Symmetry groups for understanding and interpreting structural grids of kinetic skins in architecture

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MİMARLIKTA SAYISAL TASARIM XV. ULUSAL SEMPOZYUMU

Mimaride Kinetik Yüzeylerin Yapısal Gridlerini Anlamak ve Yorumlamak için Simetri Grupları

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Özet

Kinetik yüzeylerin yapısal gridleri, mekanik ve görsel önemlerine rağmen, erken tasarım aşamalarında çoğunlukla ihmal edilmektedir. Grid tasarımı, gridin barındırdığı kinetik yüzey ile birlikte düşünülmelidir çünkü bu yapılar mekanik bileşenleri ile mutlak bir uyum gerektirmektedir. Aksi takdirde, yüzeyin hareketi sırasında en ufak bir değişiklik mekanizmayı bloke edebilir. Kinetik yapılar kontrollü mekanizmalar olduğu için hareket ve mekanizma önem arz etmektedir. Bu nedenle, yapısal verimliliği ve tasarım çeşitliliğini artırmak için tasarımcıların kinetik kaplamaların yapısal gridlerini anlaması ve yorumlayabilmesi gerekir. Bu bağlamda, bu makale, simetri gruplarını tasarımcılar için alternatif bir yol olarak önermektedir. Simetri gruplarının sağladığı desenler kinetik yapıların grid sistemlerine dönüşebilir.

Mevcut çalışmalar çoğunlukla bir desen oluşturma aracı olarak simetri gruplarını araştırmaktadır. Yeni desenler yaratmanın ötesinde, simetri grupları tek bir motiften veya bütüncül bir yapısal ağdan oluşan kinetik yüzeylerin gridleri hakkında bir anlayış vermektedir. Bu anlamda, bu makale mevcut çalışmalardan ayrılır. Buna göre, bu makale, simetri grupları ile mimarideki kinetik yüzeylerin grid düzeni arasındaki ilişkiyi göstermeyi amaçlamaktadır. Bu bağlamda simetri gruplarının matematiksel örüntülerini kinetik yüzeylerle ilişkilendirerek bu grupları kinetik yüzeylerin grid tasarımı için yorumlar. Bu yorumlama yüzeyin hareketine dayandırılarak yapılmaktadır çünkü kinetik yüzeyler form değiştiren hareketli bileşenlerdir.

Bu çalışmanın kinetik yapılar alanına özgün katkısı, tasarım çeşitliliği için yapısal gridleri anlama ve yorumlamanın alternatif bir yolu olarak mimarlara veya tasarımcılara simetri gruplarını sunmasıdır. Çalışmanın sonucu, bir grid tasarımının yapısal hareketin kendisine doğrudan bağlantılı olduğunu göstermektedir. Bu nedenle kinetik yapıların hareketi sırasında hareketi tanımlayan kılavuz çizgilerinin merceğinden düşünülmeleri gerekir. Tasarımlara bütüncül bir bakış açısı sunmasının yanı sıra, kinetik yüzeylerin simetri gruplarına bağlı olarak oluşan desenlerini dikkate alınarak tasarım çeşitliliği arttırılabilir.

Anahtar Kelimeler: *Kinetik yapılar, simetri grupları, yapısal grid.*

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MİMARLIKTA SAYISAL TASARIM XV. ULUSAL SEMPOZYUMU

Symmetry Groups for Understanding and Interpreting Structural Grids of Kinetic Skins in Architecture

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Abstract

Structural grids of kinetic surfaces are mostly neglected in the initial design phases in spite of their mechanical and visual significance. The grid design needs to be considered together with the hosted kinetic surface because these structures should be compatible with their mechanical components. Otherwise, the slightest change in the assigned motion can bloke the mechanism. Motion and mechanism are significant as kinetic structures are controlled mechanisms. Hence, designers need to understand and interpret structural grids of kinetic skins to increase efficiency and design variety. In this regard, this paper proposes symmetry groups as an alternative way for designers since these symmetry groups are related to tessellations. Indeed, These tessellations can be grid systems in architecture.

Existing studies mostly investigate symmetry groups as a pattern generation tool. Beyond creating new patterns, they give an understanding of kinetic surfaces' grids whose pattern can be either a single motif or an entire network. In this sense, this paper differs from existing relevant studies. Accordingly, this paper aims to show the relation between symmetry groups and the grid layout of kinetic surfaces in architecture. In this regard, it associates mathematical patterns of symmetry groups with kinetic surfaces. Then, it interprets these groups for grid design of kinetic skins in terms of the motion as kinetic surfaces are the moving bodies shifting their form.

