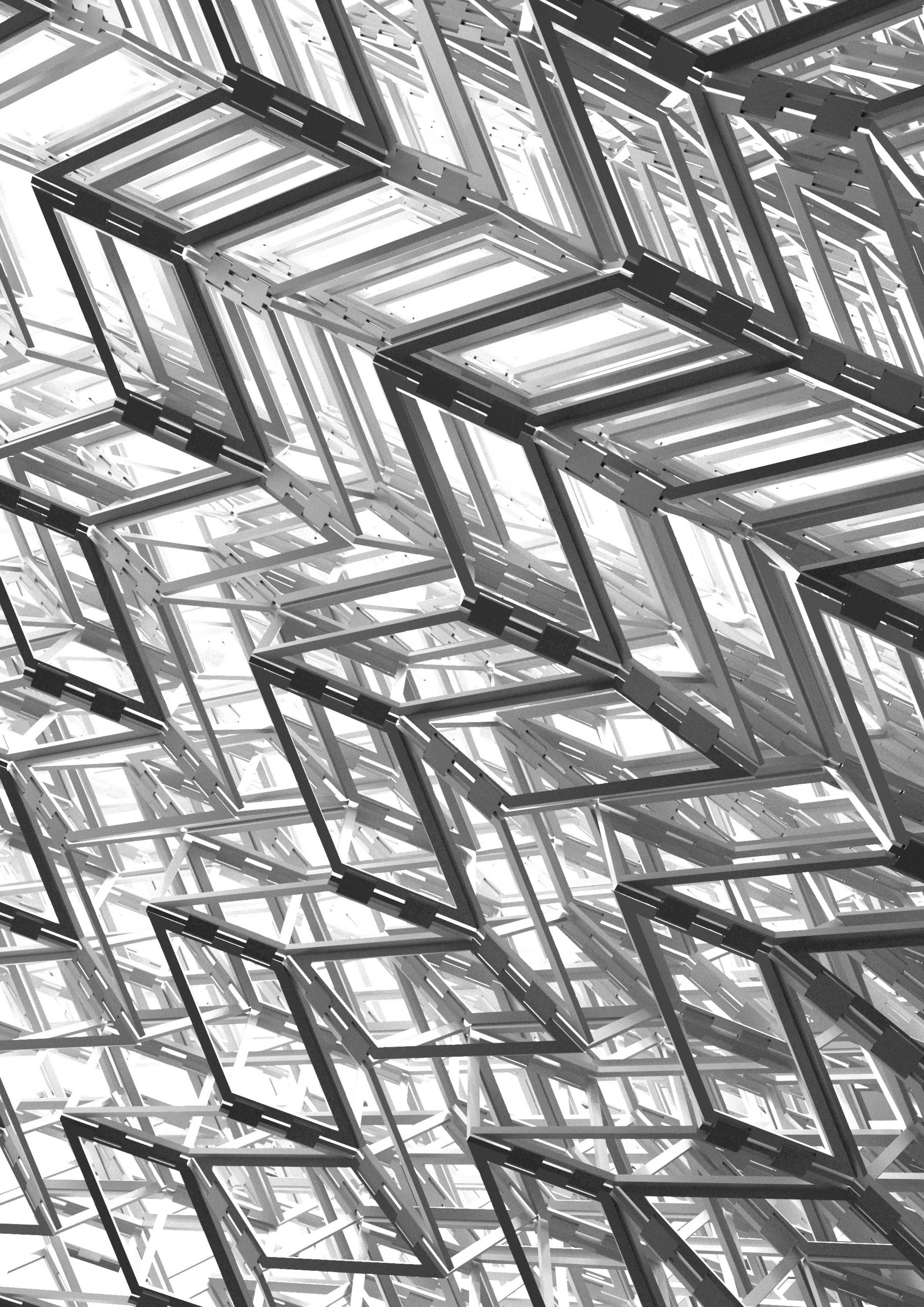


Kiri-tract

By Weixia Luo & Zhirun Huang

Instructor: Daekwon Park

Direct Research 2025

School of Architecture, Syracuse University

Special Thanks to HOK

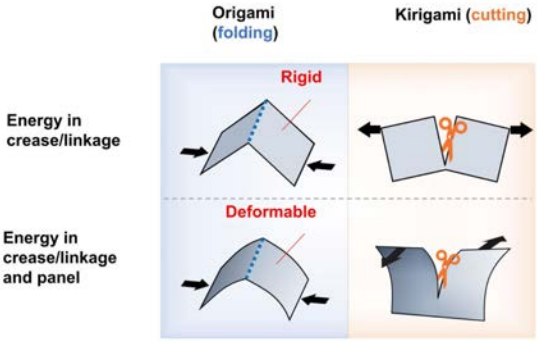
Kirigami + Tessellation

Dynamic Transformation + Stable Expansion = Adaptive, Lightweight and Scalable Systems

Direct Research 2025
Weixia Luo & Zhirun Huang

As architecture increasingly demands adaptability, reconfigurability, and material efficiency, this research proposes a hybrid structural system that integrates kirigami and tessellation principles. By merging kirigami's cut-and-fold logic with tessellation's modular and geometric consistency, we develop a lightweight, transformable surface system—Kiri-tract—that can transition from 2D to 3D and respond to environmental conditions. Through physical prototyping, digital simulation, and joint system development, we demonstrate the system's potential for deployable façades, modular pavilions, and adaptive interiors. This paper presents the design logic, fabrication process, and spatial applications of the system, positioning it as a scalable, responsive architectural framework.

Direct Research 2025
Weixia Luo & Zhirun Huang

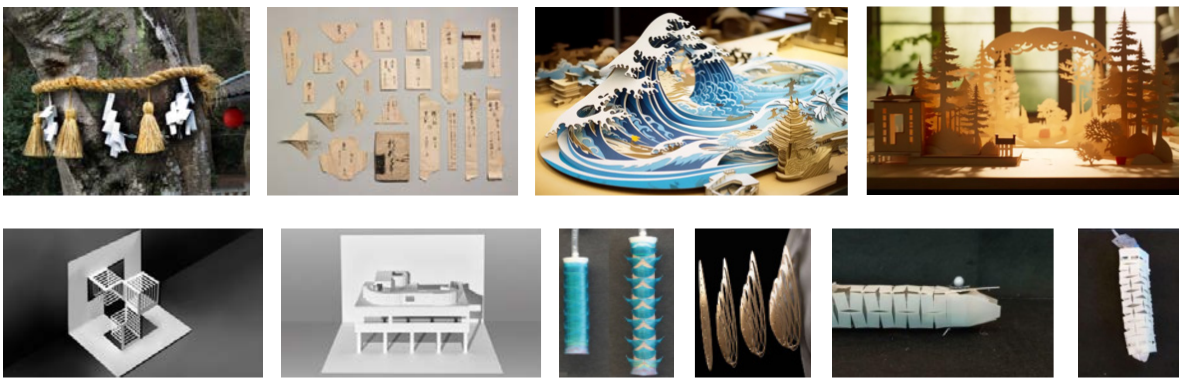


Categories of origami- and kirigami-based mechanical metamaterials.

Confronting the realities of climate change, spatial adaptability, and material efficiency, architecture today increasingly emphasizes systems that are both responsive and reconfigurable. Architects and engineers alike are seeking design strategies that allow built environments to react to environmental stimuli such as light, temperature, wind, or user movement.

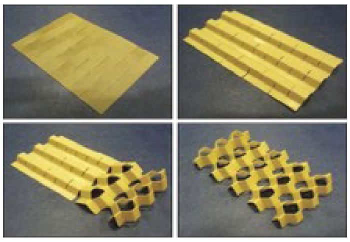
Within this context, geometry-driven transformation systems—particularly those informed by kirigami, origami, and tessellation—have emerged as promising frameworks for developing deployable, lightweight, and transformable architectural components.Kirigami, derived from the Japanese words kiri (cut) and kami (paper), originated as a ceremonial paper-cutting art and has evolved into a strategy for enabling dynamic transformation through patterned cuts.

