Transformative Formworks: Towards Mass Customization of Double-Curved Surfaces

Alireza Borhani
Dept. of Architecture,
Texas A&M University
borhani@tamu.edu

Negar Kalantar
Dept. of Architecture,
Texas A&M University
kalantar@tamu.edu

Abstract

To create a highly customized and non-repetitive double-curved element, this research investigated the possibilities, developments, and challenges related to a digitally-driven, reconfigurable molding system called a “transformative” formwork. This formwork is a promising step toward closing the economic gap between existing free-form components and the designs made possible by digital advancements.

A transformative formwork is an array of adjustable vertical elements called bars, coupled with a membrane or “interpolation layer” that rests upon the bar tops. To have a physical double-curved surface similar to this design in a digital model, it is essential that the material of the interpolation layer be streachable. If a non-stretchable material is used for the formwork membrane, the formwork will not accurately generate most of the smooth, double-curved surfaces. This research reviews the results of a preliminary method of resolving this obstacle. By turning an inextensible material into a flexible and stretchable layer, this process presents a newfound capacity to generalize relief-cut patterns into general tiling arrangements, changing the local properties of the formwork membrane. In such cases, every non-developable surface can be fabricated.

Introduction

Boosted by digital modeling tools and Computer-Aided Design (CAD) paradigms, an unprecedented level of formal freedom is currently being enjoyed in the fields of architecture and engineering [10]. Moreover, powerful computational simulation tools are becoming more widely available for assessing the structural robustness and mechanical resilience of free-form components.

Despite industry and academia’s growing interest in designing complex shapes and advancing digital technology, the translation of free-form geometry into real objects has proven to be both difficult and costly. Since the current fabrication methods for geometrically complicated forms are lacking, designers are often left to rationalize the project’s geometry to maximize the number of flat, repetitive, and standard pieces; this reduces the high fabrication costs associated with curved parts [7]. However, forcing a designer to simplify her non-Euclidean building eliminates the opportunity to reflect on changes in the field of design.

The Formal Fluidity of Concrete

Among the various materials used in free-form buildings, concrete is the most widely preferred; this is due to its economic efficiency, workability, strength, and durability [8 & 23]. Since the 20th century, the fluid nature of concrete has challenged many architects seeking to make free-form structures, including Pier Luigi Nervi, Felix Candela, and Oscar Niemeyer, just to name a few. Yet except for exclusive projects, buildings with double-curved concrete panels remain a rarity in contemporary architecture [18].

A number of different tools, materials, and techniques can be employed to cast curved panels out of concrete, such as Computer Numerical Controlled (CNC) foam milling and wire foam cutting; steel, timber, and fiberglass formworks; rubber molds; and pneumatic and textile formworks. Currently, the fabrication process for free-form paneling systems often depends on milling unrecyclable and one-off formworks [2] out of polystyrene foam (EPS) or fiber board (MDF), consuming significant time and manpower. Depending on their use, these formworks are limited by cost, precision, and size [13]. For a project that requires a significant number of heterogeneous panels with a small degree of repetition, there is little opportunity to reuse formworks. For instance, when casting the facade elements for the Zollhof Towers (Dusseldorf, Germany) designed by Frank Gehry, over 350 individual Styrofoam formworks were milled by CNC [5]. This labor-intensive project was literally completed twice: once in Styrofoam as a formwork and a second time in concrete.

The rarity of free-form concrete architecture can be attributed to the high cost of the required formworks, usually from 35% to 60% of the total cost of the concrete structure [6]. The price of a custom-made milled formwork for a double-curved precast cladding element (with a moderate curvature) could make up 60% to 75% of the total concrete work's cost [20].

Transformative Formwork

Luckily, a custom reusable "transformative" formwork can be used to address the shortcomings of subtractive digitally-driven formworks, offering an alternative to disposable CNC milling-cut foam (see Figure 1). This rapidly reconfigurable formwork provides an economically feasible and less labor-intensive fabrication method for both the pre- and post-form processes, and less material waste.

A transformative formwork can be used in two different ways. The first is to cast hardening materials such as concrete on the formwork. The second is to deposit a material that can be softened (e.g., a sheet of heated thermoplastic or glass) that will take the form of the formwork after it cools down [22]. The material can be placed on the formwork either before or after its deformation [19]. The transformative formwork can also be used as either a direct (e.g., by horizontally casting concrete on it) or indirect (e.g., by producing a new mold for vertical concrete casting) formation tool.