The original contribution of this study to the field of kinetic structures is that it offers architects or designers symmetry groups as an alternative way to understand and interpret structural grids for design variety. The result of the study shows that a grid design is linked to the motion during deployment, so they need to be considered from the lens of descriptive guidelines of moving bodies. Considering tessellations of kinetic surfaces based on symmetry groups, design variety can be increased, and their design would be performed from a holistic perspective.

Keywords: *Kinetic structures, symmetry groups, structural grid.*

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1. Introduction

Many responsive structures have structural grids to which they are implemented buildings main skeleton in performative design. These structures become an integral part of the main building and significantly impact interior space, as exemplified in **Figure 1**. These grids host kinetic surfaces during deployment to allow proper delivery of the assigned motion. Therefore, their design should be compatible with the motion, topology of the kinetic structure, and buildings main structure. Despite their mechanical and visual significance, structural grids of kinetic skins are mostly neglected in the initial design phases. Their design should be considered together with kinetic surfaces since kinetic structures require compatibility of their mechanical components as well as visual aesthetics. Otherwise, the slightest change in the assigned motion can bloke the mechanism. Hence, designers need to understand and interpret structural grids of kinetic skins to increase efficiency and design variety. In this regard, this paper proposes symmetry groups as an alternative way for designers as these symmetry groups are related to tessellations. These tessellations actually can be grid systems in architecture.

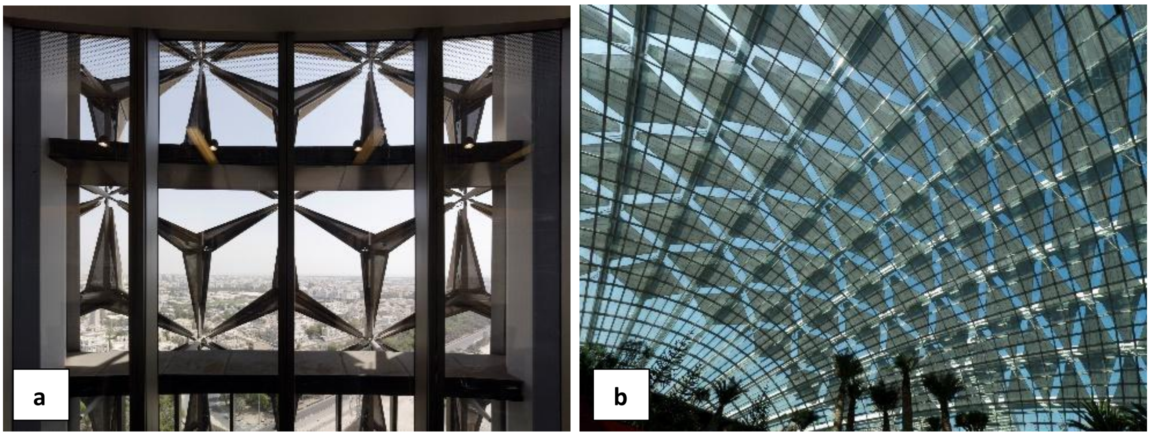

Figure 1: The interior view of kinetic structures. **a:** Al Bahar Towers (Richters, n.d.). **b:** Gardens by the Bay (Soh, n.d.).

There are studies concerning symmetry groups linked to tessellations. Miura & Tachi (2010) focus on collapsible cylindrical structures, which have particular importance in the structural engineering field. Authors perform symmetry operations to synthesize space-filling tessellations. This research reveals how tessellations affect structural quality. Schenk (2012) argues that these patterns can be combined with advanced mechanical properties such as increased bending stiffness which enables folded plate roofs to span larger areas. Sareh & Guest (2015) study the Muira-ori pattern in relation to the symmetry groups. Based on manipulations of the initial pattern, design variations are performed, either as flat or curved. These tessellations need to be reviewed from the lens of mathematics since underlying rules directly affect how a pattern is constructed. In this context, Lang (2018) investigates the mathematics of symmetries of tessellations.

According to Mehaffy (2020), the contemporary application of theories of symmetry to architecture and built environments is an immature research field. In recent years, there are studies on symmetry groups concerning human perception. Salingaros (2020) studies human perception relies upon combined symmetries to reduce information overload, yet disorganized information is too much for a human to process. Our brain automatically compares and groups architectural elements into larger wholes. We unconsciously analyze and process the information in any composition using mathematical relations that endow meaning to our environment. When it comes to building facades as the outer surface of the building, Azemati et al. (2020) state that the façade is an important part of the urban-scape and has a significant influence on the aesthetic preferences and physiological reactions of people. Given that the aesthetic experience of the façade as well as its perception and feeling by humans is mostly done through the visual sense and begins with the visual scan of the work, so the study of the interaction between "bottom-up" and "top-down" processes can be accompanied by a study of eye movement behavior in aesthetic experience.

