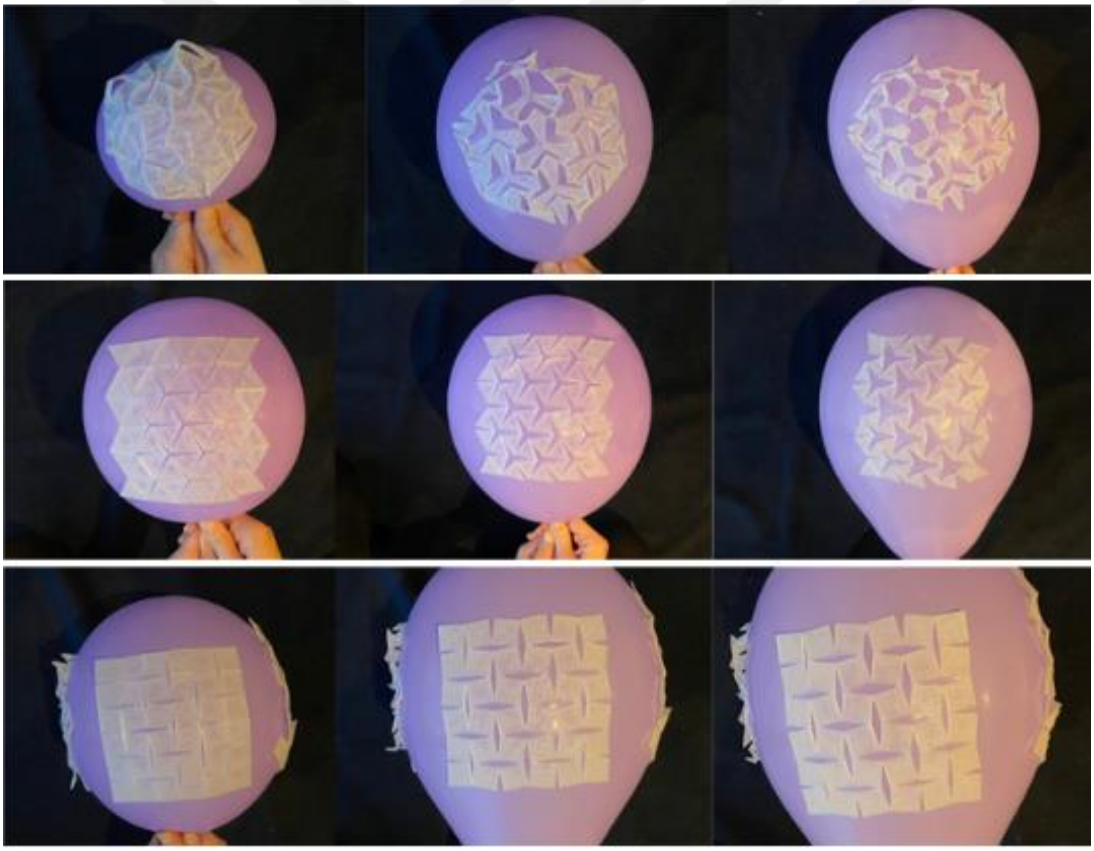

Figure 4.26: Pneumatic actuation of patterns with highest exploratory priority.

The purpose was to trigger pneumatic actuation, allowing the printed TPU systems to respond to applied internal pressure in real-time. The infill was exposed to unprecedented levels of deformation as the maximum pneumatic actuation point was reached. This method accentuated the potential of integrating auxetic patterns within responsive or pneumatic systems. Probable applications include aerospace uses, adaptive facades, soft robotics, or wearable structures.

The results were promising: each geometry exhibited a consistent auxetic response even under extreme inflation (Figure 4.27), returning back to shape when deflated.