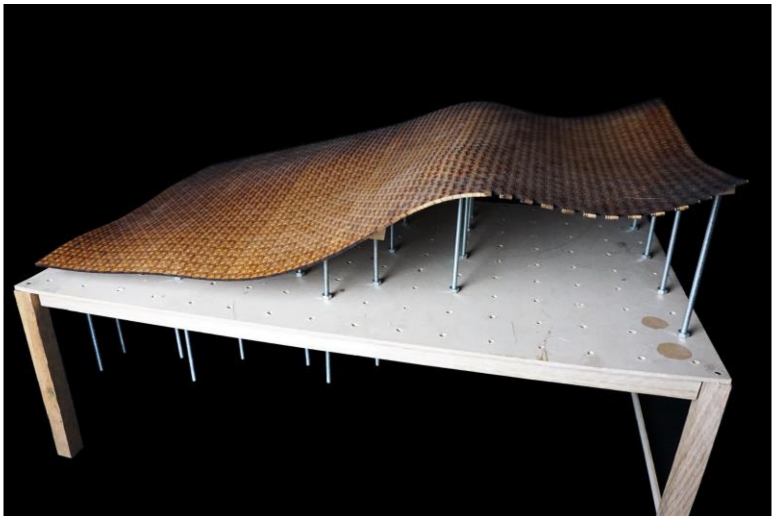

Figure 1. A transformative formwork: a dynamically reconfigurable device for generating a variety of double-curved surfaces.

Precedent Study of Reconfigurable Pin-Type Tools

Leonardo da Vinci became the first to create an adjustable formwork, in the 16th century [16]. More than 154 years ago, the first U.S. patent for such a formwork was granted; it based on the notion of a bed of pins serving as a reconfigurable tool for forming leaf springs on horsedrawn carriages [3]. This concept of the reconfigurable pin-type tool has been elaborated upon ever since, as evidenced by the numerous U.S. patents that have been issued. Interestingly, Munro and Walczyk showed that the majority of patents related to reconfigurable pin-type tooling have been issued after 1990; they differ little from the early patents, except for the use of powered actuation and control [11].

In the 1960's, Italian architect Renzo Piano created a practical transformative formwork to produce double-curved elements [21]. In 1969, he published an article [15] describing a grid-type system of actuators that could be used to make predefined curved shapes. Other researchers, such as Lars Spuybroek and Florian-Peter Kosche, also worked on the concept of a transformative formwork over a number of years. More recently, based on different actuation mechanisms, control tools, and formwork materials, various research groups around the world (both in academia and industry) have produced transformative formwork systems and analyzed their advantages and challenges [16]. Examples of these approaches include, but not limited to, the following:

1. A “**Pinbed**” made out of high-density adjustable pins for industrial prototyping [14].
2. A “**Flexible Mould**” used to deform horizontal concrete when it reaches an acceptable yield strength. After hardening the concrete, a single- or double-curved element is produced [20]. In Denmark, the Adapa Company uses this system to cast thin, double-curvature panels [1].
3. A “**Wax Formwork**” used as a zero-waste counter-mold [13].

Beds of pins of variable heights have been applied in a wide variety of industries and settings, and on many scales, ranging from a handheld toy to a large, custom-cast sail. For example, by pushing a small object against an array of tiny, rounded metal nails in a PinPressions™ toy [4], a person can make a three-dimensional mold of the object that appears as a sculpture (see Figure 2). Alternatively, to orient Kevlar yarn on one continuous headsail and thus match the loads on it more efficiently, a gigantic 3DL sail [12] was manufactured on a full-sized three-dimensional mold supported by a large number of digitally controlled actuators (see Figure 3).

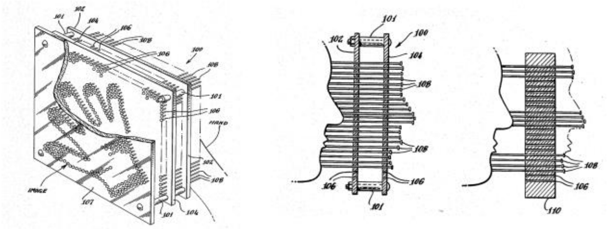

Figure 2. PinPressions toy: Since the nails are free to slide in and out, they can be displaced to different positions to accept new forms. Image source: https://patentimages.storage.googleapis.com/pdfs/US4654989.pdf

Figure 3. A gigantic reconfigurable three-dimensional mold was used to make one continuous three-dimensional headsail that stands up to wear and tear.