In recent years, another field of study related to symmetry groups in architecture is pertinent to material science concerning performative design. According to Mao et al. (2020), existing architecture design approaches such as bioinspiration, Edisonian, and optimization generally rely on experienced designers' prior knowledge, limiting broad applications of architectured materials. Particularly challenging is designing architectured materials with extreme properties, such as the Hashin-Shtrikman upper bounds on isotropic elasticity in an experience free manner without prior knowledge. Therefore, the authors present an experience-free and systematic approach for the design of complex architectured materials with generative adversarial networks. The networks are trained using simulation data from millions of randomly generated architectures categorized based on different crystallographic symmetries. On the other hand, Tiong et al. (2020) state that the robust and automated determination of crystal symmetry is of utmost importance in material characterization and analysis. Recent studies have shown that deep learning methods can effectively reveal the correlations between X-ray or electron-beam diffraction patterns and crystal symmetry. Despite their promise, most of these studies have been limited to identifying relatively few classes into which a target material may be grouped. On the other hand, the deep learning-based identification of crystal symmetry suffers from a drastic drop in accuracy for problems involving classification into tens or hundreds of symmetry classes severely limiting its practical usage. Hence, the authors demonstrate that a combined approach of shaping diffraction patterns and implementing them in a multistream DenseNet substantially improves the accuracy of classification.

To sum up, existing and emerging studies mostly investigate symmetry groups from the perspectives of cognitive science, material science, and mathematics. Although the prior motive of most of the studies depends on the performative design, they still consider symmetry groups as a pattern generation tool or from their categorization accuracy. Nonetheless, beyond creating new patterns, they give an understanding of kinetic surfaces' grids whose pattern can be either a single motif or an entire network. In this sense, this paper differs from existing relevant studies. Accordingly, this paper aims to show the relation between symmetry groups and the grid layout of kinetic surfaces in architecture. In this regard, it associates mathematical patterns of symmetry groups with the kinetic surfaces and interprets these groups for grid design of kinetic skins in terms of the motion as kinetic surfaces are the moving bodies shifting their form.

2. Methodology

The generation of an entire kinetic surface is based on the way modules come together. In fact, it depends on symmetry groups which are based on translation, rotation, reflection, and glide reflection. These groups affect the entire system both formally and structurally. Kinetic structures which are associated with 17 wallpaper groups are the combinations of type of symmetry groups as indicated in **Figure 2**.

Based on the 17 symmetry groups which are briefly explained above, this paper firstly relates symmetry groups with a grid layout of kinetic surfaces. It shows how symmetry operations can be assigned to construct or decode kinetic modules. These modules can be a single motif or an entire surface. Then, these groups are inspected in regard to the motion because grid design can alter during the deployment of moving bodies. It is significant to understand what type of forces should be applied to the kinetic surfaces because some of them are linear that may work with tension and/or compression. Some of them are rotational and there are very few types of hybrid forces. Therefore, symmetry groups are to be employed to analyze these type of motions.

The deployment in assigning symmetry groups takes into account the way grids are applied to the building surface. These grids are considered depending on whether it is mobile during movement of the kinetic surface. The results are then discussed together with possible potentials for future studies.

