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# ORIGAMI-INSPIRED KINETIC FAÇADES: APPROACHES, MATERIALS, AND TECHNOLOGIES

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# ORIGAMI-INSPIRED KINETIC FAÇADES: APPROACHES, MATERIALS, AND TECHNOLOGIES

***ABSTRACT***

The traditional role of the façade, historically centered on providing protection against environmental conditions and reducing $CO_2$ emissions, has been significantly redefined through advances in software technologies and material sciences. These developments have led to the emergence of the façade system as a structurally independent component functioning as an active regulator of energy consumption, thereby creating new opportunities for research and innovation. One approach to studying these systems involves the application of folding principles derived from origami, which facilitates the design of modular geometric structures capable of dynamic environmental responses. Façades composed of interconnected, homogeneous elements can effectively regulate daylight penetration and thermal energy accumulation, particularly in zones exposed to direct external influences.

To further develop such systems, it is essential to design an origami pattern whose geometric and mechanical characteristics can potentially respond to the given structural and technical challenges. This study explores the potential application of selected origami patterns in kinetic façade systems, with a focus on analyzing the actuation mechanisms that control the movement of geometric modules. Furthermore, the research evaluates the justification for integrating kinetic façade systems into contemporary architectural practice, with the aim of contributing to the development of sustainable, adaptive, and energy-efficient building envelopes.

***Keywords***: *kinetic façade systems, origami pattern, modular structures, parametric design, energy efficienc.*

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## 1. THE APPLICATION OF ORIGAMI IN CONTEMPORARY ARCHITECTURE

Origami is understood as a technique of folding materials into a regular geometric arrangements and has broad application in the design of movable structures. Origami paper models have the ability to transform under the influence of external forces while maintaining stability—even when such transformations alter their folding geometry. This characteristic has been recognized as a potential basis for the development of innovative façade systems composed of movable elements designed to respond to external influences such as sunlight, ventilation, and energy regulation [1]. Origami offers innovative possibilities for the development of adaptive architectural structures, combining functionality and aesthetics through geometric transformation [2].

There are two main approaches to incorporating origami into the façade system design. In the first instance, the façade is considered primarily a visual element, where the origami pattern serves as the initial inspiration for its form. The second approach treats the façade as a functional or structural component of the building, where the origami pattern serves as the basis for the development of structural and/or kinetic façades capable of operating independently of the rest of the building [3].

The façade's influence on the building is fundamental, regardless of whether it is designed as an integrated or independent component. Its primary functions include ensuring energy efficiency, controlling lighting, and providing protection from adverse environmental factors. However, the integration of new technologies enables façades to become dynamic and responsive systems that actively interact with their environment, thereby enhancing performance and improving overall energy efficiency [4]. More detailed investigations into the development of active façade systems have shown that origami-based solutions are highly justified, as they effectively address design challenges while combining both function and aesthetic quality.

For the successful application of origami in kinetic façades, parametric design must be employed, with particular emphasis on digital modeling and simulation tools. Through parameter analysis, the geometric characteristics of origami models are evaluated to determine their suitability for architectural application.

Traditionally regarded as a form of artistic expression, origami has been increasingly adopted in civil engineering and architecture as a tool for developing innovative and functional solutions. Of particular interest is its application to kinetic façade systems that adapt to external conditions, allowing for the active control of environmental influences on the building. One of the fundamental characteristics of origami is its capacity to compress large surfaces into relatively small volumes, making it a promising strategy for designing adaptable architectural elements [5]. Origami-based façade systems have been shown to utilize space and materials more efficiently, thus reducing the need for heavy and bulky structural components. By introducing fold-based movement into lightweight façade systems, a high degree of flexibility in motion is achieved, which directly contributes to optimizing the building's energy performance [6].

Several origami patterns with specific geometric characteristics applicable to advanced structural solutions, suitable for multifunctional implementation in architectural practice, have been analyzed:

- The Miura-ori pattern is based on a regular scheme of parallel folds that form an accordion-like structure. This folding system enables isotropic expansion and compression, allowing it to compact into a small volume and then expand without losing its structural integrity. Geometrically, the pattern consists of a series of rhomboid units whose overlap enables elasticity and flexibility of structure.

- The **Waterbomb pattern** is based on a combination of triangular and quadrilateral units that generate nonlinear folds during transformation. Folding this pattern results in a three-dimensional deformation, allowing the surface to expand in multiple directions and form curved geometries. The pattern relies on the principle of elastic stability, ensuring controlled motion without local buckling of individual elements.
- The **Yoshimura pattern** arises from axial compression of cylindrical surfaces, resulting in the spontaneous formation of triangular folds. This folding approach distributes loads evenly throughout the system, with the overall stability depending on the ratio between the length and span of each fold.
- The **Kresling pattern** is distinguished by its zigzag folds and a specific helicoidal topology. When folded, these units deform to provide a high degree of structural stability. The geometry is based on a configuration of polygonal units that overlap at precise angles, allowing for elastic deformation without compromising structural strength.

Several origami patterns with architectural applications are illustrated in (Figure 1) [7].