Image source: https://northsails.com/sailing/locations/manufacturing-minden-usa

Transformative Formwork as a Machine

A transformative formwork includes an array of individually adjustable vertical elements such as pistons, actuators, or leadscrews that are fixed on a base and either uniformly spaced or closely packed. Here, these vertical elements are identified as bars. The height of each bar can be independently rearranged, resulting in a variety of positions; the result is a matrix of nodal points on a single- or double-curved surface. According to the geometric delineation of the surface in the digital model, the bars can automatically or manually be moved up and down to become the defined shape.

The precise height of each bar is critical to making the desired free-form shape from the digital model. To adjust the formwork and set each bar to the correct position, a numerical dataset is extracted by measuring the vertical lines in the digital model. Each line begins at the base and ends at the surface, corresponding to the height of each actual bar (see Figures 4 & 5).

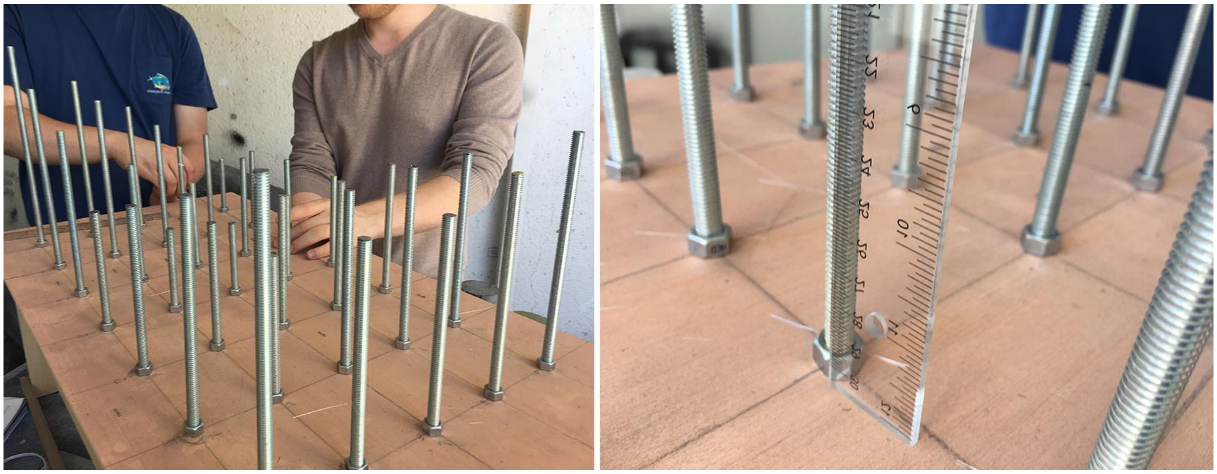

Figure 4. The height of each bar corresponds to the CAD model of the desired double-curved surface. The process of setting the formwork relies on moving the pins up and down, relative to one another.

The bars are not directly workable as a formwork. Therefore, the spaces between the bars must be interpolated by resting a membrane on top; this is called the “interpolation” layer [9]. Depending on the complexity of the final form, an elastic material should be used that can be formed into any free-form surface. Once the interpolation layer has been placed on the bars, the bars’ location and means of attachment are critical to determining the layer’s deformation behavior.

The Challenge of Interpolation Layer Deflection

As mentioned above, the top formwork membrane should interpolate between a set of points defined by the free ends of the bars. Without adding this membrane, the bar endpoints would simply reveal a stair-stepped approximation of the desired surface’s nodal points. The membrane converts the discrete geometric representation of the predefined surface into a 3D smooth-surface finish.

The accuracy of the transformative formwork is critical [20]; it is derived from the precision of the formwork machine components and how the interpolation layer can be manipulated into a given shape. Since each bar specifies a point on the final surface, the complexity and precision of this surface depends on the number and location of each bar, and the distances among them. Although bar actuation mechanisms (e.g., mechanical, pneumatic, or hydraulic) and bar position control methods (e.g., manual or automatic, and in a serial or parallel fashion) are important to achieving a uniform membrane with continuous curves in all directions, the final surface resolution of the membrane relies on the stepped height of each bar.