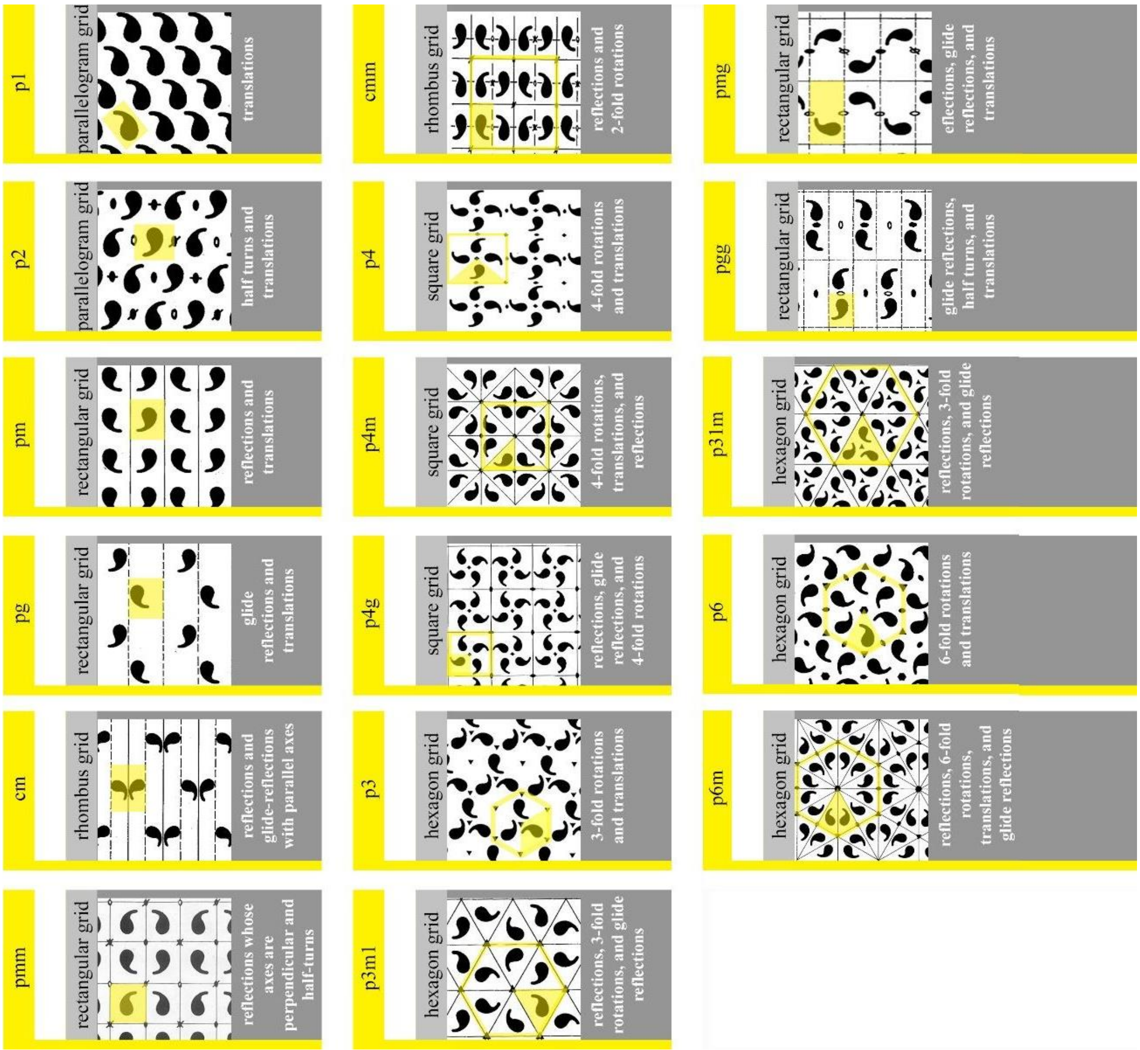

Figure 2: Wallpaper groups. Source for the template images (Wallpaper symmetries, n.d.)

3. Understanding of Symmetry Groups as A Grid Layout for Kinetic Skins

The construction of symmetry groups is described over symbols, as illustrated in **Figure 3**. Those symbols depict the graphical layout of the isometries to indicate key points or lines where motifs' transformations occur. **Figure 4** exemplifies how patterns are analyzed based on reflection axes and/or rotation centers. However, the selection of a motif plays a crucial role in assigning symmetry groups. For example, the selection creates P4 and PMM symmetry groups according to the way motion is delivered in these pictures. Rather than only a pattern generation, the critical criterion in assigning symmetry groups of kinetic structures is its behavior and response in time.

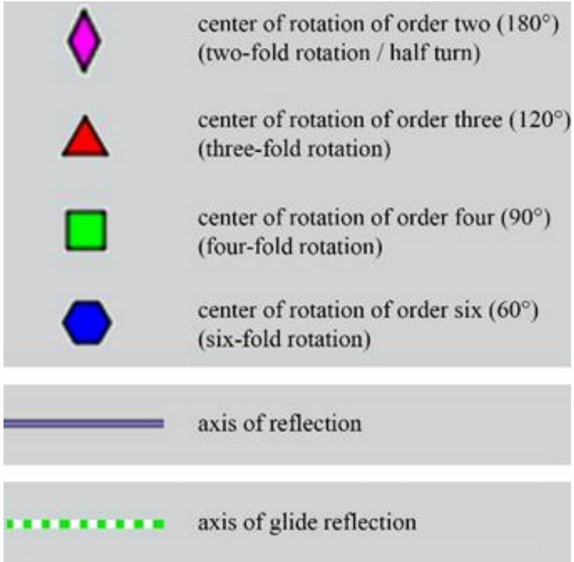

Figure 3: Symbols used in isometries of the Euclidean plane.