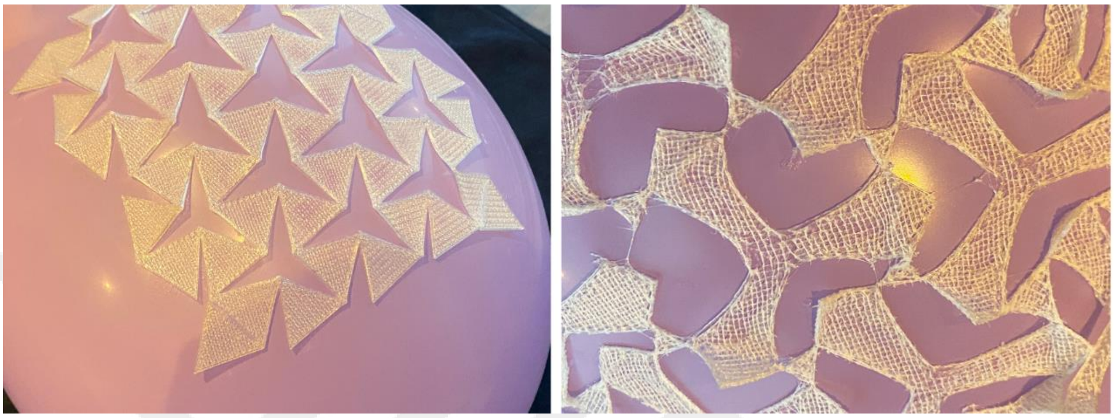

Figure 4.27: Extreme pneumatic actuation close-up.

The pneumatic deformation tests confirmed the robustness of TPU 95A and the uniformity of fabrication achieved through the slicer-controlled infill strategies and geometric logics established in this chapter. The qualitative visual feedback obtained through inflation helped validate earlier observations from manual experiments, indicating that deformation behavior arises from the internal micro-architectural configuration rather than from external mechanical articulation. Among the fabricated categories, multidirectional auxetics as well as rotating square and rotating triangle auxetics exhibited the most coherent deformation, and therefore were nominated for inflation. The results indicate their suitability for further investigation under controlled pneumatic actuation and at greater or more sophisticated scales.

The observations related to the pneumatic assessment are not meant to feed back into the design-to-fabrication workflow but to elaborate the qualitative understanding of auxetic deformation beyond the manufacturing and documentation contexts (Table 4.3).

Table 4.3: Observations on inflated specimens.

Observation	Description	Explanation
Synclastic bulging	The overall mesh inflates outward forming a smooth convex surface.	Auxetic geometry expands uniformly; positive Gaussian curvature.
Edge stabilization	Fixed anchors hold the perimeter, so the center bulges most.	Boundary conditions resist lateral movement.
Uniform pattern dilation	Internal pattern scales slightly with pressure, maintaining connectivity.	The mesh's negative Poisson's ratio leads to isotropic expansion.
Curvature concentration near center	Higher curvature at central region, flattening toward edges.	Similar to real pneumatic domes; pressure equalizes; edges resist.

When situated alongside practical cases dealing with material behavior, the vision behind this deformation experiment can be visibly perceived. Early research observed deformation by analogue experiments in which gravity, tension, or compression acted upon membranes, textiles, and cable-net assemblies, exposing material behavior under forces and emphasizing the role of geometric reason in deformation response (Chilton & Isler, 2000; Otto & Rasch, 1996; Nerdinger, 2005). These examples set deformation as a consequence of material configuration rather than an imposed condition. Following research extended these studies toward kinetic and pneumatic systems, where air pressure acts as a core driver of deformation in lightweight, materially efficient assemblies, (Warmburg & Meister, 2025). Correspondingly, computational design treated deformation as an embedded response, emphasizing that material behavior could be encrypted in geometry, material selection, and fabrication logic rather than controlled externally (Menges, 2012a; Menges & Reichert, 2012b). Auxetic metamaterials make great sense in this context due to their inherent in-plane expansion and out-of-plane synclastic curvature, which can be regarded as an extension of two-dimensional auxetic deformation. This directly links micro-architectural geometry to curvature behavior (Davini et al., 2017), and supports the view that auxetic behavior originates from geometry rather than from base material properties alone (Lakes, 2017).