Two types of membrane, soft and stiff, can be used to form fair, curved surfaces from the bar endpoints. A stiffer membrane provides more equally distributed curvatures, but covers a smaller number of bars with more distance between them. This method offers less control over the geometry of the final surface. Adding to the number of bars not only provides more control over what is obtained, it allows the membrane to be softer [18]. However, in some cases, providing a large number of closely-spaced bars and employing a softer membrane cannot guarantee an even and uniform surface. Using a very soft membrane may cause a dimpled surface, due to local distortions and higher curvature peaks near the bars' endpoints. To suppress this dimpling, a balance of flexibility, rigidity, and thickness must be maintained. The behavior of interpolation layer is contradictory, because while flexibility and a low elastic modulus are essential to accommodating large strain deformations with an elastic response, the layer should also be stiff enough to control deformation and minimize dimpling on the concrete panel produced.

For the interpolation layer to be similar to the form designed in the digital model, deformability is essential; this allows the membrane to smoothen the surface. Since the membrane will be deformed from a flat piece into the designed curvature, in some cases it may be stretched both crosswise and lengthwise. In response to the applied deformation, the membrane must remain non-porous.

Limitations on the possibilities available from transformative formworks are mainly related to the maximum curvature of possible shapes [17]. This comes back to a lack of specific control over the membrane's shape, due to the weight of the concrete and inherent inflexibility of the membrane; it cannot be formed into all desired curved surfaces [21]. Because of the substantial mass of the concrete, a relatively thick material must be used as a membrane, which limits the final panel radii. Here, the physical properties of the membrane's material must allow for geometrical compatibility with non-developable surfaces and a maximum compliance with the desired curvilinear form.

A double-curvature surface is considered non-developable, because it cannot be flattened onto a plane. Most available materials are inextensible, and therefore cannot be deformed beyond a certain limit or flex freely on their own planes. Materials that can be used to make non-developable surfaces with relatively large maximum curvatures are not diverse enough to withstand extensive deformation without stretching, wrinkling, fracturing, or tearing. For instance, a piece of thin plywood is not amenable to creating curved surfaces with very small curvatures. Applying the extra force needed to form non-developable surfaces results in the material being damaged.

The Kerfing Method as a Smoothing Solution

As discussed above, since the membrane layer on the formwork cannot interpolate between the points to match the design drawing, the main challenge is to minimize the differences between the drawing and the membrane's surface. To deform the interpolation layer into a complete double-curved surface, strong forces must be applied in specific areas. Normally, these areas will not tolerate excessive forces and the layer breaks. However, by removing some material in highly stressed areas, the behavior of the layer changes such that it deforms easily.

To turn a rigid planar surface into one that is flexible, a generalized algorithm can be applied to different polygonal meshes; the result is relief-cut patterns consisting of interlocked Archimedean spirals. By controlling the local properties of the pattern, different stiffness values for specific areas can be achieved [24]. By obtaining different degrees of flexibility and rigidity, the formwork interpolation layer can then be deformed as a double-curvature surface (see Figure 5). Here, the process of relief cutting is called kerfing [25].

Figure 5. Applying kerfing patterns to the interpolation layer makes possible the creation of almost all double-curved surfaces.

By cutting many continuous slits into plywood in a specific, labyrinthine pattern, many small hinges can be generated with single degrees of freedom [26]. Deforming a surface with numerous laser-cut slits results in a rotation of the hinge points relative to their neighbors, permitting the surface to exhibit a non-zero Gaussian curvature, up to a certain limit. To bend the kerfing surface in any direction, different degrees of stiffness can be obtained at both the material and structural levels. The kerfing pattern provides a tolerance to certain levels of deformation, within the limits of the fracture strain of the material and the specific geometry of the relief cuts (see Figure 6).

In response to the external forces of the formwork, the introduction of relief cuts on the inextensible material of the interpolation layer allows reversible extension and compression. Introducing the proposed kerfing pattern turns intrinsically rigid material (such as plywood) pliable. A parametric model simplifies local or global changes to the density of the relief-cut patterns, modifying the deformation behavior of the layer. Closer slits drastically increase the deformability of the interpolation layer, buckling it in or out to produce concave or convex surfaces without significant shearing.

