INFORMING DEFORMABLE FORMWORKS

Parameterizing Deformation Behavior of a Non-Stretchable Membrane via Kerfing

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Abstract. The process for constructing freeform buildings composed of many non-repetitive shapes and waste-free formwork systems remains relatively unexplored. This research reviews a method for fabricating complex double-curved shapes without utilizing single-use formworks. This work answers questions regarding the manufacturing of these shapes in an environmentally-friendly and economic fashion. The proposed method, called a “transformative formwork,” could replace state-of-the-art CNC-milled molds and is potentially suitable for large-scale construction. The transformative formwork uses a stretchable membrane or “interpolation layer” that can be manipulated into any curved surface by using vertical bars capable of being rearranged into different heights. Here, to accurately generate most of the smooth, double-curved surfaces, laser kerfing is used for bending interpolation layer into almost any complex shape. A parametric model simplifies local or global changes to the density of the kerfing patterns, modifying the deformation behavior of the layer. Several kerfed interpolation layers produced for four transformative formworks showed that the application of this method.

Keywords. Transformative Formwork, Interpolation Layer, Relief-cut Patterns, Positive & Negative Gaussian Curvatures, Interlocking Archimedean Spiral-Patterns, Kerfing.

1. INTRODUCTION

Buildings built based on single- or double-curved elements require lengthy construction times and high expenditures. Making a great number of rigid, single-use formworks is time-intensive. Moreover, due to the uniqueness of each freeform building, these formworks cannot be reused or modified in the future.

The excessive manpower, time, and materials required to make and adjust formworks also constitute a noteworthy price factor. The cost of formworks for reinforced concrete can often make up 30% to 40% of the overall cost for the building shell (Sascha et al, 2015). Custom-made milled formworks for double-curved precast cladding elements with moderate curvatures can account
for the primary share of the total concrete work’s cost. The overall price of a formwork for such a project is estimated at between 60% and 75% of the total (Schipper et al, 2015). Limitations in relation to cost, time, quality, safety, and resources for constructing double-curved results are all reduced when constructing freeform buildings.

2. A TRANSFORMATIVE FORMWORK

To produce the desired form, formworks use either hard or soft membranes that allow for the casting material to be deposited on top. A transformative formwork has a soft membrane that can temporarily hold the preferred shape once the user adjusts a large number of vertical bars that are placed close together underneath the membrane. The advantages of this system lie in the transformability of the formwork membrane and adjustability of the entire system.

The dynamic surface of the formwork, called the “interpolation layer,” is formed into a given shape by following the tips of the vertical bars in their altered heights. The heights of the bars are adjusted based on the dataset derived from a digital model (see Figure 1). Through the use of a grid of X Y coordinates, the heights of bars that represent the ultimate shape of the interpolation layer can be set either manually or digitally via controlled actuators.

Figure 1. A transformative formwork: Placing a membrane with a kerfing pattern on the bars.

3. CURVILINEARITY IN ARCHITECTURE: Overcoming Challenges

Architecture still struggles with non-linear building components and complex geometry when the goal is to minimize the associated costs of the formwork, wasted materials, and labor. Although for years both industry and academia have researched flexible formworks, builders are still awaiting practical answers. Currently, this type of formwork has not been sufficiently adapted to the practice of architecture to be used in full-scale projects (Grnewalda et al. 2014).

Architecture’s interest in diverse geometries, stemming from the new opportunities made possible by CAD software, has grown extensively in the past few years. The primary motivation for the development of a transformative formwork was to move the construction industry one step closer to the digital
possibilities of the present. By maintaining a freedom of form in built architecture, transformative formworks ensure the economic feasibility and constructability of buildings with non-repetitive yet precise geometries.

The reusability of transformative formworks eliminates much of the waste associated with individual formworks fabricated from advanced CNC-milled systems that used only once in freeform constructions. By replacing disposable CNC-cut foam pieces, the reduction in materials is considerable, especially for large-scale projects. At first glance, it may seem that the sizeable financial investment needed to make transformative formworks will comparatively increase the cost of construction. However, the production of a reasonable number of components for a project will quickly cover the initial investment.