More recent research shows that auxetic membranes and lattices can exhibit predictable curvature, wrinkling, and large deformations under internal pressure, proving that responses to inflation are ruled by patterned topology and cellular logic. Inverse-design has been employed for programmable deformation under inflation

(Eguchi et al., 2022). Additional studies confirm that bistable auxetic assemblies facilitate deployment (Wang et al., 2025) and that re-entrant auxetic lattices are allow controllable deformation under pressure and compression (Farshbaf et al., 2025). Material response in such systems strongly depends on lattice density, topology, and material elasticity. For example, patterned tile-based systems can be modified to regulate stress distribution and curvature response, underpinning the role of micro-architecture in governing metamaterials (Soyarslan et al., 2022). In practice, these principles are manifested in adaptive inflatable envelopes and responsive architectural systems (Flor, 2020), as well as computational knitting trials where response is defined by geometry-driven fabrication strategies (Zaha Hadid Architects, 2018). The role of this inflation experiment is not to introduce a new actuation model or to execute quantitative validation, but to situate observed deformation tendencies within established curvature-related research (Figure 4.28), signifying potential directions for future inquiries.

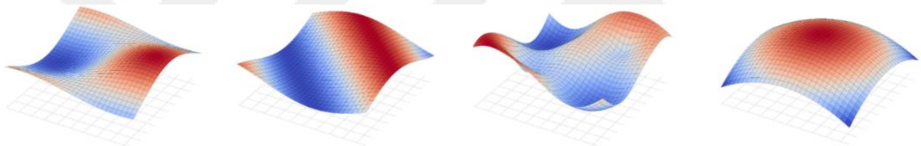

Figure 4.28: Comparison of curvature logics – anticlastic, adaptive, bending-active, synclastic (Ordered left to right).

A visual programming definition portraying potential synclastic bulging under programmable pressure induction was developed; it remains basic but is included to show potential digital simulation progress (Figure 4.29). Table 4.4 displays the parameters defining the deformation.

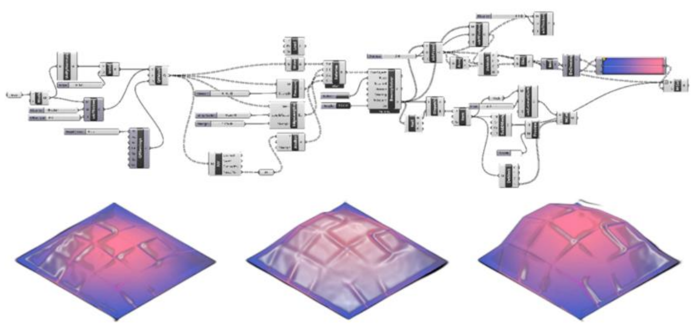

Figure 4.29: Visual programming definition for inflation-based deformation.

Table 4.4: Digitally simulated pneumatic actuation parameters and values.

Goal	Component	Typical Value
Edge Length	Elasticity	1.0
Bending	Flexural stiffness	0.3
Pressure (sealed mesh)	Pressure value	0.5–3.0
Unary Force (open mesh)	Force magnitude	0.05–0.2
Anchors	Strength	10–50

To position the outcomes of this thesis within broader academic and methodological context, figure 4.30 summarizes primary and secondary auxetic properties discussed throughout the literature and figure 4.31 plots all cited works within a reference synthesis. Plain nodes denote literature review sources, orange strokes indicate experiment citations, blue strokes represent pneumatic or non-planar deformation studies, and the pink stroke marks the author's thesis-related publication.

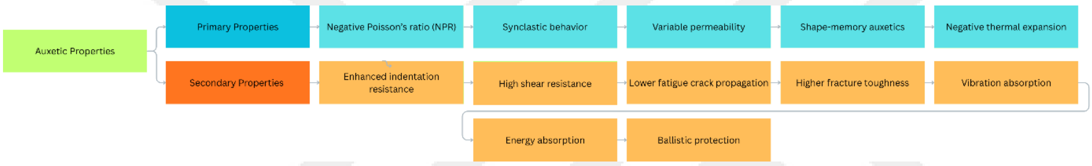

Figure 4.30: Classification of primary and secondary auxetic properties – Adapted from Periyasamy and Srinivasan (2025).