Unlike origami, which relies solely on folding, kirigami introduces voids and incisions that expand the material's capacity for both in-plane and out-of-plane deformation. Recent applications in biomedical devices, robotics, and material science—such as minimally invasive stents (Blees et al., 2015), shape-shifting implants, and soft robotic skins (Rafsanjani et al., 2019)—demonstrate kirigami's ability to program precise and reversible shape change.



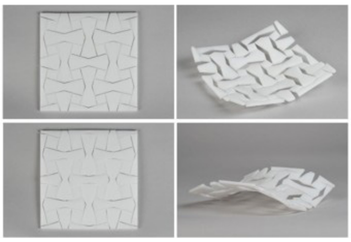
Applications of Kirigami Across Different Industries: Categories of Shide, traditional Japanese festivals, architectural design, Stent, ADM Sheet, Kirigami Robot

Direct Research 2025
Weixia Luo & Zhirun Huang



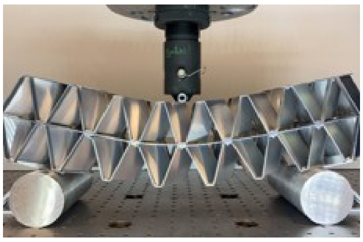
Morphability

Converts 2D materials into 3D structures with dynamic shape change



Adaptability

Allows materials to flex, stretch, and retain structural integrity.



Lightweight

Achieves high load-bearing capacity despite its lightweight structure through strategic cutting.

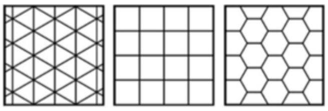
To better understand kirigami's architectural potential, we categorized its deformation behavior into two modes:

- *In-plane deformation: planar stretching driven by expanding cut patterns.*
- *Out-of-plane deformation: bending and folding that create volumetric forms.*

From these studies, three key attributes emerge that make kirigami particularly relevant for responsive architecture.

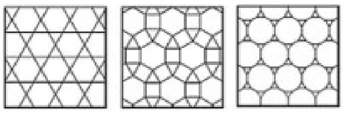
Kirigami system embodies three core qualities: morphability, adaptability, and lightweight design. It demonstrates morphability through its ability to transition from flat sheets into complex three-dimensional forms with minimal actuation, enabling dynamic spatial configurations. Its adaptability allows it to passively respond to environmental stimuli such as wind, heat, and light, enhancing performance without the need for external energy input. Finally, the system achieves lightweight design by maximizing structural and spatial efficiency while minimizing material usage, making it both sustainable and versatile.

In parallel, tessellation—the repetition of geometric units without overlaps or gaps—has long informed architectural design, computational geometry, and biomimicry. Traditional applications include Islamic ornamentation, ceramic tiling, and Byzantine mosaics, while modern interpretations such as Buckminster Fuller's geodesic domes highlight tessellation's structural performance and material economy. Furthermore, biomimetic studies have revealed how natural structures such as insect wings, fish scales, and plant cell membranes utilize tessellated logic to balance rigidity and flexibility (Sanchez et al., 2019). Tessellation offers distinct advantages in both architectural and material systems by combining geometric logic with spatial efficiency.



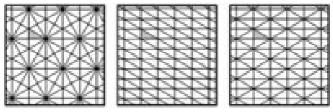
Regular Tessellation

Any shape that has all equal sides and equal angles.



Semiregular Tessellation

Allows materials to flex, stretch, and retain structural integrity.



Monohedral Tessellations

Made up of only one shape, though the shape may be rotated or flipped.

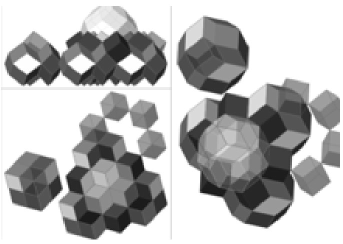
Islamic Traditional Tellesslation Patterns

Aperiodic Tessellation

Dynamic Tessellation

Voronoi Tessellation

It provides space-filling efficiency, allowing for maximum surface coverage without material redundancy, which is critical for optimizing resource use. Its pattern diversity supports a wide range of geometric configurations and aesthetic expressions, enabling designers to tailor forms to both functional and visual goals. Moreover, tessellation exhibits multi-scale applicability, making it suitable for applications ranging from nanoscale materials to large-scale construction systems, thereby bridging disciplines and scales within architectural design.

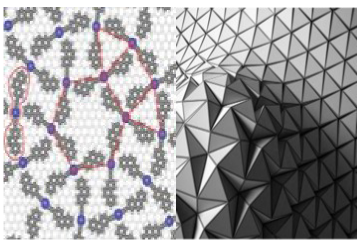


Space-Filling

Maximizes spatial efficiency and structural optimization.

Diverse Patterns

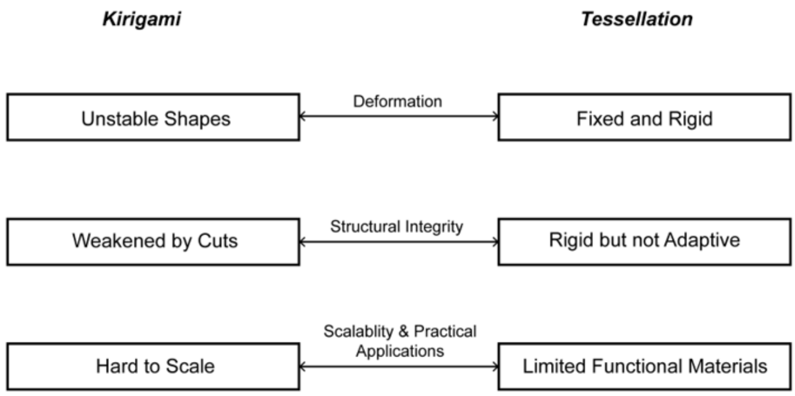
Can be periodic (regular) or aperiodic (non-repeating).



Nano to Macro

Applies from nanoscale materials to large scale architecture.

Despite their individual strengths, both kirigami and tessellation face limitations. Kirigami structures, while flexible, often lack stability at large scales due to weakened material continuity.



Tessellation, though structurally rigid, is inherently static and unresponsive. This duality presents an opportunity to explore a hybridized system.

Can kirigami and tessellation be integrated into a deployable architectural system that is both structurally coherent and environmentally adaptive?

This project investigates that potential through the development of a Kirigami–Tessellation hybrid system. We explore how kirigami's flexible transformation mechanisms can be embedded within tessellated frameworks to enhance modularity, scalability, and responsiveness. Our goal is to generate programmable surfaces capable of transforming from 2D to 3D, with embedded logic that supports both compact storage and spatial expansion.

To validate this system, we conducted early investigations using three types of tessellated base grids: triangular, hexagonal, and square. Physical and digital prototyping revealed that while triangular units created complex folding paths and hexagons enabled smooth curvature, square tessellation provided the best performance in terms of folding reliability, spatial compressibility, and modular repeatability.

We tested material behaviors using 3D-printed nylon powder, laser-cut chipboard, thermoplastic polyurethane (TPU). Nylon proved dimensionally stable but too brittle; TPU was highly flexible yet lacked form retention; chipboard was precise but weak under repeated stress. These trials revealed the need for joint mechanisms to balance deformation and structural continuity. Inspired by ball-and-socket systems, we designed custom connectors and iteratively tested them through both digital simulations and physical mock-ups. Throughout the process, parametric design tools enabled us to simulate cut placement, force response, and deformation trajectories. Simulations were essential for identifying failure points, optimizing cut density, and refining transformation behavior.