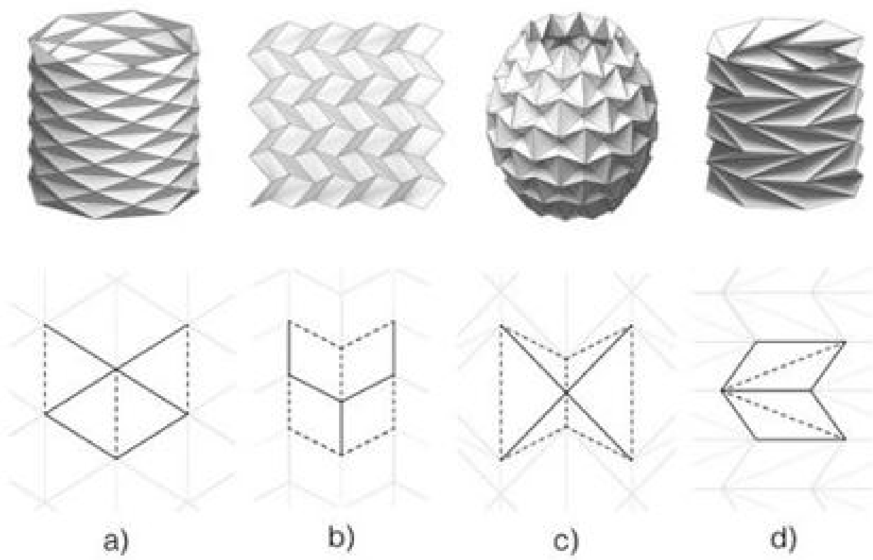



*Figure 1. Origami Patterns: a) Yoshimura, b) Miura ori, c) Waterbomb and d) Kresling [7]*

A shared characteristic of structures based on the aforementioned patterns is their ability to fold and unfold in space, which strongly supports their application in architectural practice.

However, due to the complexity of the movement inherent in each pattern, their integration into structural elements requires additional control mechanisms to reduce motion complexity and ensure precision during the folding process. By introducing interdisciplinary methods that combine material mechanics, robotics, and algorithmic design, it is possible to develop adaptable architectural systems based on these patterns with enhanced performance characteristics, thus expanding the scope of their application.

## 2. METHODOLOGICAL APPROACH TO THE DESIGN OF KINETIC FAÇADES

This paper presents an interdisciplinary approach to the design of kinetic façades inspired by origami, based on the application of origami patterns according to their geometric and mechanical properties, parametric modeling of the patterns, and their evaluation with the aim of developing optimized kinetic façade systems.

The methodological approach comprises the following steps:

***Selection of Patterns***: The initial step involved the selection of relevant origami patterns with potential for application in kinetic façades. The patterns were chosen based on a preliminary analysis of geometric parameters, mechanical properties, and kinetic capabilities, with particular emphasis on those that ensure both stability and transformability in architectural contexts.

***Geometric and Mechanical Analysis*****:** For each pattern, key geometric parameters were defined (such as side lengths, fold angles, and number of modules), along with fundamental mathematical expressions describing the transformation (e.g., surface area, volume, module length). Simultaneously, a mechanical analysis was conducted, encompassing aspects such as structural stability, elasticity, and resistance to deformation, grounded in existing research and calculations.

***Parametric Modeling and Simulation*****:** The selected patterns were modeled using Rhino and Grasshopper software, where parametric models were developed to enable dynamic manipulation of key parameters. Motion simulations were conducted to evaluate the behavior of elements and systems under various conditions, including external loads such as temperature, wind, and light. Additionally, the performance of connection systems and synchronization mechanisms was examined.

***Evaluation of Materials and Connections:*** Materials and inter-module connections with suitable mechanical and physical properties were analyzed. These properties were integrated into the parametric models to simulate the behavior of façade systems under realistic conditions.

***Optimization and Testing***: Based on simulation results, parameters were adjusted to optimize the kinetic performance, structural stability, and functional adaptability of the façade systems. Various usage scenarios and environmental resilience factors were tested to ensure the adaptability and long-term durability of the systems.

***Identification of Constructive Challenges*****:** Potential issues related to the transition from digital models to physical prototypes were analyzed, including joint tolerances, material limitations, and actuation mechanisms. Strategies for overcoming the identified challenges were proposed.

The key segments of the conventional methodological approach, previously outlined, are presented in this paper.

## 3. KINETIC FAÇADES BASED ON ORIGAMI MODELS

Kinetic façade systems consist of envelopes composed of movable elements, allowing the façade to adapt to changing external conditions through their motion. These systems can operate based on four types of movement: translation, involving the linear displacement of elements in space; rotation, referring to the turning of elements around a fixed axis; scaling, which entails proportional changes in the dimensions of elements; and deformation, which involves changes in shape due to internal or external forces (Figure 2) [8].

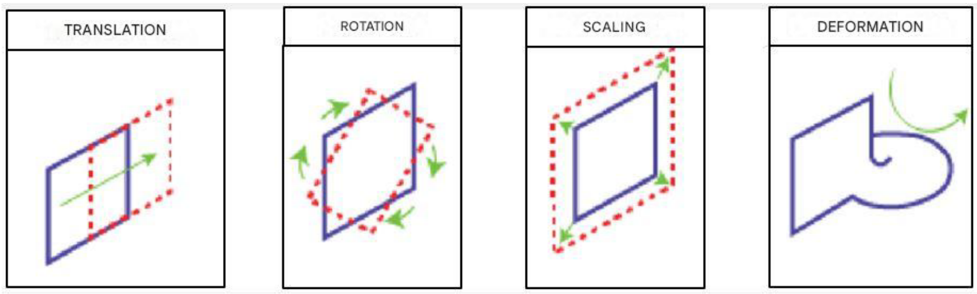



*Figure 2. Basic types of movement of elements in the façade system.Photo taken from [8]*

Kinetic façades based on origami patterns utilize a combination of translation, rotation, and scaling, allowing for a high degree of system flexibility. Notable examples include the façade of the Institut du Monde Arabe, where scaling is used to regulate daylight, and the SDU Campus Kolding by Henning Larsen Architects, where rotating panels control solar gain. The application of origami with complex types of motion holds significant potential for the development of advanced façade systems that surpass conventional methods in terms of both efficiency and geometric complexity.