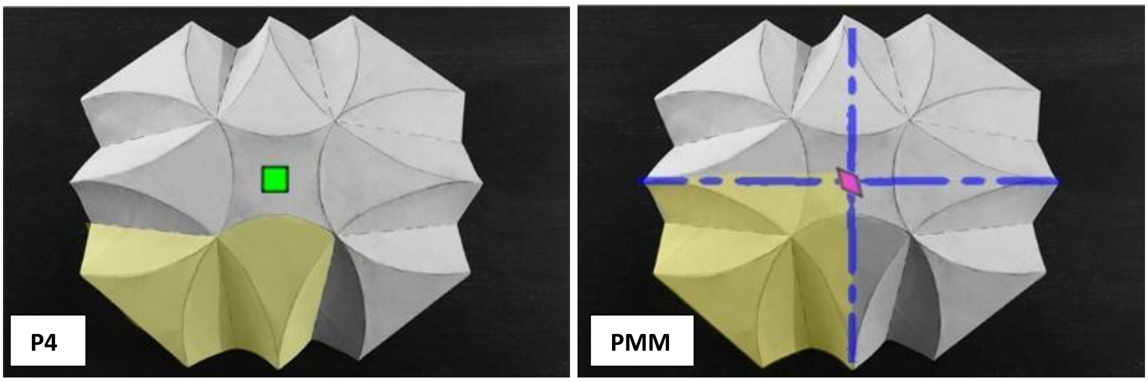

Figure 4: Selection of motif changing symmetry group (developed by the authors).

The discussions stated above are exemplified in **Figure 5.** The rectangular grid of the symmetry group is altered based on the direction of applied forces. In fact, rotational motions are frequently sustained by triangular and hexagonal tessellated grids, whereas translational motions are sustained by square and rectangular ones because the tiles come together to create a tessellation that is already rotational. It should be noted that the grid can change based on motion or designers' choice of overall appearance.