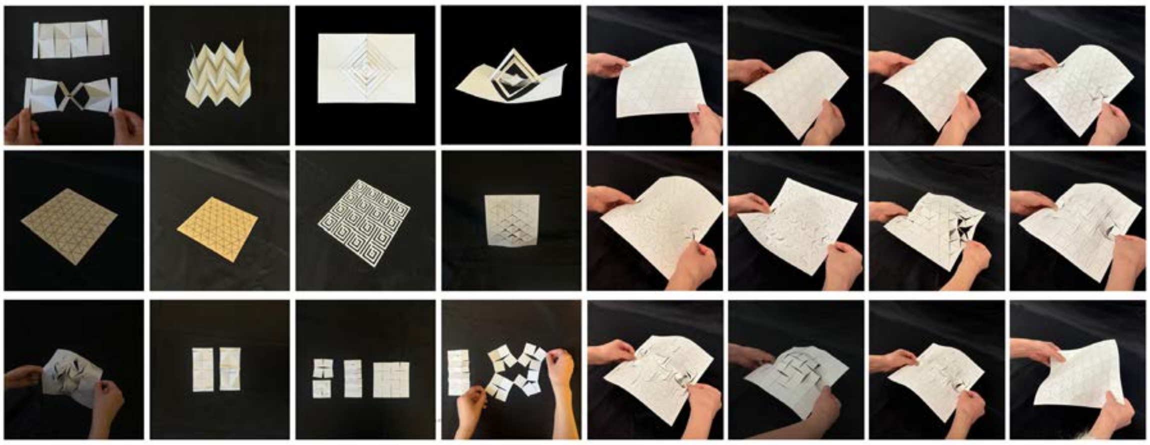
Based on our findings, we structured the research around three core inquiries:

1.2D–3D Transformation and Environmental Adaptation – How can the system dynamically respond to environmental inputs while transitioning between flat and volumetric states?

2.Deformation Control and Structural Stability – How can cuts, folds, and joints be tuned for predictable, repeatable movement without compromising integrity?

3.Modularity and Scalability – How can tessellated kirigami units be aggregated for applications at architectural scale?

These three trajectories form the conceptual and technical framework of our proposed system and guide the development of prototypes, applications, and future material integration strategies discussed in the following sections.



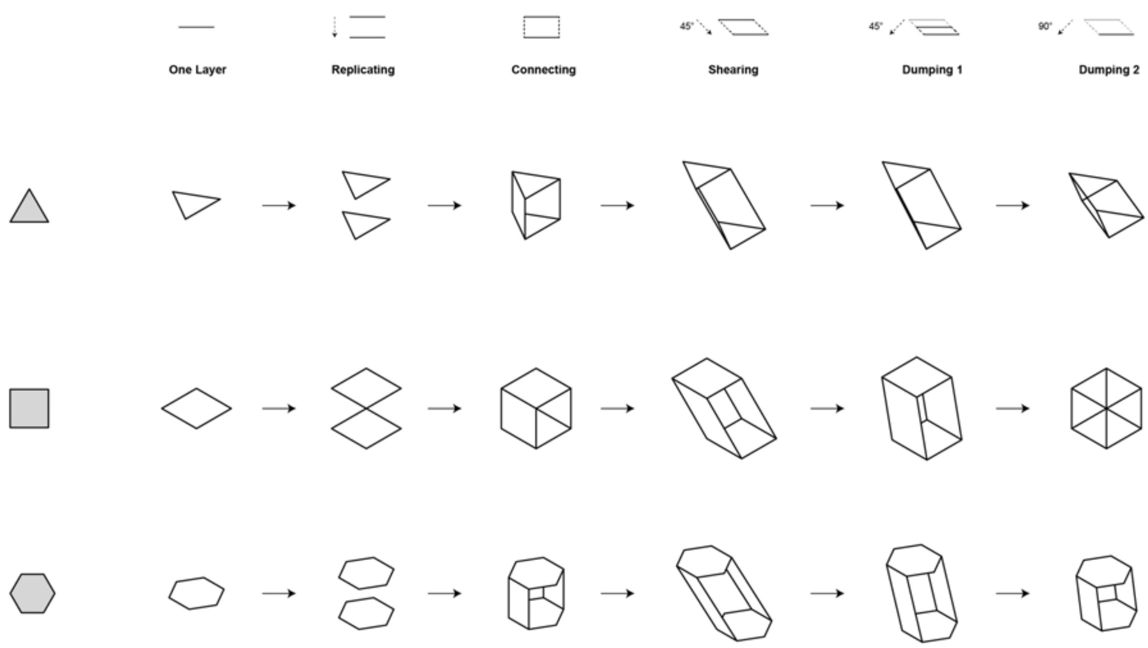
Physical Kirigami Prototypes： Explorations of cut patterns, tessellation embedding, surface deformation behavior, and folding–unfolding sequences through early-stage paper and chipboard models.

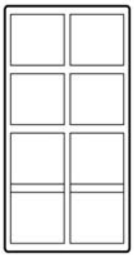
Our design exploration began with a series of physical kirigami prototypes aimed at understanding the geometric logic of various cut patterns. Using paper and laser-cut chipboard, we tested a variety of kirigami motifs by adjusting the slit length, density, angle, and symmetry. These initial mockups allowed us to directly observe the behavior of kirigami in both in-plane stretching and out-of-plane folding, especially focusing on how minimal force can initiate curling, expansion, or spatial bending.

We then evaluated how three different base materials—paper, plastic, and wood—respond to kirigami cuts. Paper was highly flexible and suitable for exploring initial pattern logic, but lacked structural support and could not maintain a stable 3D form, leading to collapsed or unstable deformation. Plastic sheets were more rigid and durable but resisted bending, which limited their ability to achieve volumetric transformation. Wood (such as thin veneer or chipboard) performed well under laser cutting and allowed for clean edges, but its stiffness prevented significant deformation and often caused cracking along fold lines. These experiments revealed a critical insight: while cut geometry is fundamental, material pliability is essential to enable three-dimensional transformation in kirigami systems. This led us to consider material selection alongside structural reinforcement strategies in the following design stages.

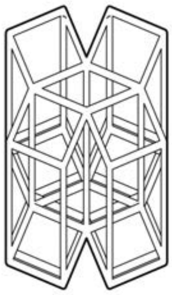
After testing isolated kirigami patterns, we introduced them into three distinct tessellated frameworks—triangular, square, and hexagonal—to stabilize the transformation sequence. By embedding the cuts within these geometric grids, we observed how each tessellation affected deformation behavior, pattern repetition, and structural integrity.

Through comparative analysis, we concluded: Triangle-based tessellations provided strong visual richness, while hexagon-based patterns allowed for smooth, continuous curvature; however, neither could effectively compress, fully fold, or stack vertically. In contrast, square-based tessellations emerged as the most versatile, being the only configuration capable of fully collapsing into a two-dimensional state and reliably expanding into three-dimensional forms. This makes them ideal for modular transformations in adaptive architectural systems.