### 3.1. GROUPS OF KINETIC FAÇADE SYSTEMS

The application of origami to façade systems represents an innovative approach to architectural design. Its innovation lies in the ability to translate precise geometric folding patterns onto a façade system, enabling the simultaneous movement of individual elements within the system—particularly in segments exposed to external environmental conditions. Such façade systems are capable of automatically responding to external stimuli, thereby potentially regulating the microclimate within the building.

According to Moloney’s classification [9], kinetic façades can be divided into three main categories based on the degree of origami geometry implementation:

- **Group I** includes façades that employ flexible materials to achieve structural flexibility with minimal deviation from the original folding pattern. These systems rely on the material’s elasticity to respond to external factors such as wind or temperature variations.
- **Group II** consists of façades that utilize adapted origami patterns with enhanced geometric configurations. In these systems, the folding patterns are modified to improve structural performance and system stability.
- **Group III** includes façades inspired by origami but which do not implement the kinematic logic of the origami model. Here, the form of origami is used purely for aesthetic purposes, while the components themselves do not undergo transformation or motion.

Systems in the first group largely retain the mathematically precise geometric schemes of origami, while the second group introduces modifications to optimize structural behavior [10]. The third group combines various origami-inspired forms to achieve primarily visual impact. Whether merely inspired by or entirely constructed according to origami patterns, kinetic façades have found broad application—from passive microclimate regulation to the creation of interactive architectural structures that redefine the boundaries between function and artistic expression.

### 3.2. TYPES OF KINETIC SYSTEMS

According to the general typology of constructive kinetic systems, there are three main categories [11], [12]:

- Embedded Systems
- Deployable Systems
- Dynamic Kinetic Structures

*Embedded systems* are integrated into the primary structure of the building, forming an inseparable part of the architectural form. These systems are fixed to the building but allow a certain degree of movement, which contributes to the visual character of the structure. Embedded façade systems often employ technologies such as photochromic or thermochromic materials, as well as electromechanical actuators, to regulate the amount of light penetration into the building.

*Deployable kinetic systems* consist of movable elements that change their spatial configuration, making them particularly suitable for temporary or modular structures, such as pavilions and experimental buildings [13]. An example of such a system is the Expo 2017 pavilion in Astana, whose façade was designed to respond dynamically to solar exposure. Additionally, the use of digital tools for parametric design enables designers to optimize these systems for maximum energy efficiency [14].

*Dynamic kinetic systems* operate independently of the building's primary structure and are typically attached as secondary architectural elements. They may serve to control the microclimate within the building or to shape the façade through interactive modules. This category includes structural façades with actuator systems, movable canopies, and mobile façade panels, as exemplified by the Al-Bahar Towers. Such façades frequently utilize advanced algorithms for climate parameter analysis and real-time adaptation, thereby enhancing the building's energy performance [15].

The basic categories of constructive moving systems are illustrated in (Figure 3) [16].

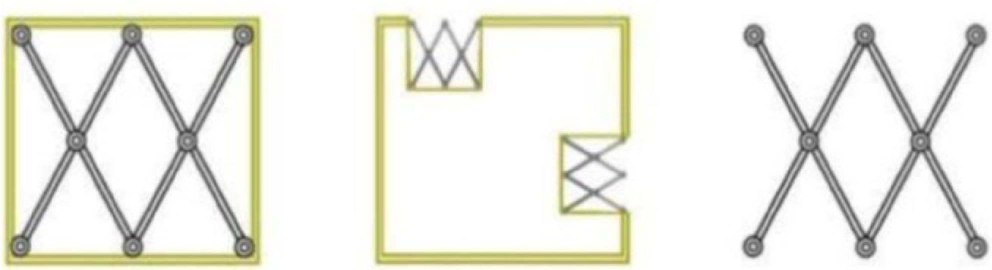


*Figure 3. Basic categories of constructive moving systems: embedded, deployable and dynamic kinetic systems [16]*

The systems subject to further analysis belong to the category of foldable and dynamic systems, whose general characteristics are closely linked to patterned origami and targeted façade groups. Their detailed study is essential for the development of a sustainable architecture that addresses the ecological and energy challenges of the modern era [17].

### 3.3. MECHANISMS FOR DRIVING KINETIC SYSTEMS

The range of motion of foldable kinetic systems directly depends on the way their components are connected and the degree of freedom that such connections allow. The functional adaptability of kinetic systems relies on the types of mechanical joints that ensure controlled movement of the elements within the system. The selection and application of appropriate mechanical joints are crucial for achieving the desired functionality of kinetic systems.

The types of joints can be classified into three main categories: pantograph joints, hinge joints, and track-and-gear joints.

Pantographic connections articulately connect linear elements (bars), visually forming a scissor-like array. These are commonly applied in transformable façades with a high degree of adaptability, enabling dynamic control of lighting and ventilation. Pantograph systems can be configured as single-line zigzag chains, allowing expansion in horizontal or vertical directions, or as double scissor arrays, providing greater structural stability and more precise movement control [18]. The integration of smart materials and actuators into pantograph systems enhances kinetic performance and improves the energy efficiency of façade structures [19].