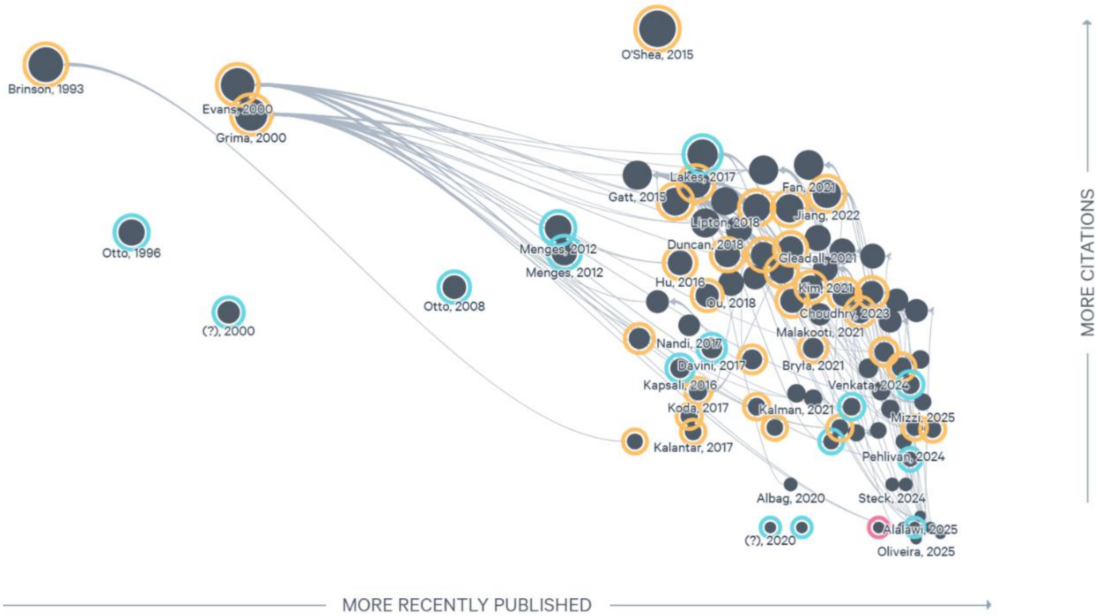

Figure 4.31: Reference synthesis of works cited throughout the thesis.

5. CONCLUSION

The contributions of this thesis are grounded in an experiment-driven methodology centered on infill-based fabrication of auxetic metamaterials with systematic prototype documentation, complemented by a preliminary deformation observation probing geometric responses under volumetric inflation and indicating potential directions for future investigations involving controlled pneumatic loading and quantitative deformation analysis. The research began from a speculative premise: what if the internal structure of a material, its infill, could act as the basis for creating configurations that breathe, stretch, and deform with intent? From this inquiry emerged a design-to-fabrication methodology centered around experiment-driven prototyping. It reframed infill not as a secondary or passive parameter, but as programmable micro-architecture through which mechanical response and material behavior could be intentionally encrypted. In this sense, geometry was treated not merely as form, but as an operative system governing how material responds to applied forces.

The methodology encompassed hands-on exploration, computational pattern generation, digital simulation, physical prototyping, and iterative feedback. Initial investigations focused on planar auxetic geometries defined by negative Poisson's ratio behavior. Parametric modeling environments enabled the systematic manipulation of unit geometry, rotation logic, and pattern density, allowing deformation tendencies to be examined prior to fabrication. Within this stage, an exploratory prioritization of pattern families was established based on geometric clarity, deformation legibility, and frequency in literature, sorting patterns from high to low potential to be tested. These geometries were first materialized using rigid PLA to validate geometric articulation, print fidelity, and deformation logic independently of elastic material behavior, establishing a baseline for subsequent transitions. The research then shifted toward elastomeric systems through silicone casting and infill-based TPU 3D printing. The shift towards TPU marked a critical stage in which flexibility, breathability, and elastic recovery could be examined under manual deformation. Within this phase, the slicing environment emerged as a fundamental design space. TPU-specific fabrication strategies were developed by calibrating wall counts, infill densities, extrusion speeds, and toolpath logic to mitigate common defects such as stringing, delamination, and loss of structural coherence. Through sequential iterations, the study demonstrated how subtle tunings in slicing parameters could significantly influence deformation behavior, stressing the sensitivity of auxetic performance to both micro-architectural and fabrication decisions. Across this process, a range of non-auxetic and auxetic typologies was developed and documented.