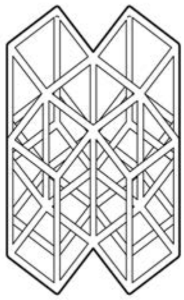




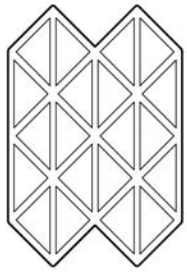
State 1: Initial State



State 2: Intermediate Transformation



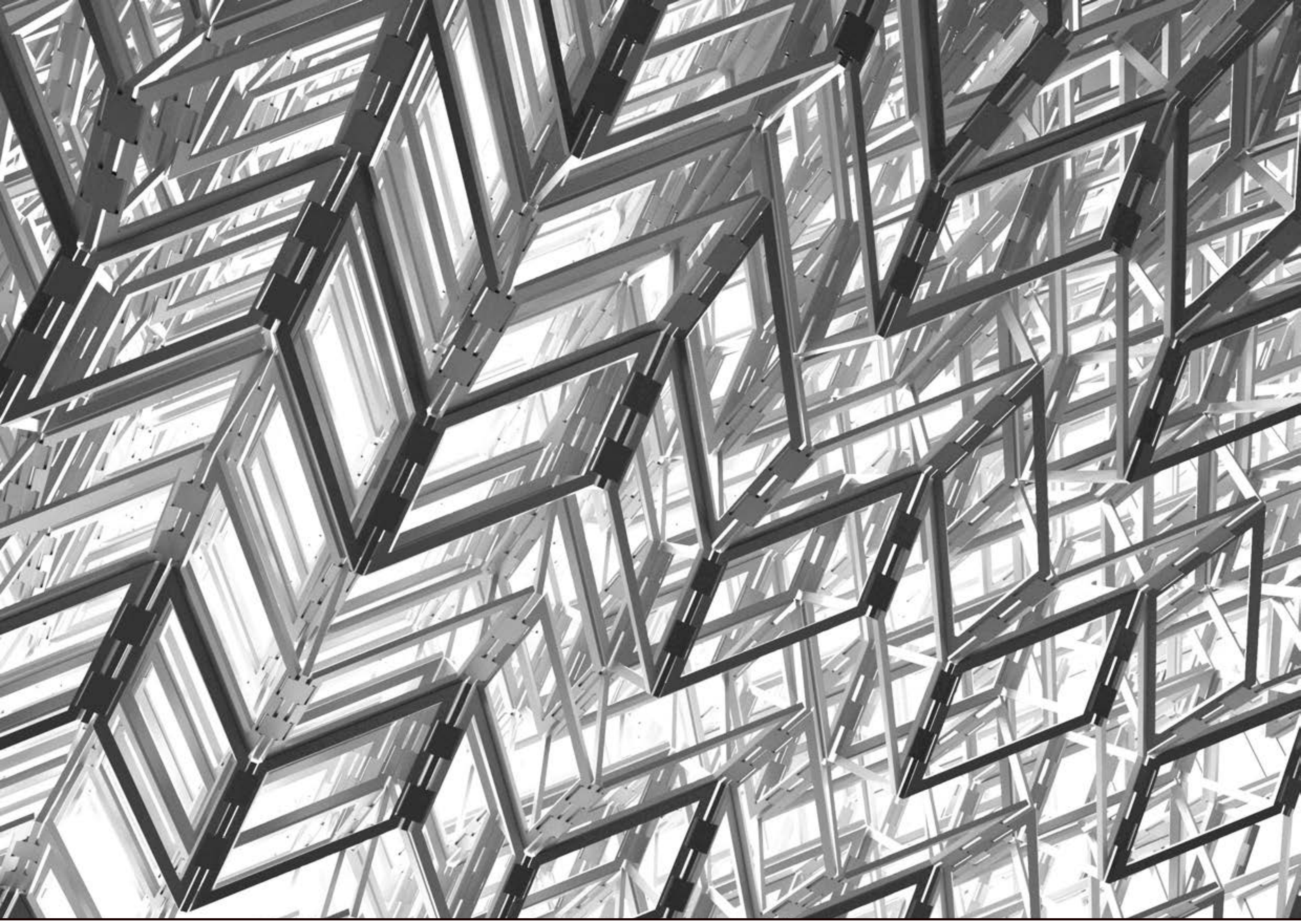
State 3: Advanced Deformation

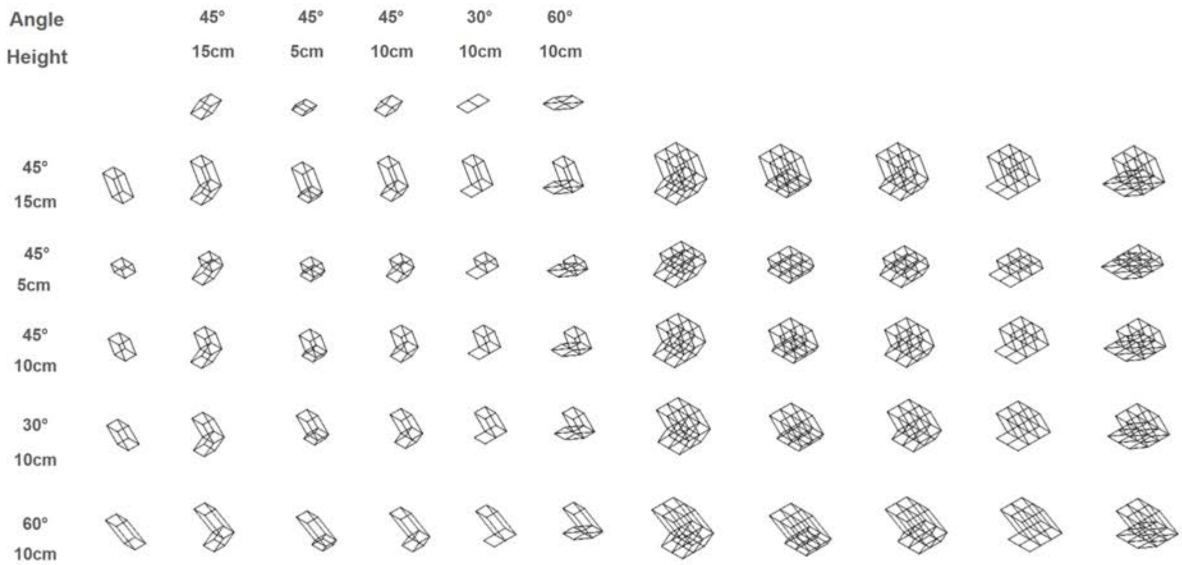


State 4: Fully Deployed

This conclusion led to the development of our custom system, named Kiri-tract, a design strategy that integrates square tessellation with cut-and-fold mechanisms to optimize the transition between flat and spatial states.

Direct Research 2025
Weixia Luo & Zhirun Huang



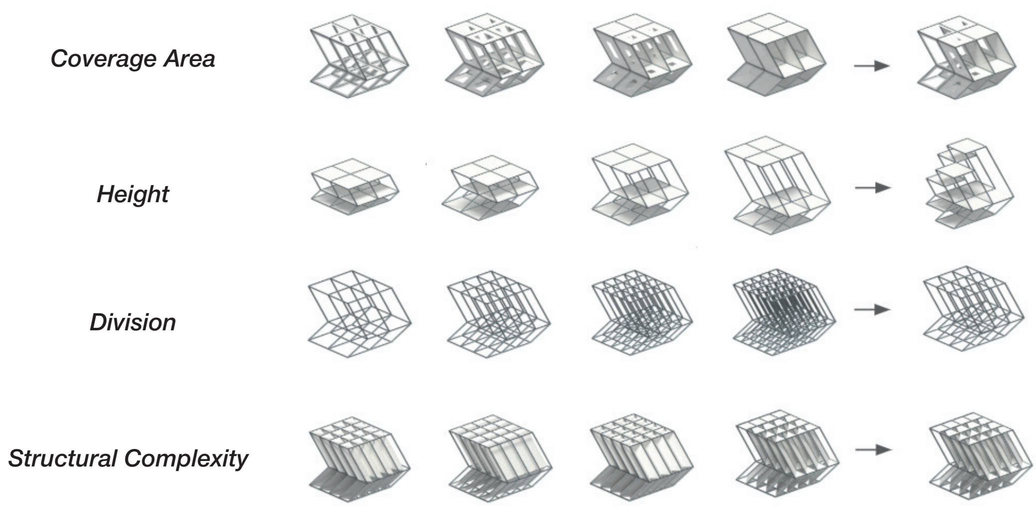


Test with different combinations of angles and heights.