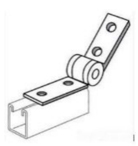
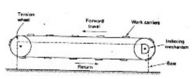
Hinge connections are used in systems where rotational and/or linear movement of façade segments is anticipated. Elements are connected by rotational pivots, enabling movement of a façade part along a single axis, usually perpendicular to the façade plane. Hinge-based systems offer several functional advantages: sequential modulation of the façade, where individual panels operate independently and can open or close according to external stimuli; simulation of origami-like folding, with programmed movements capable of creating complex spatial effects and digital control, which precisely adjusts panel orientation in real-time. Although limited in degrees of freedom, these joints can be significantly improved using advanced materials and techniques.

The mechanism based on caterpillars and gears employs precisely calibrated linear force transmission to control the movement of façade segments. This mechanism operates through the rotation of a central gear track, which transfers force to connected elements, enabling the linear translation of façade panels in a controlled direction [20]. Algorithmic motion control can be integrated into this mechanism, allowing the system to automatically adjust to external conditions [21].

The choice of an appropriate joint depends on the type of kinetic system and the initial geometric pattern on which the system is based. Each joint typology offers specific advantages regarding the constructive characteristics of the system. The development of smart materials and algorithmically controlled mechanisms expands the possibilities of kinetic façade applications, making them a key element of contemporary architectural practice (Table 1).

***Table 1.*** *Types of mechanical connections in kinetic structural systems*

| Type of Joint / Mechanism | Operation Description | Constructive Characteristics | Functions and Advantages | Application Examples |
|---|---|---|---|---|
| **Pantograph Joints** | Hinged rods forming a | Lightweight structure, high expandability, | Adaptive lighting and ventilation, horizontal/vertical | Adaptive façades with zigzag extension, |

| | | | | |
|---|---|---|---|---|
|  | scissor-like sequence | integration of smart materials | expansion, high flexibility | transformable roofs |
| **Hinged Connections**  | Rotational joints allowing segments to move around a single axis | Digital control capability, sequential panel opening, compatible with origami geometry | Folding simulation, complex spatial effects, independent panel operation | Origami-inspired façades, adaptive building envelopes |
| **Gear and Track Mechanism**  | Linear translation via rotating gear track and linked caterpillar-like system | Robust structure, algorithmic control, high motion precision | Synchronized movement of multiple panels, real-time control, load resistance | Industrial façades, pavilions with movable walls |

### 3.4. MODES OF MOVEMENT IN KINETIC SYSTEMS

Kinetic systems most commonly exhibit rotational and/or translational movement of structural elements. Rotational movement is applied in foldable systems where unit elements are connected by mechanical joints that provide a certain degree of freedom during movement. In scissor-like systems, where bars are pivotally connected at joint points, rotation occurs around these connection points. Although pantograph systems do not have folds like origami, they serve the same purpose—multifunctionality in the deployed state and compactness when folded. Pantograph systems achieve a high degree of mobility in the unfolded state, along with a certain level of motion control.

Origami-based kinetic systems utilize an overlapping system where the joint between two overlapping surfaces is a fold line or crease. Unlike the joint point in the previously mentioned systems, a crease is a continuous connection between elements that is structurally restrictive and challenging to execute.

For proper crease formation, it is crucial to precisely define the geometric arrangement of elements as well as determine the degrees of freedom, which is most commonly achieved through the use of advanced algorithms and digital control systems [29]. Equally critical is the appropriate selection of hinge connections that maintain a continuous crease joint between elements.

Linear connections and possible joint details are illustrated in (Figure 4) [22]

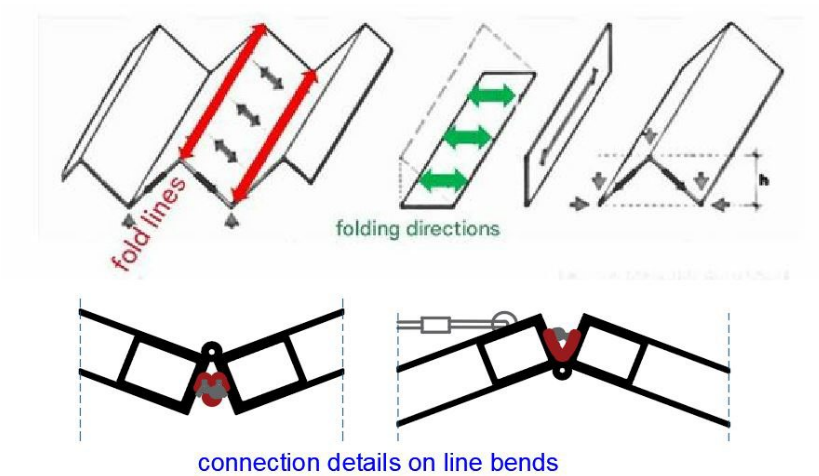



*Figure 4. Linear connections when bending plate elements and possible connection details (Adapted and modified from [22] using AutoCAD 2021).*

The integration of sensors into kinetic systems enables automated control of individual elements. Sensors that respond to external stimuli provide automatic adjustment of the positions of individual components within the façade system, ensuring optimal regulation of lighting, ventilation, and temperature inside the building.

New technologies achieve high precision in motion control, resulting in façade systems being assigned multiple functional requirements, thus becoming a distinct phase in the design process.

## 4. GEOMETRIC, MECHANICAL, AND FUNCTIONAL ANALYSIS OF ORIGAMI PATTERNS APPLIED TO KINETIC FAÇADES

In contemporary architecture, the concept of kinetic façades is associated with adaptive systems that fulfill complex functional and aesthetic requirements. By analyzing applicable origami patterns, their geometric and mechanical properties have been identified, demonstrating the potential to address the complexity of designing such systems. To highlight key parameters of the identified properties, an individual analysis of applicable origami patterns was conducted, focusing on their geometric parameters, mechanical behavior, functional capabilities, and practical application in architecture. A comparative overview of their characteristics is presented in tabular form.