4. INEXTENSIBLE MATERIALS: The Problem of Stretching

The interpolation layer is the transitional layer between the bars and cast concrete. The main challenge to setting the interpolation layer into different single- or double-curved shapes is in creating a smooth surface between the bars, while using typical materials that do not tend to be substantially stretchy. Stretchability is a structural property that helps a surface not resist deformation forces and thus achieve the expected amount of distortion. Since most surfaces resist deformation, they cannot typically flex in crosswise and lengthwise directions under applied forces. In the best cases, stretchable surfaces mainly stretch in one direction. To make possible all three-dimensional forms, the interpolation layer should be stretchable in as many different directions as possible.

Besides the stretching direction of the interpolation layer, the amount of flexibility or rigidity is a prime factor in regulating the formwork. Although using a very flexible material minimizes difficulties with adjusting the interpolation layer into the preferred curvature, this may lead to a decrease in the layer’s strength. As a result, when the interpolation layer is pressed down between the vertical bars, the pliable membrane will not be strong enough to resist deformation in response to the weight of the casting material, at least without a change in the expected shape of the formwork. In such cases, the discrete nature of the bars and lack of support under the interpolation layer may cause the tips of the bars to create an uneven surface and deep dimples. Concrete curing time is usually between several and 24 hours. Heavy concrete castings that remain on the supple interpolation layer for a significant period of time will cause distinct dimples on the final cast pieces.

To enhance the quality of the final cast pieces, it is essential to suppress undesired defects and produce smooth, dimple-free surfaces. Aside from aesthetic reasons, dimpled areas are more subject to wear and tear, which may necessitate later replacement of the interpolation layer. Experimenting with different materials, however, could serve to reduce dimpling. Among a broad spectrum of possible factors, the rigidity of the interpolation layer has some of the most significant influence on the sizes of imprints from the bars, as well as dimple depth. Although the rigidity of the material and a sufficient thickness will help remove marks made by pressing the bars onto the membrane, the interpolation layer can at times be imprecisely placed on the bar tips. In such cases, the accuracy
of the final surface will be unsatisfactory (Borhani et al. 2017).

Different materials’ resistances to deformation vary in response to tensile or compressive loads. Since each material does not stretch uniformly, there is no guarantee that it can be bent to the desired shape under a given load. Thus, it is essential that the interpolation layer flex predictably under a wide range of twists and extensions.

5. KERFING: The Freedom to Flex

By making the material flexible where necessary, it is possible to achieve a 3D shape from a 2D solid. A series of slender lines cut in close proximity to one another will turn a flat sheet of rigid material into its own hinge, allowing it to bend over a given length. Well-suited to the laser cutting process, these cut lines are known as kerfs, relief cuts, living hinges, or lattice hinges (see Figure 2). Kerfing exploits the intrinsic capacity of a material to flex around an array of cuts (Akleman et al. 2017).

Laser kerfing is an effective method for bending rigid sheets into almost any complex surface. Depending on the material’s properties, the underlying geometry of the kerfing pattern, density of the kerfing lines, and cutting tools available, the kerfed sheet should ultimately be bendable to any necessary degree.

Together, a series of kerfed lines creates a kerfing pattern. A good kerfing pattern should leave some part of the sheet unmarred. The kerfed lines must be interconnected to a network of uncut material across the entire sheet. The spacing between the uncut parts is very important. Increasing the distances between uncut parts and reducing the spaces between cut lines will enhance the flexibility of the sheet. It is unwise to group the kerfing lines too close to or far apart from one another. The likelihood of unsteadiness will increase if the cuts are too close. If the cuts are too far apart, the remaining material may resist bending and eventually snap. The average size of the uncut parts should be small enough to allow for twisting in one or multiple directions. The maximum degree of twist for each