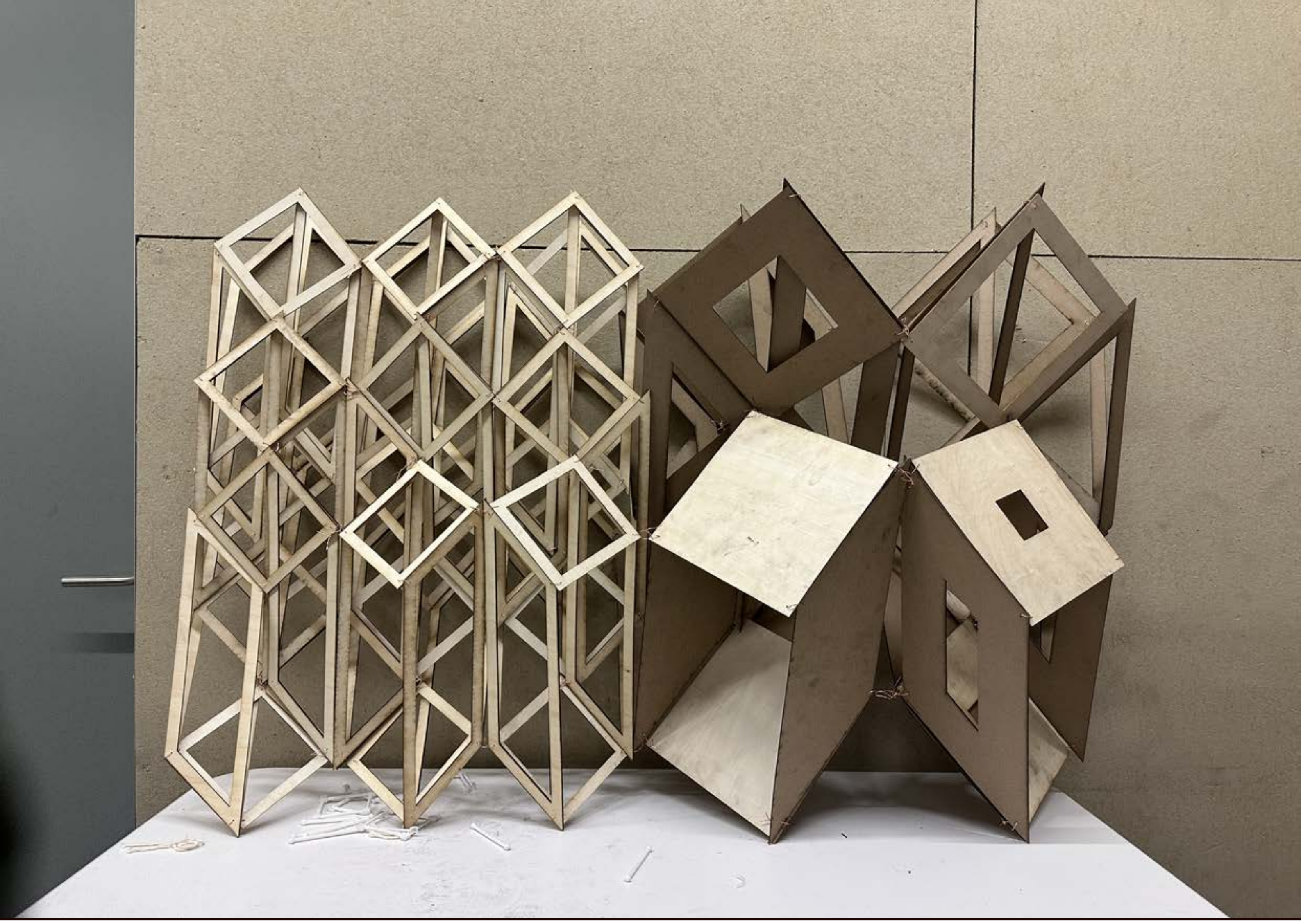
Building upon this framework, we explored various modular configuration logics—including cut orientation, unit angles, and aggregation hierarchies—through four series of design experiments aimed at evaluating the system's performance across different spatial scenarios. First, we analyzed surface coverage areas between units to understand how different arrangements influence spatial continuity and connectedness. Second, we tested vertical stacking strategies to assess the system's structural stability and adaptability at varying heights. Third, we examined different subdivision patterns to evaluate the impact of density and partitioning on spatial function. Finally, we introduced triangular variations to explore more complex geometries and enhanced structural articulation within the tessellation. Each of these experimental series was physically modeled and tested, forming a key body of research. From these explorations, we selected into a 3×3 prototype grid, marking a critical design the most effective modules and assembled them into a 3×3 prototype grid, marking a critical design milestone that bridges experimental investigation with architectural application.

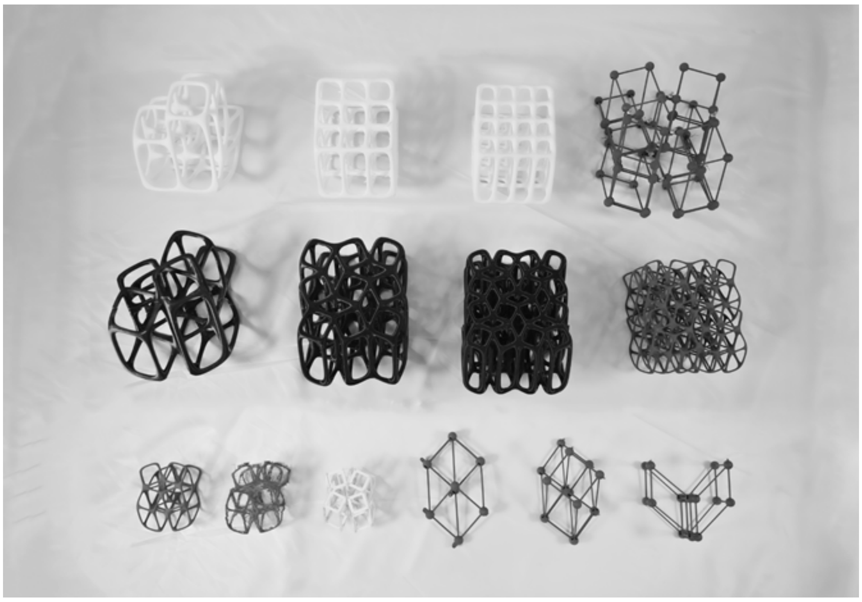
Alongside physical prototyping, computational simulation played a key role in our iterative design process. Using parametric modeling tools such as Rhino and Grasshopper, we simulated kirigami deformation behavior under both passive and activated conditions.

Through mesh relaxation and finite deformation analyses, we explored the unfolding sequences of various cut geometries, examined the bending behavior under in-plane compression, and studied the global transformation from a flat surface into a volumetric form. These simulations provided critical insights that informed both the material logic and spatial performance of the system.



Direct Research 2025
Weixia Luo & Zhirun Huang



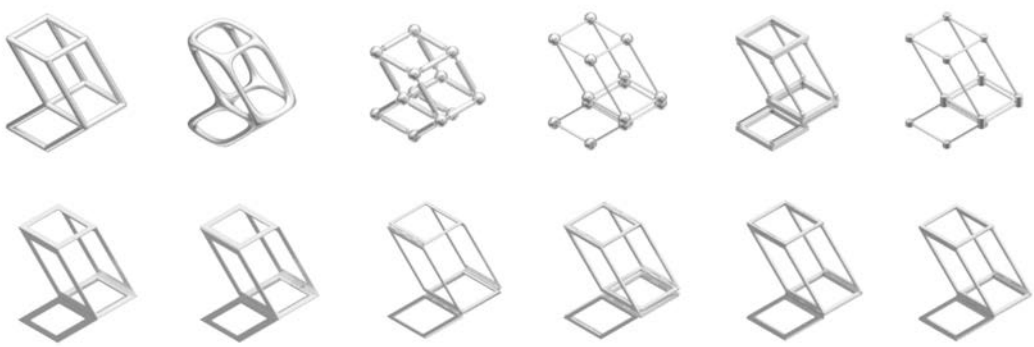


This conclusion led to the development of our custom system, named Kiri-tract, a design strategy that integrates square tessellation with cut-and-fold mechanisms to optimize the transition between flat and spatial states.

Throughout the design process, we conducted a series of structural studies to explore how joint mechanisms could be integrated seamlessly into the framework. A primary objective was to conceal the joints as much as possible, minimizing visual distraction and mechanical exposure. Inspired by systems such as the Kite structure, which achieves elegant articulation through embedded hinge logic, we experimented with various configurations—from external spherical connectors to fully enclosed, interlocking components.

Each iteration aimed to refine both the structural integrity and visual coherence of the system, progressively reducing reliance on visible connectors. The transition from exposed ball joints to concealed, frame-integrated pivots allowed the geometry to remain clean and uninterrupted, enabling the dynamic transformation to appear monolithic and fluid. This investigation ultimately informed a joint strategy that balances mechanical functionality with formal clarity, ensuring that ensuring that motion is embedded within the geometry itself rather than added onto it.