### 4.1. PROPERTIES OF THE MIURA-ORI PATTERN

Miura-ori is a two-dimensional planar pattern composed of parallel folds creating sequences of repeating rhomboid modules, allowing the entire structure to transform in one direction. Its geometric parameters are defined by the length of the longer side of the module *a*, the length of the shorter side *b*, and the folding angle *ϑ*.

The surface area of one module can be calculated as the area of a rhomboid:

$$A = a \cdot b \cdot sin\theta \tag{1}$$

A key characteristic is that the foldable surface simultaneously contracts and expands in multiple directions while maintaining its planarity. Mechanically, Miura-ori exhibits a negative Poisson's ratio, meaning that it expands in one direction when stretched in another. This property makes the Miura-ori pattern highly suitable for systems requiring synchronized and controlled multi-directional movement.

Practically, it has been applied in projects such as the Al Bahr Towers (Aedas Architects), where an automated system with mashrabiya panels controls solar shading, and on the façade of the Tokyo Museum, where panels dynamically contract and expand according to sunlight, reducing the need for artificial climate control.

### 4.2. PROPERTIES OF THE WATERBOMB PATTERN

The Waterbomb pattern consists of symmetrical triangular elements that, through successive folding, enable spherical expansion and contraction. It is based on alternating "mountain" and "valley" folds and utilizes bistability during transformation. Geometrically, it is characterized by radial symmetry and clearly defined rotation centers, enabling uniform opening and closing. Since the symmetrical triangles form within a regular square grid, the primary parameters are the square side length l and the folding angle a. By varying these parameters; the basic module can transition from a flat to a conical shape, whose volume after transformation is given by the formula:

$$V(\propto) = l^3 \cdot sin \propto \qquad (2)$$

In geometric terms, the order of folding changes as a result of volume variation. The fundamental mechanical property of such a structure is its high resistance to axial stresses. It has been implemented in the experimental Origami Pavilion (ICD Stuttgart) as a movable sun-shading device and in the "Waterbomb Pavilion" (Singapore), where it serves as a deployable principle for temporary structures.

### 4.3. PROPERTIES OF THE YOSHIMURA PATTERN

The Yoshimura pattern originates spontaneously from the axial compression of a cylindrical surface. It consists of repeating hexagonal and rhomboid elements formed by diagonal folds. Geometrically, it is defined by a regular arrangement of rhomboid modules, with key parameters being the radius of the cylindrical base $r$, the height of the module $h$, and the folding angle $\beta$.

The surface area of one module can be calculated using the formula:

$$P = 2 \cdot r \cdot h \cdot sin\beta \qquad (3)$$

The Yoshimura pattern is characterized by efficient load transfer and high load-bearing capacity in one direction. It exhibits axial stiffness and elasticity under torsional loads. It is applied on façades requiring a high degree of stability and complex form language. Experimentally, it has been used on façades at ETH Zürich and MIT Media Lab, where movable panels bend in response to temperature or electrical stimuli.

### 4.4. PROPERTIES OF THE KRESLING PATTERN

The Kresling pattern is a helicoidal origami structure formed by twisting cylindrical bodies. Geometrically, it consists of triangular elements spirally arranged around a circular base.

The main parameters are the base radius *R*, the height of the module *h*, and the folding angle $\vartheta$.

The length of the spiral can be calculated as:

$$L = \sqrt{[(2 \cdot \pi \cdot R)^2 + h^2]} \tag{4}$$

Its defining features include bistability and the ability to align with a central axis of rotation. The pattern also demonstrates a high degree of torsional resistance.

Kresling is applicable in kinetic systems requiring spiral motion. Practically, it has been utilized in research projects such as Flectofold and HYTAF, focusing on the development of pneumatic panels. It has also been implemented in the “Spiral Kinetic Skin” façade project in Munich, as part of a kinetic façade responsive to changing weather conditions.

***Table 2.*** *Comparative Geometric and Mechanical Analysis of Origami Patterns*

| Pattern | Geometric Parameters | Transformation | Mechanical Properties | Formula(s) |
|---|---|---|---|---|
| **Miura-ori** | a – longer side of the module<br>b – shorter side of the module<br>θ – folding angle | Linear contraction and expansion<br>Unidirectional transformation with planarity | Expansion in both directions | $A = a \cdot b \cdot sin\theta$ |
| **Waterbomb** | l – side length of the square<br>α – folding angle | Spherical expansion and contraction | Bistability, nonlinear volume change,<br>resistance to axial stress | $V(\propto) = l^3 \cdot sin \propto$ |
| **Yoshimura** | r – radius of the base<br>h – module height<br>β – folding angle | Axial compression<br>Bending due to external influences | Axial stiffness, elasticity under torsion | $P = 2 \cdot r \cdot h \cdot sin\beta$ |
| **Kresling** | R – base radius<br>h – module height<br>θ– folding angle | Spiral expansion and contraction | Bistability, torsional resistance,<br>capability of central axis rotation | $L = \sqrt{[(2\pi R)^2 + h^2]}$ |

The tabular overview of the patterns' properties summarizes the fundamental geometric parameters and mechanical characteristics, which form the basis for developing parametric models within software environments. Each of the analyzed patterns can be abstracted through clearly defined input variables such as segment lengths, folding angles, number of modules, or axes of symmetry.

Thanks to this approach, by inputting these variables into software tools, it is possible to instantly visualize changes in the model’s behavior as parameters are modified. For example, adjusting the folding angle in the Miura-ori pattern or the number of modules in the Waterbomb pattern enables geometry optimization, depending on the application context—whether it concerns solar shading regulation, ventilation, or façade transformation.