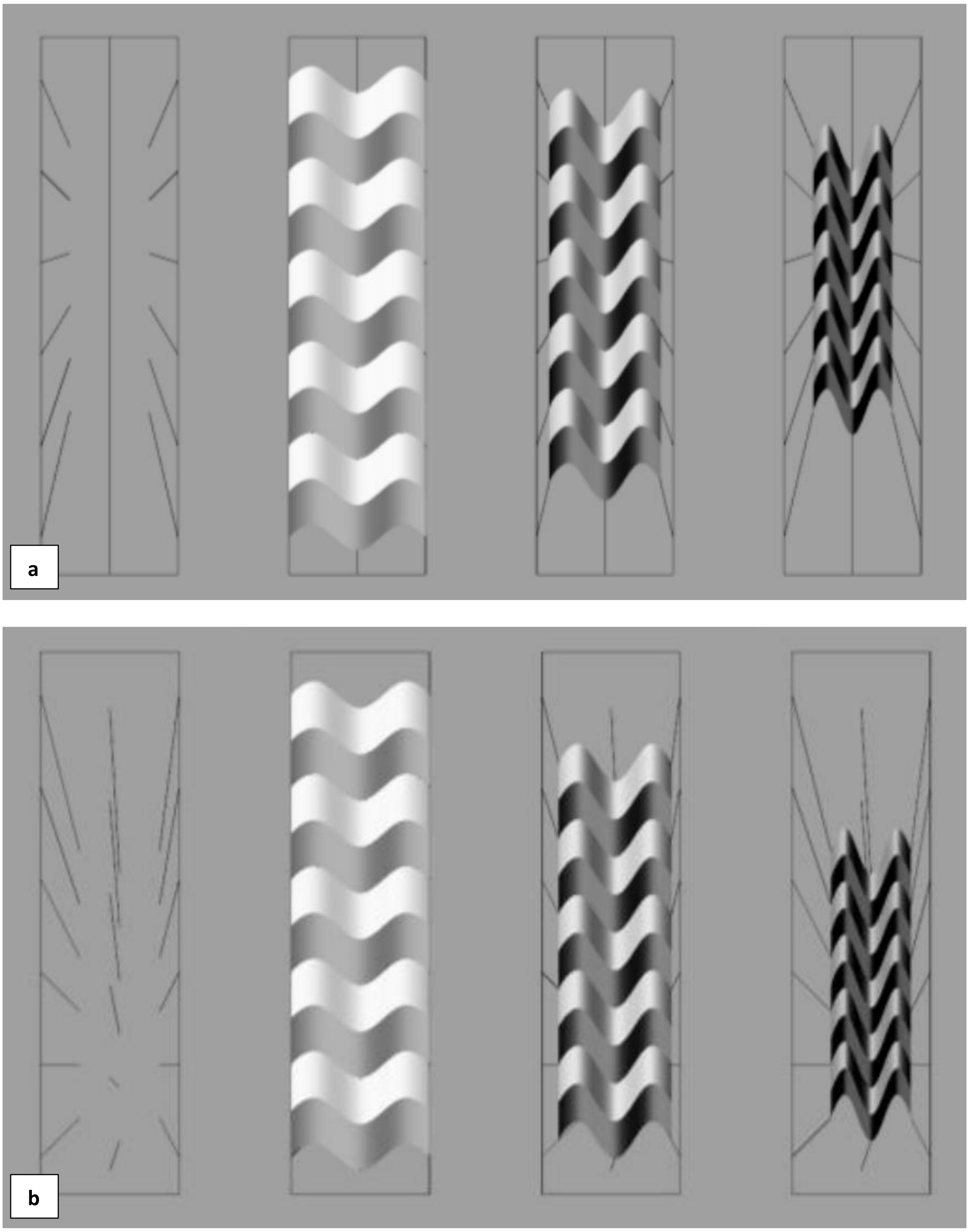

Figure 5: Generation of the grid based on applied forces and the symmetry group. Surfaces in Figure **5a** and **5b** have the same modules yet with distinct directions of the applied forces (developed by the authors)

Even if a surface is a free form that is defined randomly, it still represents the relations among its descriptive lines, because it maintains relations between tangent points of curvatures, distances between consecutive lines, and their symmetry axes. Unless descriptive lines were related to each other, it becomes harder to be able to move precisely. Formations of descriptive lines of many patterns represent symmetry adopted mobility. Understanding geometric formations is essential because even in creating digital simulations, mathematical understanding of kinetic surfaces' patterns allows designers to create appropriate mappings of lines that are linked to grid layouts.

In curved folding, the grid may not be linear or perpendicular in shape, as the pattern shrinks from two directions during motion as indicated in **Figure 5**. Hence, it depends on 2 degrees of freedom (DOF). These two directional forces can be eliminated to some extent if the curved system ends with its saddle points. Otherwise, the remaining parts require additional forces for actuation.

Another critical point in assigning symmetries is the scale of kinetic surface modules. Their grids should be compatible with the building form, floor height, and structural components of the building so that kinetic surfaces can be implemented to the building as an integral part. Therefore, it can be beneficial to start with modifying grids accordingly. Then, kinetic motifs can be mapped to the scaled grid. For instance, in **Figure 6** the grid is mapped into a building skin created according to the ruled surface. The significant thing that should be stressed is that motion remains the same regardless of the change in scale, however, the mechanical and structural behavior of the grid would alter. For instance, required amount of forces, cross section of the grid, material strength would change.