![Figure 2. Applying different kerfing patterns to remove materials in highly stressed areas.](image)
section might be small, but when many small twists are propagated on the sheet, their overall deformation degree is multiplied, causing considerable flexibility. In addition to twisting the uncut parts, in some cases, the long and slender cut sections can also be twisted a few degrees; this helps to augment the pliability of the material. The overall pliability of a sheet with a suitable kerfing pattern can be broken down to the radius of the twist of uncut and cut parts. In general, the smaller the size of the uncut sections and the thinner and lengthier the cut areas, the more pliable the sheet. Although the kerfing lines may have varying lengths or widths, the rule is to cut them only to the point that minimizes the likelihood of cracking during and after twisting. The material is more likely to break when the uncut parts are too small.

Another possibility is to make partial-thickness cuts on one side of the sheet, allowing it to bend around the cut lines. During this bending, the uncut surface is locally stretched or compressed. Obviously, the depth of the cuts should be less than the material’s thickness. Cutting the material’s thickness at varying depths alters the bendability of the sheet. Using this approach, the thickness of the material, depths of the partial cuts, and tolerance of the cutting tool are all important. Consequently, applying this method to thin wood is difficult. The flexibility of a sheet of material with partial-thickness cuts is less than that of a sheet with slits that go completely through.

Some specific 3D forms may call for a kerfed sheet to be even further deformed. In such cases, to achieve a further bending capacity in the material, the kerfing technique can be used in conjunction with other bending methods. For instance, a wooden kerfed sheet can be steamed at high temperatures and chemicals applied until the material becomes pliable or plasticized.

6. INTERPOLATION BETWEEN THE POINTS: More than One Direction

Although most precedents employing kerfing patterns used designs comprised of simple parallel lines, here, the goal is to bend a completely rigid sheet into different curved shapes, depending on the orientation of the kerfing lines. Different kerfing patterns make it possible to bend sheet around single, double, or multiple axes. Multi-directional kerfing patterns allow the material to bend in a variety of directions. A pattern comprised of parallel kerfing lines in a single direction is suitable when bending is required in only one direction. Adding kerfing lines perpendicular to the first series of lines will make available two-directional bending in association with non-linear forces. In addition to perpendicular and/or parallel lines, kerfing patterns can be made from convergent or divergent lines. By utilizing multiple kerfing-line angles, it is possible to bend the sheet into a wide variety of complex shapes. To allow the interpolation layer to flex in any direction and adapt itself to any desired shape, several tessellated patterns should be converted into a series of Archimedean spiral cuts; these can be twisted in all directions. The spirals should be connected together in some places and disconnected in others. The Archimedean spiral cuts increase the capacity of the interpolation layer to bend into complex three-dimensional shapes. Here, by adapting the 2D meandering pattern of Dujam Ivani sević (Ivani sević 2014), the
main goal is to generalize the method, and enable a stiff piece of material to bend in all directions, this makes possible both positive and negative Gaussian curvatures.

From one uncut point of the pattern with Archimedean spiral cuts, a minimum of two spirals of right angles proceed progressively further and further away, turning around themselves. Each of these spirals moves towards another uncut point, while changing its winding direction to form a biskelion spiral. The turning point is the intersection locus of two or more spirals. In this way, an overall interlocking Archimedean spiral tessellation is composed out of the chain of interlinked biskelion spirals, with a minimum two-fold rotation. The regular tessellation can be made of triangular, rectangular, or hexagonal, flat, coil-like spirals. In addition, more irregular tessellations can be constructed out of a set of convex polygons by systemically linking with neighboring polyskelion spirals (Zarrinmehr et al. 2017a). Here, one of the basic kerfing patterns is composed of quadskelions, with quadruple spirals made of four couples of biskelion spirals that shaped interweaving Archimedean spirals. Each side of the square-based biskelion spiral winds itself around one uncut point of the interpolation layer. The distance between the windings of each spiral is kept constant.