Moreover, this approach enables the integration of algorithms for simulating mechanical properties of the models (such as flexibility, stability, or torsional deformation), turning the software tool into not only a geometric modeling platform but also a comprehensive system for interdisciplinary parametric analysis. The previously mentioned opens up opportunities for optimizing façade systems according to specific performance criteria—energy efficiency, climate adaptability, modularity, and ease of assembly.

Ultimately, transferring the defined parameters from the table into software facilitates the automation of the kinetic façade design process and its adaptation to various constructive requirements. Thus, origami evolves from mere inspiration to a concrete engineering tool.

## 5. PARAMETRIC DESIGN

The parametric design of kinetic systems based on origami enables the examination of complex geometric models through the simulation of various loads and external influences. Preparing a model for parametric design involves the prior selection of an appropriate origami pattern upon which the kinetic system's construction will be based. This preparation requires a multi-criteria analysis encompassing the evaluation of geometric characteristics, mechanical properties, aesthetic potential, element compatibility, functionality, and kinetic capabilities of the patterns [23]. Within this analysis, origami patterns are selected based on their properties and potential for implementation in kinetic façade systems, whereby it is essential to isolate a model that meets specific design requirements.

Following pattern selection, the fundamental geometric matrix is modeled using software tools, most commonly Rhino and Grasshopper. The analysis of the modeled pattern is conducted by varying parameters and observing the model's behavior in response to these changes. In this way, the geometric characteristics are optimized, narrowing down the selection to those that satisfy the established design criteria. Once parameters for individual elements (typically triangular or square-shaped) are set, it becomes possible to investigate their boundary values by varying the parameters. The next step involves multiplying individual elements and connecting them into a system by simulating hypothetical connections along the joining lines. Subsequently, parameter testing is repeated to determine the behavior of the interconnected system composed of individual elements.

When such a system is considered as a kinetic façade, additional parameters (such as external variables like solar exposure or wind simulation) can be incorporated into the model testing. Based on these extended parameter tests, a comprehensive analysis of the kinetic system's behavior under real-world conditions is obtained. A summary of parameters used for parametric analysis is presented in (Table 3).

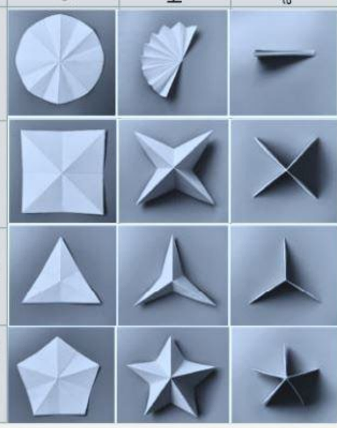
***Table 3.*** *Parameters for parametric analysis of kinetic systems based on origami*

| Parameter | Description | Values | Note |
|---|---|---|---|
| **Rotation Angle** | Degree to which the element rotates around a central point | 0° - 180° | Controls rotation between elements, affecting system mobility. |
| **Folding Angle** | Angle between folded parts of the element | 10° - 90° | Determines how elements overlap, impacting stability and energy performance. |
| **Joint Position** | Location of the joint or hinge in the system | (X, Y, Z) | Affects synchronization of movement and system balance. |
| **Material Elasticity** | Resistance of the material to stretching and compression | High, Medium, Low | High elasticity enables better movement adaptation; low stabilizes the form. |
| **Deformation** | Maximum allowable deformation under load | 0–5% | Helps assess flexibility in response to environmental changes. |
| **UV Resistance** | Degree of protection against UV radiation affecting material durability | High, Medium, Low | Impacts long-term durability in outdoor conditions. |
| **Light Transmission** | Ability of the material to transmit light, important for interior comfort | 30% – 80% | Affects how much light enters, influencing the building's energy performance. |
| **High Temperature Tolerance** | Ability of material to withstand high temperatures without deforming | High, Medium, Low | Determines suitability for extreme environments (e.g. hot climates). |
| **Number of Movements** | Number of distinct movements the element can perform in all directions | 2, 3, 4 (high complexity) | Affects system dynamics and interaction with external stimuli. |

### 5.1. PARAMETRIC ANALYSIS OF THE BASIC ELEMENT OF THE SYSTEM

In the process of evaluating the characteristics of geometric elements derived from origami patterns, the highest rating, according to previous research, was awarded to the quadrilateral element, which—based on prior analysis—belongs to the Waterbomb pattern (Table 4) [24]. The distinguishing features of this element compared to others are its versatile shaping possibilities and compactness in the folded state. Within the quadrilateral matrix, precise edge alignment is possible when overlapping multiple identical elements, effectively eliminating irregularities at vertex overlaps. This property makes it particularly suitable for applications in constructions that require high precision during folding and unfolding operations.

***Table 4.*** *Rated characteristics of basic geometric shapes from origami samples* [24]



| FORM | developed | half unfolded | assembled | EVALUATION OF CHARACTERISTICS | simplicity | aesthetics | rigidity | economy | functionality | folding | mobility | materialization | OVERALL SCORE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LAP | | | | | 0.6 | 0.7 | 0.9 | 0.6 | X | 0.1 | 0.5 | 0.54 | 3.94 |
| QUADRANGLE | | | | | 0.8 | 1.0 | 0.8 | 0.8 | 0.8 | 0.9 | 0.8 | 0.84 | 6.74 |
| TRIANGLE | | | | | 0.9 | 0.9 | 0.8 | 0.8 | 0.8 | 0.7 | 0.9 | 0.83 | 6.63 |
| PENTAGON | | | | | 0.6 | 0.6 | 0.7 | 0.7 | 0.5 | 0.6 | 0.6 | 0.63 | 4.93 |

After selecting the most favorable geometric form, the next step is its integration into the context of a structural assembly created by its multiplication. This involves monitoring its behavior within the broader system, where the parameters of the basic element are previously defined with precision, as these parameters directly determine how the element will behave within the structural assembly [21].