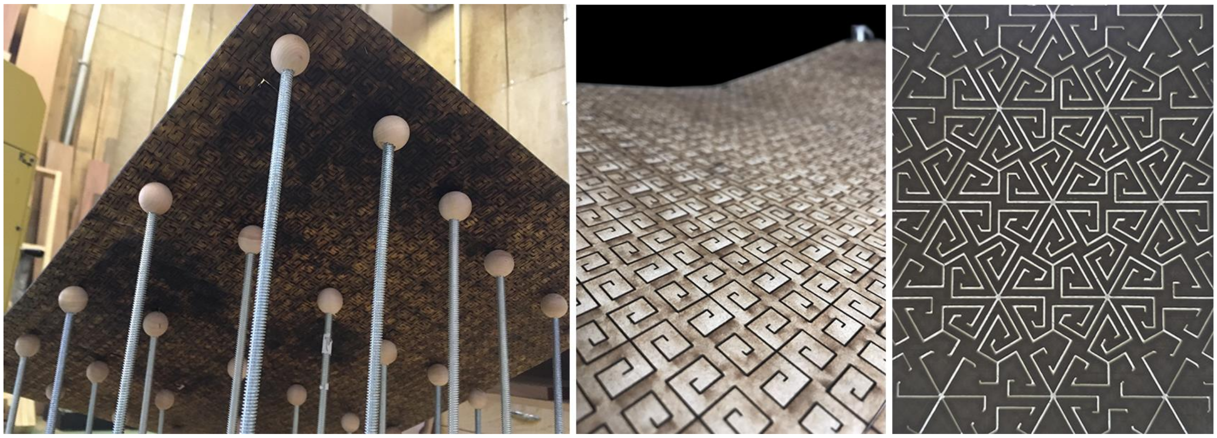

Figure 6. Placing a membrane with a kerfing pattern on the bars allows the interpolation layer to display smooth transitions and generate different non-developable double-curved surfaces.

Conclusion

Due to its rapid molding, low required manual labor, and relatively reduced material cost, transformative formworks have the potential to facilitate the mass-customized production of double-curved concrete elements and reduce the waste material normally discarded after using milled formworks. As discussed above, most reconfigurable formworks consist of an interpolation layer that cannot easily be formed into all desired curved surfaces. However, the stiffness of this layer can be modified by using a kerfing method to cut interlocked Archimedean spirals in the material. Choosing flexible and stretchable materials instead of those that are inextensible gives the interpolation layer the freedom to locally expand in all directions. The knowledge behind generalizing relief cut patterns is important to overcoming the main fabrication challenge of generating very precise and complex curvilinear geometries; this process couples a profound understanding of material deformation with reconfigurable formwork capabilities. The interpolation layers produced by all transformative formworks prove that the application of a kerfing method satisfies the level of accuracy required in the final panels, as described in their corresponding digital models.

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References

[1] Adapa, Adaptive Mould, Accessed: May 14, 2017, website: http://adapa.dk

[2] Bell, B., Read, T. Cord, Ede, A. & Barnes, N., 2014, “Casting non-repetitive Geometries with Digitally Reconfigurable Surfaces”, *ACADIA 14: Design Agency, Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture*, Los Angeles 23-25 October, 2014, pp. 453-462.

[3] Cochrane, J., 1863, “Bending Metal Plates” *U.S. Patent No. 39,886*, issued September 15.

[4] Fleming, W., 1987, “Vertical Three-Dimensional Image Screen”, *U.S. Patent No. 4,654,989*, issued April 7.

[5] Guzik A., 2009, “Digital fabrication inspired design: Influence of fabrication parameters on a design process”, *Master Thesis*, London (UK): University College London, 71 p.

[6] Johnston, D., 2008, “Design and Construction of Concrete Formwork”, *Concrete Construction Engineering Handbook*. Boca Raton: CRC Press.

[7] Kihong, K. & Chung, D., 2015, “Digital Fabrication Methods of Composite Architectural Panels for Complex Shaped Buildings, Emerging Experience in Past, Present and Future of Digital Architecture”, *Proceedings of the 20th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA 2015)*, Daegu 20-22 May 2015, pp. 703-712.

[8] Lee, D., Hong, W., Kim, J. & Kim, S., 2015, “Conceptual Study of Production Technology of Free-Form Concrete Segments”, *International Journal of Engineering and Technology*, vol. 7, No. 4, p. 321

[9] Lušić, M., Wimmer, M., Maurer, C. & Hornfeck, R., 2015, “Engineering framework for enabling mass customisation of curvilinear panels with large surfaces by using pin-type tooling”, *4th CIRP Global Web Conference, CIRPe 2015: Understanding the life cycle implications of manufacturing*, Procedia CIRP Volume 37, pp 265 – 270.