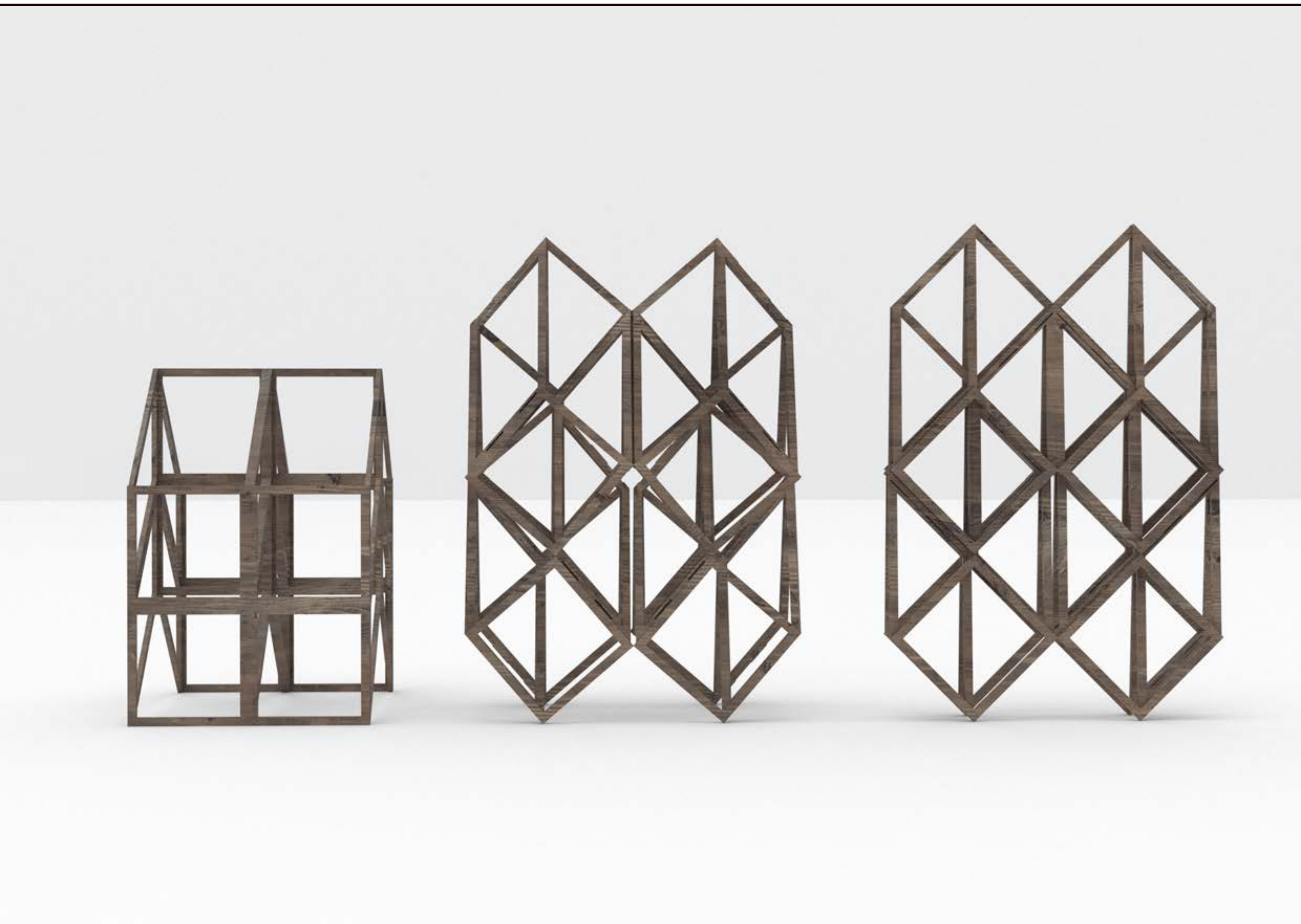
The final joint solution not only enhanced the aesthetic coherence of the structure but also improved its deployability and durability. By embedding movement within the geometric logic of the frame, we established a system that supports repeated transformation without compromising structural clarity. This approach offers a scalable foundation for future applications, where joint invisibility and mechanical precision are essential for adaptive, high-performance architectural systems.



Iterations in Joints Exploration

“By integrating Kirigami and Tessellation, we unlock new potentials in transformable structures: controlled environmental adaptation, enhanced structural stability, and scalable modularity. This integration paves the way for deployable architectural systems that respond dynamically to spatial and environmental demands.”

Direct Research 2025
Weixia Luo & Zhirun Huang



We also developed custom scripts to visualize the interaction between cut density and tessellation type. By adjusting parameters such as slit number, curvature bias, and axis symmetry, we could predict deformation limits and proactively identify stress concentrations or failure points.

Simulation results further confirmed our physical findings: square tessellation offered the most stable deployment pathway, maintaining geometric coherence during folding and unfolding. This validated our decision to use square-based units in further system development.

We also investigated combined in-plane and out-of-plane transformation modes, modeling how the system might respond to environmental triggers or spatial constraints. This dual-mode capability expanded our understanding of deployability—not simply as geometric change, but as environmental adaptability.

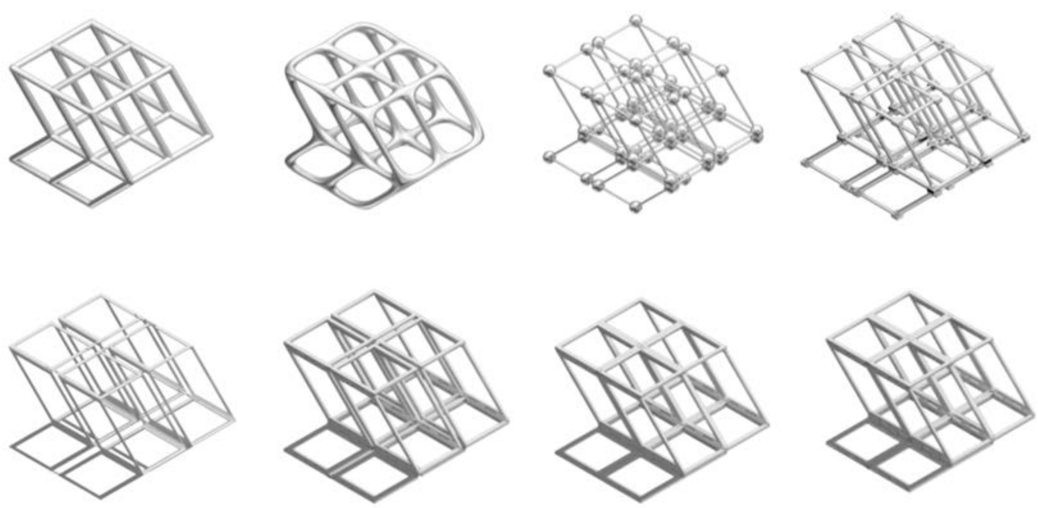
Finally, we applied computational tools to explore scaling strategies, including:

•Aggregation logics for large-scale systems;

•Tolerances and joint behavior at increased sizes;

•Performance implications for façade systems and temporary architectural installations.

Through this combined physical-digital feedback loop, we refined the logic of the Kiri-tract system into a deployable, lightweight, and environmentally responsive structural design.



Iterations in Module Exploration

The development of the Kirigami + Tessellation system followed a methodical, iterative process grounded in material exploration, structural refinement, and modular experimentation. From early chipboard models to more advanced assemblies with concealed joints and 3D-printed components, the design evolved through successive rounds of testing, adaptation, and integration.

The design process began with a series of laser-cut chipboard prototypes, which offered a fast and accessible means to test initial kirigami patterns embedded within tessellated geometries. Chipboard was selected for its ease of fabrication and ability to clearly represent cut logics. These early physical models allowed us to understand how variations in slit orientation, length, and repetition influenced both in-plane stretching and out-of-plane folding.

Moreover, chipboard models revealed the critical mechanical behavior at joints and fold lines. We observed that the material, while suitable for planar study, lacked the flexibility and resilience required for more advanced transformation. Under repeated manipulation, the models began to tear or crack along stress points, indicating the need for materials that could better accommodate deformation over time.