The property that governs the behavior of an individual element (module) within the origami system is its geometry in both the folded and unfolded states. Understanding this geometry is crucial, especially when system stability is a requirement [25]. In this regard, accurately defining the parameters of the individual element enables maximum efficiency in its integration into the structural system.

The final steps in this process involve selecting the materials whose properties will be specified during simulations of the element's behavior within the façade system. This ensures that the design solutions meet high standards of both functionality and aesthetics.

## 6. MATERIALS

In the design of kinetic façades, besides the careful selection of basic elements, the choice of materials is of essential importance. Materials must meet several requirements: low weight, ease of installation, resistance to external environmental factors, fire resistance, and a certain degree of daylight transmission. Meeting these requirements is crucial for material selection, as it directly affects the efficiency, durability, and functionality of the system.

Some materials that can fulfill these specific demands include fiberglass-reinforced PTFE and silver carbon fibers, both recommended due to their distinct characteristics. Fiberglass-reinforced PTFE, due to its high resistance to temperature and UV radiation, is often used in projects that require excellent durability against harsh external conditions, such as buildings located in regions with extreme weather. This material is extremely lightweight, facilitating installation and reducing the overall weight of façade systems. An example is The Eden Project in the United Kingdom, where fiberglass-reinforced PTFE was employed for geodesic domes composed of interconnected panels. This material enabled the structure to be highly resilient to external influences while allowing light transmission, thus creating controlled internal conditions favorable for plant growth.

On the other hand, silver carbon fibers possess not only low weight but also outstanding mechanical properties, making them suitable for kinetic façades requiring high mobility. At the Mercedes-Benz Museum in Stuttgart, carbon fibers were used for the façade structure that dynamically responds to external stimuli. The low weight of the fibers, combined with their ability to withstand high stresses, reduced the need for energy-intensive mechanical systems for movement.

Besides these specialized materials, other composite materials are also employed in kinetic façade construction, such as:

- ETFE (ethylene tetrafluoroethylene) films, used in the Beijing National Aquatics Center. This material allows significant light transmission while exhibiting high resistance to environmental factors. ETFE films are lightweight and easy to install, making them suitable for kinetically demanding and aesthetically complex systems.
- Aerogel, a lightweight gel-like material in which the liquid component is replaced by gas, is also being investigated for kinetic façade applications. Aerogel possesses excellent insulation properties and can reduce energy consumption, which is critical for maintaining internal temperatures in buildings that use movable elements for thermal regulation.

Material selection depends on the specific requirements of each project, including resistance to weather, ease of assembly, mechanical strength, and light transmission. The analysis preceding material choice involves incorporating material characteristics into parametric models and simulating model behavior under assumed external influences.

***Table 5.*** *Properties, Constructive Characteristics, and Applications of Materials in Kinetic Façade Systems*

| **Material** | **Properties** | **Constructive Characteristics** | **Examples of Application** |
|---|---|---|---|
| **Teflon with fiberglass** | High temperature and UV resistance, extremely lightweight, translucent | Extremely light, resistant to external factors, good light transmission, durable | The Eden Project (UK), geodesic domes |
| **Silver carbon fibers** | Low weight, excellent mechanical properties, high stress resistance | High strength, lightweight, long-lasting, suitable for kinetic façade systems | Mercedes-Benz Museum (Germany), kinetic façades |
| **ETFE film** | Resistant to external conditions, lightweight, high light transmittance | Easy to install, flexible, suitable for complex geometries | Beijing National Aquatics Center (China) |
| **Aerogel** | Extremely light, excellent insulation, low thermal conductivity | Ultra-low density, high thermal insulation, energy-saving potential | Experimental projects, potential use in kinetic façade systems |

## 7. SIMULATION OF ELEMENT BEHAVIOR WITHIN THE FAÇADE SYSTEM

Simulation of kinetic façade system behavior, once project-specific conditions are taken into account, is crucial for verifying stability and functionality. Parametric models developed in software tools enable designers to manipulate the geometry and movement of elements in various hypothetical scenarios. By varying parameter values (such as rotation angle, joint position, or fold angle), it is possible to examine the system's behavior under simultaneous exposure to different influences.

For example, in kinetic façade projects using flexible materials, behavior simulation can demonstrate how the façade reacts to changes in temperature, light, or wind force. These simulations primarily test the joint systems on the parametric model to achieve synchronized movement of elements. Furthermore, simulation allows designers to monitor the behavior of elements and connections under conditions that are not always easily replicable in experimental testing of physical models. This includes simulating façade responses to multiple simultaneous external influences in real-time at a specified location.