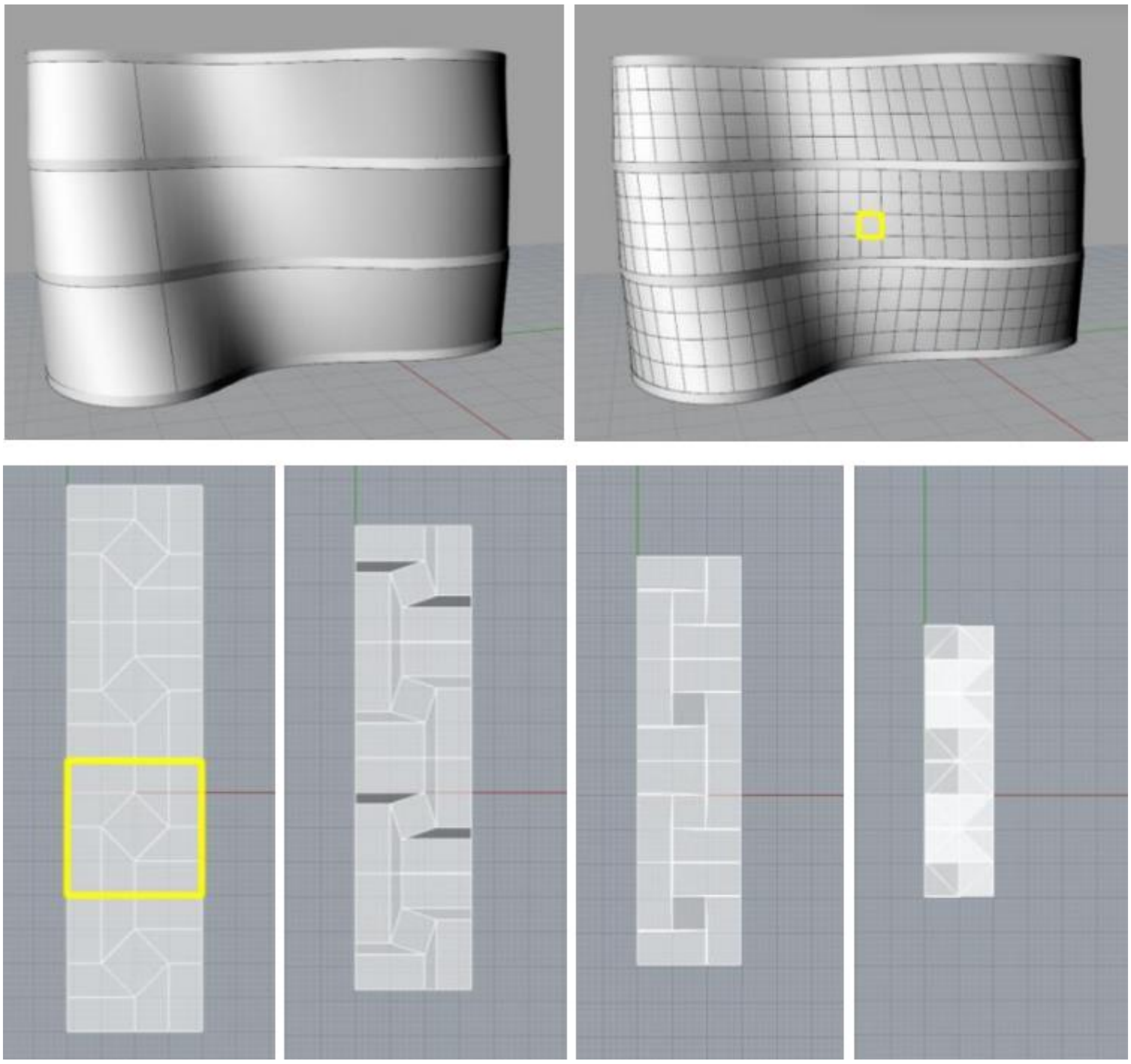

Figure 6: Arranging the grid based on building (developed by the authors)

4. Interpreting Symmetry Groups for Grid Design of Kinetic Skins in Terms of Motion

Symmetry groups help to understand grids not only as static but also motion embedded patterns. As the moving parts of the kinetic surface, the grid can also be kinetic in harmony with these parts and the building structure itself. Many physical applications in architecture implement kinetic surfaces with orthogonal static grids with regular patterns. This is critical from the interior perspective for residents of the building. Beyond having regular patterns, the grids can be interpreted in different ways concerning motion.

Within the context of motion, the grid can be classified under three categories based on the status of the grid structure's motion: fixed, semi-fixed, and moving. This classification depends on symmetry groups and applied forces. The fixed grid remains static during the deployment of the kinetic surface that it holds. A semi-fixed grid indicates a grid whose structure is static, yet some of its mechanical elements can move partially. The last category is the moving grid which moves together with the kinetic surface as a network.

Figure 7 exemplifies these three categories over analog origami models. In Figure 7b, the triangular grid holds the belt-like mechanism (ropes) to pull the curved folding shape towards the center of the triangle. This belt can also be a telescopic bar fixed to the corners of the triangle. Moreover, it can be applied sub-grids into its fixed grid to transmit motion in a balanced way, particularly in curved folding (Figure 7a). Sticks are associated with structural grids and rails to allow motion of curved folding.

Furthermore, the grid can also alter its configuration to allow assigned motion. Instead of actuating the panels directly, actuators can trigger the structural grid so that the grid itself triggers the panels or coverings (Figure 7c). However, the definition of joints is different in this case. Sticks are placed in a play dough that behave like a spherical joint based on their associated angles, and their movement is observed in terms of their motion path lines inside the play dough. This observation gives a clue about how joints should be since those holes in the play dough define where to place rigid links and their range of rotation angles.