To address this, we initiated a series of material studies, focusing on how to support both in-plane tension and out-of-plane bending. We tested various soft and semi-rigid materials—including thermoplastics, synthetic composites, and elastomers—to identify suitable candidates. These tests led to the realization that a hybrid material strategy, combining flexible infill surfaces with more rigid framing systems, could balance responsiveness and stability.

This composite logic informed the later stages of design, enabling us to prototype units capable of

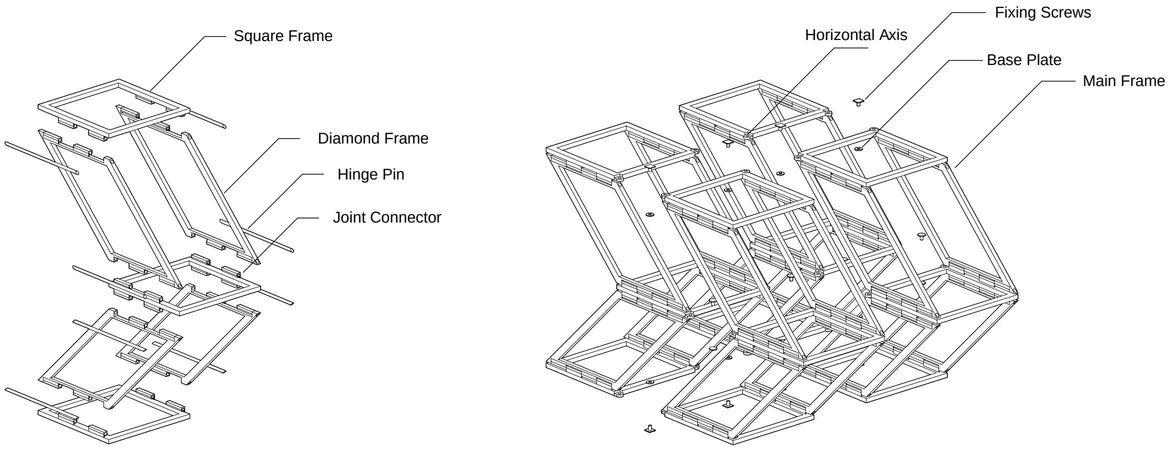
smooth transformation while maintaining structural clarity.

As the project progressed, the focus shifted to the development of efficient, modular joint systems. In early prototypes, we employed external ball-and-socket joints to enable multi-axial motion between modules. These joints provided the necessary freedom of movement and allowed units to fold and expand in various spatial configurations. However, they also introduced significant challenges:

- *Visual interference: The exposed joints disrupted the formal purity of the modular geometry.*
- *Mechanical fragility: Their external positioning made them vulnerable to displacement or wear during repeated transformations.*
- *Assembly complexity: These joints required precise alignment, making them difficult to replicate or scale across multiple modules.*

In response, we developed a more refined, concealed joint mechanism, which was embedded within the structural frame of each tessellated unit. This revised approach not only preserved the formal integrity of the system but also enhanced structural performance by reinforcing the frame. The concealed joints were based on a slot-and-rotation mechanism, using layered fabrication and iterative adjustment through 3D printing. The resulting joint allowed for sufficient rotation while remaining visually integrated and protected from wear.

This evolution from external to internal joint systems marks a key turning point in the project—transforming the system from a diagrammatic prototype to a more robust, buildable module capable of deployment in real spatial conditions.



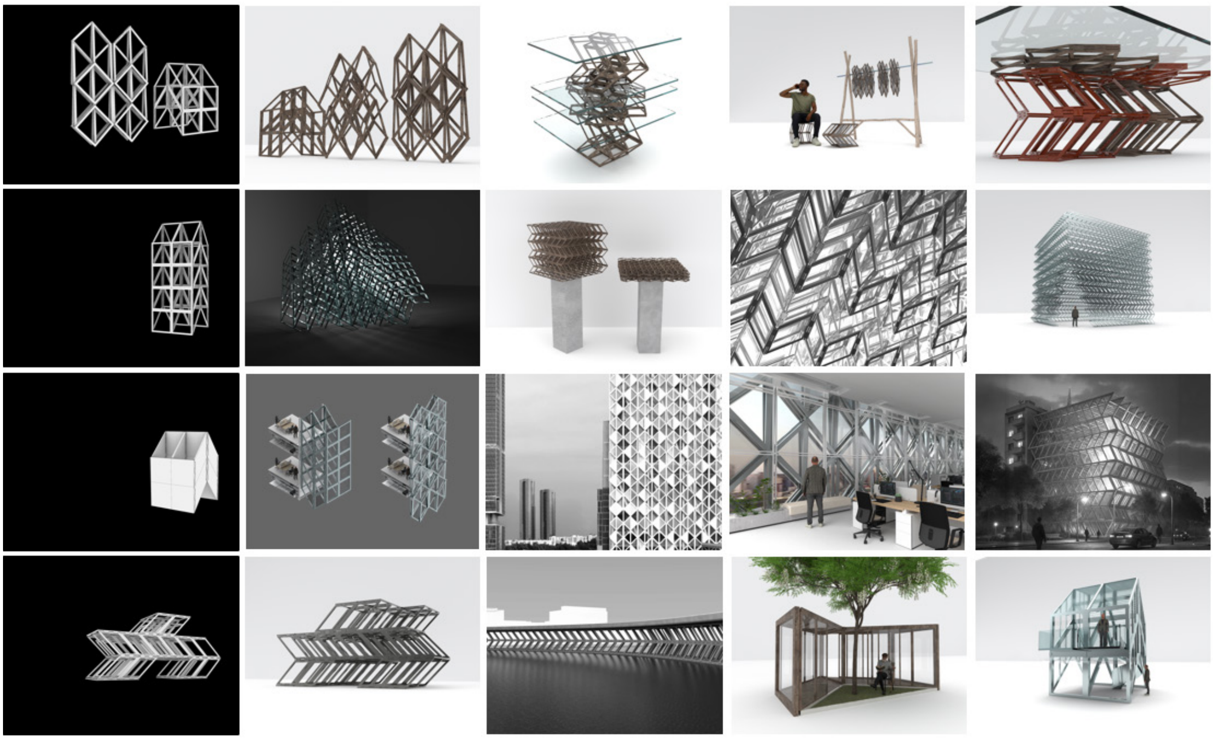
By the end of the fabrication phase, the Kirigami + Tessellation system evolved from a conceptual folding mechanism into a scalable, transformable structural language, capable of operating at multiple scales—from façade systems to deployable spatial enclosures.

The Kirigami + Tessellation hybrid system offers a deployable, self-supporting, and responsive structural solution that merges the dynamic transformation capabilities of kirigami with the modular logic and scalability of tessellation. Inspired by geometric strategies found in nature, this system operates across a wide range of contexts—including architecture, furniture, public installations, and emergency infrastructure—offering both adaptive performance and formal expressiveness.

In its folded state, the system is flat, lightweight, and easy to transport or store. Once deployed, it transforms into a stable three-dimensional configuration without the need for external supports. When paired with programmable materials—such as thermally responsive polymers or shape-memory alloys—the system can be passively or actively activated, adapting seamlessly to changing environmental conditions.

In architectural applications, the Kirigami + Tessellation system functions as an adaptive façade and balcony extension, with modules that dynamically respond to sunlight, wind, and heat by opening and closing to modulate shading, airflow, and temperature, thereby significantly improving passive building performance and energy efficiency. The system also operates as a transformable balcony structure, extending interior spaces into flexible semi-outdoor zones that can shift between enclosed and open states, effectively blurring the boundary between inside and outside.