7. HOW KERFING WORKS: A Balance between Flexibility and Rigidity

Besides the shape, size, and density of the proposed kerfing pattern, the bendability of one kerfed surface depends not only the Young’s modulus of the cut material, but also on how that material is loaded. A stiff material changes its shape only slightly under a given load, while a softer material’s shape changes considerably under the same load. If the same kerfed pattern is cut into different materials, they may to some extent bend into comparable deformable shapes, but they will differ in size, bending behavior, radii of the curvatures, stress level, and stiffness.

After a force is applied to deform a kerfed material, elastic potential energy is stored in that material’s uncut parts. By removing that force, the uncut sections may spring back to their original shape. In addition to the uncut areas that are allowed to deflect by a certain amount, the Archimedean spiral patterns between the uncut parts store and release elastic energy. The deformation of these spring-like pieces involves twisting, compressing, and stretching in response to the force. Because of their springiness, the spirals can simply return to their original shape after the force is removed. The rigidity of a kerfed interpolation layer with Archimedean spiral patterns depends on the number of turns and distance between successive turnings. Obviously, a spiral with fewer turns requires more force to deform than does a spiral with more turns. Besides the number of turns, the shape of the spiral is important. If a constant distance exists between successive turns, the rigidity of a square-based spiral is much higher than that of a hexagonal spiral cut into the same type of material. Depending on the elasticity of the material, when loads are placed on a kerfed interpolation layer, the uncut parts may or may not permanently deform. If the force exceeds the elastic limit of the uncut parts, the kerfed surface will no longer relax back to its equilibrium shape. Besides the material of which the interpolation layer is comprised, the magnitude of the energy’s elastic potential depends linearly on the length of the spiral. With wooden sheets, cutting the kerfing lines perpendicular to the grain direction of the material
causes a different degree of flexibility from what results from cutting the kerfing lines parallel to the grain direction.

8. PARAMETERIZING DEFORMATION BEHAVIOR

As mentioned above, a kerfing pattern is often comprised of kerfing spirals that make an interlocking tessellated pattern. This pattern can be uniform in all directions with the same spiral shape, orientation, and density, regardless of the direction of the applied forces. When moving across this kerfing pattern, it is possible to systematically vary the number of spirals (Zarrinnehr et al. 2017b), their positions, shapes, and orientations, as well as the number of their turns and the distance between their successive turnings (see Figure 3).

These alterations can be used to create a kerfed interpolation layer with dissimilar deformation properties in different locations. For instance, as the number of turns increases, the length of the kerfing spiral increases. Therefore, the rigidity of the sheet is decreased. By decreasing the number of spirals, the strength of the sheet can be increased to respond to a specific condition. Instead of dealing with predefined configurations, the algorithm proposed by our team will help to parametrically fine tune adjustment of the kerfing patterns, enabling the creation of a myriad of different spirals by using gradient-based patterns. By changing the uniformity of a regular Archimedean spiral tessellation via defined
parameters, the global properties of the interpolation layer can be altered to locally make the desired areas more flexible.

9. IN PRACTICE: Production of Double-curved Surfaces

In the context of a design studio in the Department of Architecture, the authors and four groups of students made four transformative formworks with high levels of surface variation (see Figure 4).

Each group’s formwork was comprised of a base and uniformly spaced matrix of bars; the goal was to fabricate four 32” x 18” panels. The bars were placed on the base in a grid shape. Since turning a leadscrew is the most conventional method of actuation (Munro et al, 2015), we used steel-threaded bars. Two nuts were fixed to the base of each bar to set the heights derived from charts of numerical data. The issue of height change was addressed by manually rotating the bars. The threaded bars could be set at different positions. After setting all of the bars, the interpolation layer was placed on top. In each prototype, the bars were loosely connected to an interpolation layer made out of a thin plywood sheet. The interpolation layer became stretchable by using the appropriate kerfing pattern. However, since the interpolation layer could easily be deformed (because of the kerfing), it sat on the tips of each bar and did not push back to its resting state. Originally, surface deformation was to be facilitated by pivoting the ends attached to a kerfing-cut surface and ball joints connecting the bars to the interpolation layer. The interpolation layer of each formwork was used to mold either fiberglass or concrete into highly complex geometries by establishing a relationship between the numerical data imported from digital models and curvatures in the interpolation layer. The performances of all four formworks demonstrated that kerfing is a viable solution when fabricating a continuous form with proper edge contours connecting one panel to another.
10. THE NEXT CHALLENGES