[10] Manahl, M., Stavric, M. & Wiltsche, A., 2012, “Ornamental Discretisation of Free-form Surfaces-Developing Digital Tools to Integrate Design Rationalisation with the Form Finding Process”, *International Journal of Architectural Computing*, Issue 4, Volume 10, pp.595-612.

[11] Munro, C. & Walczyk, D., 2007, “Reconfigurable Pin-Type Tooling: A Survey of Prior Art and Reduction to Practice”, *Journal of Manufacturing Science and Engineering*; 129; 3; pp 551-p565.

[12] North Sails | 3DL, Accessed: May 13, 2017, website: https://northsails.com/sailing/sails/materials/3dl

[13] Oesterle, S, Vansteenkiste, A and Mirjan, A, 2012, “Zero Waste Free-Form Formwork”, *Proceedings of the Second International Conference on Flexible Formwork, icff2012*, Zurich, Switzerland, pp. 258-267.

[14] Paunoiu, V. & Teodor, V., 2009, “Geometric Reconfiguration of the Multipoint Forming Dies Using Reverse Engineering”, *The Annals of “Dunărea De Jos” University of Galaţi Fascicle V, Technologies in Machine Building*, pp 415–418.

[15] Piano, R., 1969, “Progettazione sperimentale per strutture a guscio, experimental project of shell structures”, *Casabella*; 335, pp 38-49.

[16] Pronk, A, Van Rooy, I. & Schinkel, P., 2009, “Double-curved surfaces using a membrane mould”, *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium*, Valencia, Spain, pp 618–628.

[17] Raun, C., Kristensen, M. & Kirkegaard. P., 2010, “Flexible mould for precast concrete elements”, *Proceedings of the International Association for Shells and Spatial Structures (IASS) Symposium*, Shanghai, China.

[18] Raun, C. & Kirkegaard, P., 2015, “Adaptive mould - A cost-effective mould system linking design and manufacturing of double-curved GFRC panels”, *The 17th International Congress of the International Glass-fibre Reinforced Concrete Association (GRCA),* Dubai, U.A.E.

[19] Schipper, R., & Janssen, B., 2011, “Manufacturing Double-Curved Elements in Precast Concrete Using a Flexible Mould, First Experimental Results” *Fib symposium,* Prague, the Czech Republic.

[20] Schipper, H., Gr̈newalda, S., Eigenraama, P., Raghunathb, P. & Koka. M., 2014, “Optimization of the Flexible Mould Process for the Production of Double-Curved Concrete Elements”, *1st Concrete Innovation Conference (CIC),* Oslo, Norway.

[21] Schipper, R., Eigenraam, P., Grünewald, S., Soru, M., Nap, P., Van Overveld, B. & Vermeulen, J., 2015, “Kine-Mould: Manufacturing technology for curved architectural elements in concrete”, *Proceedings of the International Society of Flexible Formwork (ISOFF) Symposium 2015*, Amsterdam, The Netherlands.

[22] Schipper, R., 2015, “Shaping building surfaces: inspired by Renzo Piano”, *RuMoer, Periodical for Building Technologist,* 56: Form Finding.

[23] Son, S., Fitriani, H., Tai Kim, J., Go, S. & Kim, S., 2017, “Mathematical Algorithms of Patterns for Free-Form Panels”, *Proceedings of the Second World Congress on Civil, Structural, and Environmental Engineering (CSEE’17)*, Barcelona, Spain.

[24] Zarrinmehr. S, Akleman, E. Ettehad, E., Kalantar, N., Borhani, A. & Sueda, S., 2017, “An Algorithmic Approach to Obtain Generalized 2D Meander-Patterns”, *Proceedings of Bridges 2017: Mathematics, Music, Art, Architecture, Education, Culture,* Waterloo, Canada.

[25] Zarrinmehr. S, Akleman, E. Ettehad, E., Kalantar, N., Borhani, A. & Sueda, S., 2017, Kerfing with Generalized 2D Meander-Patterns,Conversion of Planar Rigid Panels into Locally-Flexible Panels with Stiffness Control, *In Proceedings of CAADFutures 2017,* Istanbul, Turkey.

[26] Zarrinmehr. S, Akleman, E. Ettehad, E., Kalantar, N., Borhani, A. & Sueda, S., 2017, Interlocked Archimedean Spirals for Conversion of Planar Rigid Panels into Locally Flexible Panels with Stiffness Control, *Computers & Graphics,* Vol. 65.