Additionally, it can be deployed as a double façade system to enhance thermal insulation, control daylight, and enrich aesthetic expression while maintaining environmental responsiveness. Beyond façades, the modular units support rapid assembly, disassembly, and flat-packing, making them ideal for deployable pavilions, exhibition structures, and emergency shelters in post-disaster scenarios



Direct Research 2025
Weixia Luo & Zhirun Huang

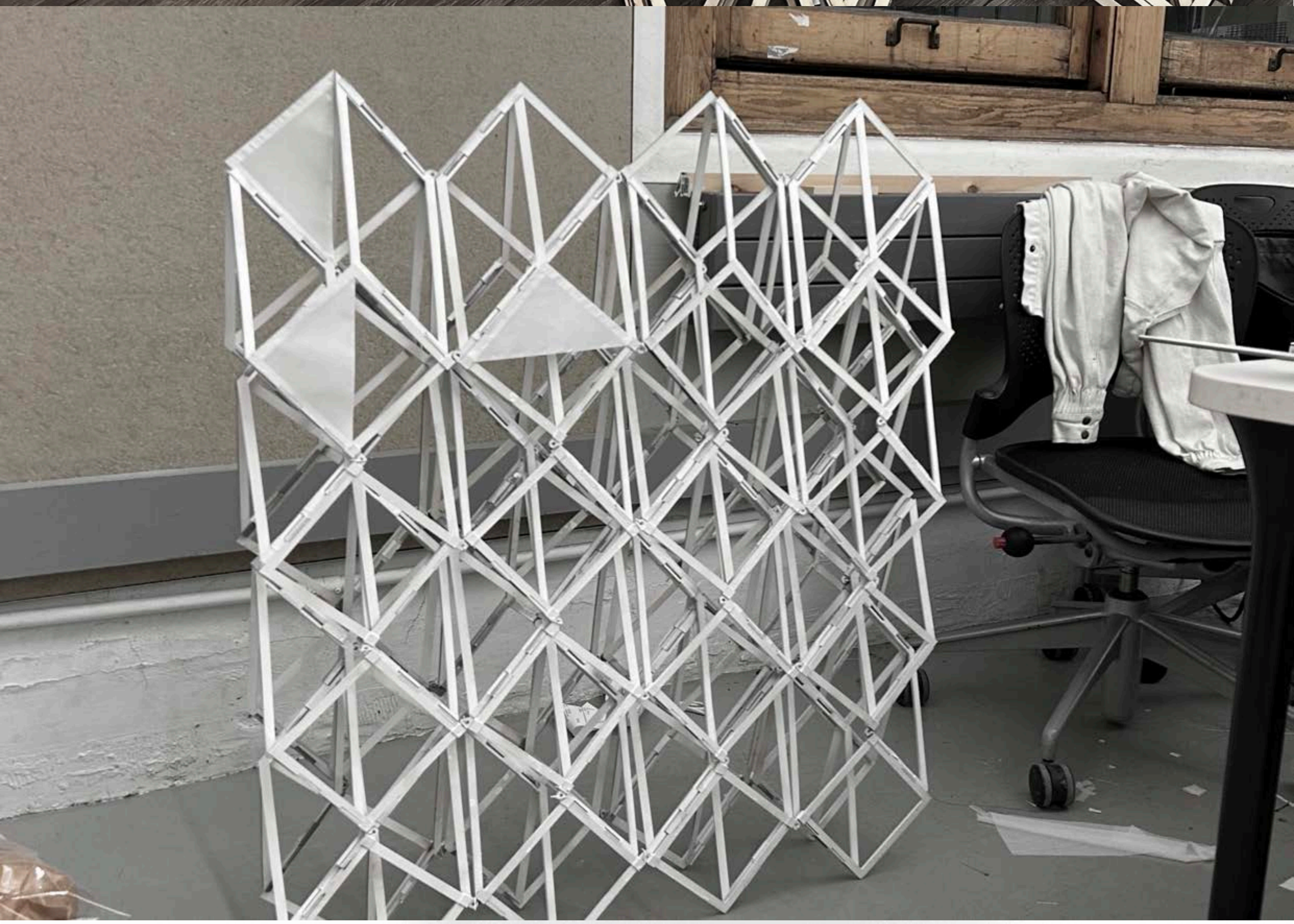
such as earthquakes, wildfires, or floods, offering lightweight yet stable configurations for immediate response efforts. In smaller-scale design contexts, the system enables the creation of foldable furniture elements such as stools, tables, and lighting fixtures that integrate structural intelligence with sculptural form, as well as reconfigurable space dividers for adaptable homes, classrooms, or co-working environments. Its geometric articulation and kinetic behavior also make it an ideal medium for interactive public art, responsive lighting surfaces, and immersive environmental installations.

Beyond individual components, the system is modular and infinitely scalable. Units connect seamlessly in horizontal or vertical configurations, adapting to topography and user-defined spatial requirements. This modularity enables incremental construction, prefabrication, and site-sensitive deployment strategies for sustainable architecture.

Our system achieves maximum spatial and functional impact with minimal material components.

Its underlying logic is simple and repeatable, yet the resulting expressions can be diverse, sculptural, and environmentally responsive. As architecture increasingly demands mobility, adaptability, and multifunctionality, this hybrid framework stands as a visionary prototype for the future of responsive and sustainable spatial design.

Direct Research 2025
Weixia Luo & Zhirun Huang



References

https://publishing.aip.org/publications/latest-content/origami-kirigami-inspire-mechanical-metamaterials-designs/

https://www.dezeen.com/2020/01/15/marc-hagan-guirey-le-corbusier-paper-models-10-kirigami-buildings/

https://www.youtube.com/watch?v=gtqGe8G--Z0

Tao J, Khosravi H, Deshpande V, Li S. Engineering by Cuts: How Kirigami Principle Enables Unique Mechanical Properties and Functionalities. Adv Sci (Weinh). 2022 Oct 30;10(1):e2204733. doi: 10.1002/advs.202204733. Epub ahead of print. PMID: 36310142; PMCID: PMC9811446.

Han, XN., Han, Y. & Chen, CF. Supramolecular tessellations by the exo-wall interactions of pagoda[4]arene. Nat Commun 12, 6378 (2021). Bashir, Stephanie. 2020. Biomimicry in Temporary Architecture: Biomimetic Concepts for Responsive Skins. Phoenicia University, College of Architecture and Design.

Bashir, Stephanie. 2020. Biomimicry in Temporary Architecture: Biomimetic Concepts for Responsive Skins. Phoenicia University, College of Architecture and Design.

Author(s). "Physics-Aware Differentiable Design of Magnetically Actuated Kirigami for Shape Morphing." Scientific Figure on ResearchGate. Accessed February 24, 2025.

Gary Choi, Levi Dudte, and Lakshminarayanan Mahadevan, “Programming Shape Using Kirigami Tessellations,” Nature Materials 18 (2019): 999–1004,https://doi.org/10.1038/s41563-019-0452-y.

https://www.eurekamagazine.co.uk/content/news/fabricating-in-the-fourth-dimension/

https://www.youtube.com/watch?v=4vfSGYToqmo

https://www.youtube.com/watch?v=9 1 NIV GrjM

https://www.archdaily.com.br/br/777864/em-detalhe-tecido-estrutural-para-construcoes-de-emergencia?ad_ medium=gallery

https://www.youtube.com/watch?v=7Mk4olS6SRo

Samuel Sivák and Silvia Maláková, “Evaluation of Topological Modification on Gear Wheel Bodies,” Acta Mechanica Slovaca 26 (2022): 22–31, https://doi.org/10.21496/ams.2022.013.

*Chen, Tian, Julian Panetta, Max Schnaubelt and Mark Pauly. “Bistable auxetic surface structures.” ACM Transactions on Graphics (TOG) 40 (2021): 1 - 9.
https://dl.acm.org/doi/10.1145/3450626.3459940*

F. Liu, T. Terakawa, S. Long, et al., “Rigid-Foldable Cylindrical Origami with Tunable Mechanical Behaviors,” Scientific Reports 14 (2024): 145,

https://www.youtube.com/watch?v=1uO0mlIIkug

https://www.youtube.com/watch?v=VlqmVkylavw

https://www.archdaily.com/114141/quadror-a-new-structural-system

Cheng, Tai-Hong & Li, Zhen-Zhe & Shen, Yun-De. (2013). Vibration Analysis of Cylindrical Sandwich Aluminum Shell with Viscoelastic Damping Treatment. Advances in Materials Science and Engineering. 2013. 10.1155/2013/130438.

As the folds settle and the modules align, we glimpse a future where space itself is never static.

Direct Research 2025
Weixia Luo & Zhirun Huang