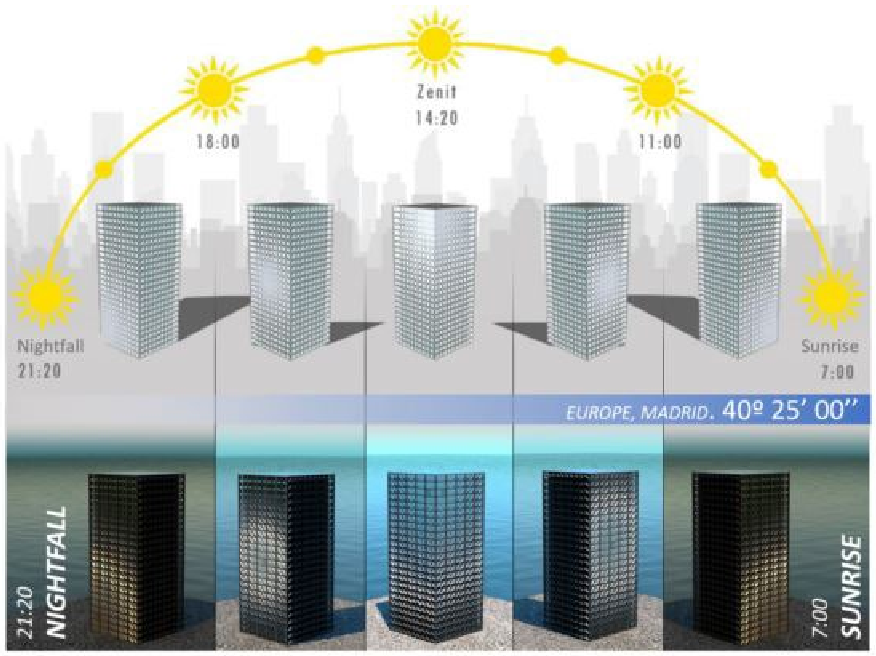



*Figure 5. Simulation of the impact of solar radiation on movable façade elements [24]*

For example, a façade exposed to simulated sunlight can demonstrate how façade elements will position themselves to allow light transmission and heat accumulation , as illustrated in (Figure 5) [24]. Such simulations enable the early detection of potential irregularities in the system before they are realized in physical form. When testing different scenarios, how and when the façade will respond to external influences during various seasons or in different geographic locations, the immediate reaction of the façade on the simulated model can be observed.

Simulations also allow for the optimization of joint systems, which is crucial for the overall functionality of the system. Since the façade dynamically adapts to external changes, the joint system must be flexible enough to enable synchronized movement yet sufficiently stable to ensure the long-term durability of the system.

## 8. CONCLUSION

This paper proposes a methodology for designing kinetic façades based on origami patterns. Incorporating these patterns into the construction of kinetic façades represents a significant step in architecture that actively communicates with its environment. The analysis of the geometric, mechanical, and functional characteristics of the patterns shows that origami is not used merely for aesthetics, but as an optimized structural tool enabling façade movement while maintaining simplicity in motion.

Applying the patterns' characteristics to façade systems allows control over surface deformations through clearly defined geometric parameters. As a result, it is possible to design façade systems that precisely open and close in response to external stimuli. Their predictable mechanical behaviors (such as isotropic flexibility in Miura-ori, bistability in the Waterbomb pattern, or torsional elasticity in Kresling) enable the construction of systems that do not require complex mechanisms but operate based on transformable geometry.

Although origami systems offer numerous advantages, their application presents certain challenges. Designing them requires a deep understanding of nonlinear geometry and material behavior during transformation. The high number of folds and joints creates sensitive points that must be carefully dimensioned and constructed. An additional challenge is the transition from digital to physical models, where deviations often occur due to material limitations, joint tolerances, and assembly complexity. Furthermore, reliable activation methods (mechanical, pneumatic, or electromagnetic) must be devised to ensure precise transformations at desired intervals.

Further research should focus on the development of multifunctional materials (such as shape-memory alloys and active polymers), optimization of digital prefabrication processes (especially 3D printing of flexible joints), and integration of sensors and automation within the panels themselves. This would create a smart façade that autonomously detects environmental conditions and responds accordingly, without the need for complex external control systems.

Ultimately, origami in architecture represents not only an inspiration but a concrete tool for designing sustainable, flexible, and intelligent architectural systems. Its application to kinetic façades has the potential to redefine the relationship between buildings, users, and the natural environment, enabling architecture to become dynamic, responsive, and energy-efficient.

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## КИНЕТИЧКЕ ФАСАДЕ ИНСПИРИСАНЕ ОРИГАМИЈЕМ: ПРИСТУПИ, МАТЕРИЈАЛИ И ТЕХНОЛОГИЈЕ

**Сажетак:** Традиционална улога фасаде, историјски усмјерена на пружање заштите од услова околине и смањење емисије $CO_2$, значајно је редефинисана захваљујући напретку у софтверским технологијама и науци о материјалима. Ови развоји су довели до појаве фасадног система као структурно независне компоненте која функционише као активни регулатор потрошње енергије, стварајући тако нове могућности за истраживање и иновације. Један од приступа проучавању ових система укључује примјену принципа савијања изведених из оригамија, што олакшава пројектовање модуларних геометријских структура способних за динамичке реакције на животну средину. Фасаде састављене од међусобно повезаних, хомогених елемената могу ефикасно регулисати продор дневне свјетлости и акумулацију топлотне енергије, посебно у зонама изложеним директним спољним утицајима.

Да би се такви системи даље развијали, неопходно је осмислити оригами образац чије геометријске и механичке карактеристике могу потенцијално да одговоре на дате конструктивне и техничке изазове. Ова студија истражује потенцијалну примјену одабраних оригами образаца у кинетичким фасадним системима, са фокусом на анализу механизама актуације који контролишу кретање геометријских модула. Штавише, истраживање процјењује оправданост интеграције кинетичких фасадних система у савремену архитектонску праксу, са циљем доприноса развоју одрживих, адаптивних и енергетски ефикасних омотача зграда.

*Кључне ријечи: кинетички фасадни системи, оригами шаблон, модуларне структуре, параметарски дизајн, енергетска ефикасност*