A) Currently, transformative formworks have their limitations. For instance, the proposed system requires further improvement if it is to allow for the construction of sharp edges and a number of bends with very small radii. Besides dealing with limited curvatures, having a predefined number of details should also be studied. The next step would be to make the desired details more pronounced. B) The final kerfing pattern of the interpolation layer should be generated with the information from the initial 3D model derived as hills and valleys. With the goal of minimizing the cutting time and maximizing the flexibility of the interpolation layer, the next step would be to optimize the layout of the selected kerfing pattern within a given boundary condition and for a given set of loads. C) Since manual adjustment of the bars is likely to cause errors, exploring digitally driven adjustable bars is also essential. By using actuators and computerized numerical information governed by CAD drawings of the desired designs, the formwork should simply rearrange itself into a variety of positions that would no longer require extensive labor and time. D) Providing uniquely shaped curved rods to reinforce a free-form concrete structure and correctly placing the rods on the formwork often demand relatively high associated costs. Finding a suitable reinforcement material to strengthen the structure that is also quick to use and cost-efficient is vital. In the future, the application of fibers or textiles for thin reinforced concrete should be investigated. In this case, fiberglass reinforced shotcrete could be sprayed onto the formwork. E) Normally, to extract entrapped air bubbles inside the concrete and improve the compactness of the final mix, a vibrator is needed to create violent agitation and rearrange the mixed particles. In the future, when considering the best method of depositing the concrete onto the interpolation layer, this research will examine the amount of vibration required for different sizes and shapes of formwork. F) On the one hand, a transformative formwork requires a tight surface upon which the concrete can be cast. On the other hand, a kerfing method must be used to cut the surface of the interpolation layer to provide geometrical possibilities via a stretchable membrane. Moreover, the formwork has a moving mechanism that is vulnerable to corrosion when the kerfed interpolation layer is not fully sealed. To solve problems associated with the interpolation layer’s permeability, this layer should be laminated between two thin, soft, elastic sheets to provide a watertight surface. Besides being impermeable, the laminated sheets offer a smooth face with a desirable level of slippage.

11. CONCLUSION

This paper investigated the possibility of mass-customized production of double-curved elements by increasing the repetition factor of a formwork. The proposed transformative formwork has the capacity to produce different elements within a single and open formwork, while also dealing with challenges related to construction duration for complex buildings. As a viable method of promoting the construction of freeform architecture, the suggested system can reduce formwork costs, targeting large-scale economically and ecologically sustainable projects. Besides constructing double-curved shapes at a lower cost, the transformative formwork will offer more accurately customized building parts. The desired
surface curvature should be achieved by a complex interplay of the interpolation layer’s stretchability, a combination of tension and compression forces acting on the layer, the bars’ relative positions, and surface contact with the bars. In this research, different kerfing patterns with Archimedean spiral cuts were examined to see if they could make the interpolation layer of the formwork stretchable in every direction and flexible enough to hold every desired form. These spiral cuts can be applied to any polygon mesh and significantly varied in their geometry and composition. To consistently use one interpolation layer with an Archimedean spiral pattern, the following guidelines should be considered:

- The interpolation layer must withstand the applied forces and recover its original shape. It is important to predict the amount of deformation that the uncut parts and spirals are capable of absorbing before the layer fractures.
- The relative resistance that the interpolation layer can impose against the vertical bars depends on the flexibility that is caused by the kerfing pattern.

The four transformative formworks created for this research illustrated different double-curved surfaces that allowed the formworks to be set to the desired curved shapes. Made from concrete and fiberglass, the produced cast pieces serve as excellent evidence of this practical method of streamlining the fabrication processes of double-curved surfaces.

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References