Among all prototypes, from simple grids to complex auxetic geometries, rotating square and rotating triangle configurations consistently exhibited high deformation responsiveness and structural resilience, while multidirectional auxetics revealed potential metastable behavior reliant on thickness and material elasticity. Hierarchical and functionally graded auxetics demonstrated how deformation could be distributed across scales or spatially adjusted through variable infill density. In this contexts, non-auxetic prototypes were purposefully retained as starting points, allowing the effects of infill logic and toolpath configuration to be isolated before proclaiming auxetic geometry. The experimental findings were merged in a prototype documentation matrix, which functioned as a synthesis tool rather than a performance ranking system. By methodically recording geometric logic, infill strategy, material configuration, and qualitative deformation response, the matrix addressed a recurring gap in research concerning auxetic metamaterials, where experimental outcomes are often reported unconnectedly. The structure of such a matrix provides a replicable framework that can be extended or recalibrated in future developments, supporting cumulative knowledge-building in fabrication-aware design of auxetics.

The final stage of the study introduced a preliminary pneumatic deformation observation, in which nominated auxetic specimens were adhesively attached to balloon membranes and subjected to incremental inflation. This phase was not envisioned as a quantitative actuation study, but rather as a qualitative reflection on how infill-based auxetic micro-architectures respond to volumetric expansion. The observations confirmed the structural reliability of TPU 95A under tweaked slicing conditions and reinforced central premise of this thesis: that deformation behavior can be governed primarily through internal geometric logic rather than external materials or complex assemblies. Multidirectional, rotating square, and rotating triangle auxetics demonstrated consistent deformation tendencies under inflation, suggesting potential for future developments involving controlled pressure systems and quantitative deformation metrics. Throughout the development of the methodology, the research was theoretically informed by prior studies on auxetics, metamaterials, and fabrication-aware design. Insights from Lakes and Alderson, as discussed in Kapsali's *Biomimetics for Architecture* (2021), supported the understanding that auxetic behavior emerges from geometry-driven deformation mechanisms rather than material composition alone. This perspective reinforced the emphasis on encoding behavior within planar micro-architectures through computational design and slicer-based control, rather than pursuing complex material composites or external actuation systems.

Like KnitCandela project (Zaha Hadid Architects, 2018), which treated computationally knitted textiles as an active medium for form generation, this work situates computational fabrication logic as a primary design driver, indicating how patterned materials can encrypt deformation behavior through geometry rather than relying on traditional formwork or external shaping processes. The study was also continuously informed by recent graduate studies, including Ahlers (2018), Bakıcı (2023), Gokstorp (2020), Lee (2022, 2023), and Staffová (2023). Their work on nonplanar slicing, high-impact infill structures, textile-integrated systems, and soft material behaviors offered critical insight into the emerging discourse of computationally fabricated composites. These references help position the study within performance-driven digital design.

Looking forward, further investigation could explore TPUs with lower Shore hardness for greater deformability, or integrate functionally graded materials (FGMs) for spatial performance tuning. Shape memory polymers (SMPs) may add self-actuation capabilities, while the development of custom slicer plug-ins could allow designers to control toolpath logic dynamically without needing to write code. Such interfaces could democratize access to programmable fabrication and extend its reach across architecture, fashion, aerospace, medical devices, and soft robotics.

In conclusion, this thesis tackles material computation from an underexplored angle by positioning infill geometry as an active design tool rather than a residual fabrication parameter. It proves that deformation, porosity, and elasticity can be calculatedly embedded within auxetic metamaterials through infill-based additive manufacturing, in this case FDM, rather than through external mechanisms or post-processing. Notably, reducing material density through infill-based 3D printing directly contributes to material efficiency, shorter print times, and lower filament consumption compared to fully solid 3D printing, positioning the proposed prototypes as fabrication-aware. An additional remark developed through comparative infill testing. When employed as a three-dimensional infill in prototyping, the 3D honeycomb pattern displayed higher cost-efficiency than gyroid, requiring both shorter print times and reduced filament consumption. Although gyroid remained valuable in terms of deformation fluidity and elastic endurance, this indicates that alternative infill logics may outperform it in sustainability criteria. This observation encourages further exploration into the design and development of infill patterns that balance mechanical behavior with material efficiency and fabrication time. Together, all these findings underline how auxetic performance, mechanical responsiveness, and sustainability considerations can be aligned within a single, replicable design-to-fabrication framework for elastomeric, lightweight auxetic metamaterials.

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