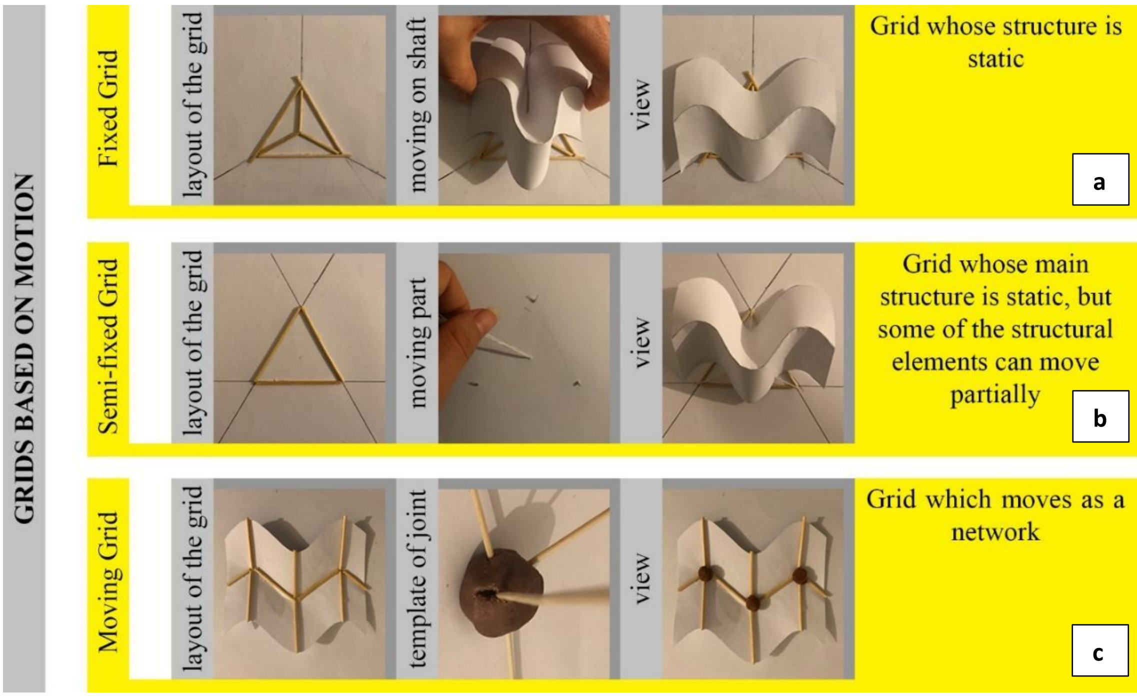

Figure 7: Alteration of a grid based on motion (developed by the authors)

5. Results and Conclusion

17 symmetry groups are mostly investigated in literature as a pattern generation tool, yet in this paper, they are introduced as a way to define kinetic surfaces' grids. This paper shows the possibility to apply the developed model to the entire kinetic skin through by matching patterns with its symmetries. When designing kinetic surfaces working as an entire network, the 2D layout of patterns are tessellations, yet, the geometry of irregular tessellations is so complex that it is harder to solve and control its kinetic system. Hence, it is beneficial to focus on regular and semi-regular tessellations. They are based on symmetry-adopted mobility either it is a single motif or an entire pattern.

It is hard to find symmetries of randomly drawn fold lines. At this point, symmetry groups can give both a kinetic motif and an entire pattern. If it turns into a whole pattern, it becomes critical to find symmetries between kinetic motifs. If it is found, any randomly drawn sketch can turn into an entire kinetic surface. Therefore, the mathematical idea behind kinetic surfaces should be paid more attention.

Understanding mathematical thoughts behind kinetic surfaces and matching their tessellations with symmetry groups allowed to grids of kinetic surfaces. It reveals the clue about the kinetic systems which is matched with symmetry groups helps to create a new language for architectural kinetic surfaces working as a network.

The assignment of symmetry groups as a layout for structural grids of kinetic surfaces revisits kinetic structures considering their application to the main building. The grid is indeed an interface between kinetic structures and the main building and makes the structures an integral part of the building. Decoding grids through symmetry groups will contribute to design space explorations for developing kinetic structures. Besides, it provokes new design alternatives that change the visual appearance of interior design. Beyond functional use, the girds frame the exterior view. Change in the view would change the user experiences as well.

This study is limited to simple paper models, which give clues about its mathematics. However, one-to-one scale prototypes are essential to understand applied forces, materiality, and detailing of the structure more accurately. In addition to mechanical and structural importance, scale is critical for different observers: people looking at the building from outside and inside. The perception of the scale differs according to the position of the people. One might see an entire kinetic surface of the façade while the other sees only the grid of a single slab. In fact, many kinetic facades used for performative purposes are multi-storey buildings that give significance to their iconic view in the city. This design criterion gives priority to the observation from the outside. Even most of the photographs of the kinetic facades are taken from the outside. This duality of observation points highlights the critical importance of scaled prototypes of structural grids.

Last but not least, different use case scenarios such as design for an exterior skin or a ceiling might have different priorities such as exposure to sunlight, gravity, and slope of the applied surface. Therefore, further study will investigate mathematical relations over one-to-one scaled prototypes in different use case scenarios.

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