Interweaving Grammar: Reconfiguring Vernacular Structure Through Parametric Shape Grammar

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ABSTRACT

This paper re-examines the interweaving method to demonstrate how architectural computation can reinterpret the advantages of this traditional crafting techniques for its geometrical compatibility and rule generativity. Firstly, the technique analyzes and reconfigures load distribution of a traditional interwoven surface to mimic its structural principle. Secondly, from this structural reconfiguration, the study applies parametric shape grammar to define interweaving rules. The rules generate various patterns with rigid local materials that fit the size of human hand. The experiment in this study shows that interweaving grammar can generate ornamental-structural components with three different load distributions, three different segmented materials and in three different spatial dimensions (point, line and plane).
I. Introduction

Interweaving has been embraced by many cultures throughout human civilization, from the domain of crafts to shelters [1,2]. Recent architectural practice has widely exercised interweaving as a campaign flag in promoting excellences of digital architecture computation as various braiding and weaving algorithms make it easy for this ancient craft to be generated through digital scripting and rapid prototyping methods [3,4,5] (Figure 1,2d).

However, some of these practices focusing in the passive role of interweaving such as decoration, instead of utilizing more of its active role, for instance, a structural configuration that is embedded in the origin of interweaving. Erwin Hauer wall screen’s can be seen as an example of interweaving passive role as aesthetic element in the building [9]. The wall

► Figure 1. **Algorithmic interweaving.** Benjamin Aranda & Chris Lasch algorithm (a) to generate digital interweaving (b). Aranda-Lasch Cellular Automata Rules (c) to generate Computational Basketry made by 3D printer (d).
consists of continuous interwoven pattern (Figure 2a) that is actually made by a stack of cast gypsum cement (Figure 2b, 2c). In addition, Aranda/Lasch computational basketry is sculpted using Computer-aided Manufacturing (CAM) using layered powder (Figure 1d). These examples show an interweaving pattern as decoration but their structures are not interweavingly assembled.

Nevertheless, the use of interweaving as an active architecture element remains actively continued in some traditional communities [7]. Interweaving techniques broadly used to generate wall and roof with elastic material such bamboo strips and coconut thatch, which uses different weaving methods to generate various patterns on the wall (Figure 3). Yet, when facing the context of modern city, where privacy and permanency of the building are highly required, the application of interweaving with such materials could no longer be accountable for.

Given the situation, this study on revisiting interweaving demonstrates how architectural computation look on the advantage of utilizing interweaving active role in answering architectural issues in developing countries, such as durability, permanency, high dependency on imported material and technology, as well as the fading local value in modern culture. Promisingly, despite the fact that it is regarded as a traditional crafting
Interweaving is substantially compatible with modern architecture principles, since its beauty comes from the truth of function and its simple knotting rule can generate complex pattern. While creating various patterns on its surface, weaving can also serve as a structural element at the same time, as both ornament and structural configuration should come simultaneously from the same rule. The following study attempts to answer this challenge by integrating interweaving techniques and structural configuration with the assistance of architectural computation. Firstly, the study analyzes load distribution in traditional interweaving surface to mimic its structural principle. Secondly, from this mimicry, shape grammar as a pseudo-code defines the interweaving grammar to generate patterns. Thirdly, the study demonstrates the application of the grammar within a rigid building component to generate architectural surface.

2. Interweaving structure
2.1. Load distribution

The study begins with the basic structure analysis in plain traditional interweaving surface (Figure 4a,b). The surface generated by at least two yarns in X and Y axis interlacing together, where each yarn runs across the two axis from side to side creating number of cells in each intersection (Figure 4c). The load distribution shows the way configuration on traditional interweaving creates structural interdependency in each cells, by which, yarn...
in X axis is being supported by vertical stress ($\sigma_y$) from Y yarn within a simple-support on the interlaced area [A] (Figure 4d). This way, each neighboring cells on both axes prevent yarn deformation caused by vertical load ($F_z(y)$). Here, $F_z(y)$ equal to $\sigma_y \times A$.

$$F_z(y) = \sigma_y \times A$$

In elastic material such as bamboo or coconut leaf, this interlaces makes two states of stress on the surface: a tension between the knots, and a bending on each cells [8] (Figure 5b). However, in rigid material that doesn’t support tension such as steel in aluminum mesh, the vertical load caused by intertwined steel rods in each cell will cause vertical shear (Figure 5c).

The yarn in each cell supported by a simple support and not fixed-ended support [8] since the local stability on that cell is depended on the density of the interwoven, which is determined by the gap between each yarn (see $\Delta X$ and $\Delta Y$ in Figure 4c). Narrower gap means denser weaving, whereas
wider gap means looser and more unstable. However, the diagram shows that an equal stress caused by both vertical load and vertical support \((F^y_Z)\) from Y yarn makes each cell perform a fixed end support. Thus, the actual fixed end support is performed by the interwoven configuration on each cell where the yarn is being supported and supporting other yarn by a knot (Figure 5d). Within an equal distance (D) between each cell, a fixed end connection creates more stability on each cell, in which X yarn’s dead load \((W_z)\) plus vertical load equal to the vertical support.

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(F^y_Z)_1 + F^y_Z)_2 + W_z = F^y_Z)_3 + F^y_Z)_4
\]

This stability offers a proper guidance to reconfigure interweaving as an active component in architecture design: That is as long as each cell performs fixed end support configuration, interweaving structure can be performed.

2.2. Reconfiguring interweaving

This structural analysis shows that interweaving configuration balances the stress between tension, bending and shear of the surface and the cells. The next pivotal aspect for this reconfiguration is the material properties such as dimension, strength, and elasticity. In traditional culture, the size of elastic materials, such as rattans or plant roots, make traditional interweaving only applicable for the production of small objects (bag, mattress, and other accessories). Segmenting elastic material to assemble larger object would only be reducing its strength and eventually its versatility. For that reason, this research pursues interweaving configuration within segmented rigid material as a building component that can be easily manufactured and interweavingly assembled by human hand. The following segmentations demonstrate different reconfiguration of interweaving structure to adapt segmented element as a structural element.

Segmentation A: Linear distribution

This segmentation literally mimics traditional interweaving configuration by dividing the long yarns into a single structural member. Figure 6a shows segmented element \(X_n\) connected to \(X_{n+1}\) and \(X_{n-1}\) by a simple support, while the \(Y_n\) vertical load \(F^y_Z\) prevents vertical shears caused by \(X_n\) dead load on that connection. In addition, the interlaced surface where \(X_n\) meet \(Y_n\) member—with no gap \((D = 0)\)—also makes \(X_n\) support \(Y_n\) horizontal stress caused by \(Y_n\) lateral movement \(F^x_X\).

Segmentation B: One-way loop distribution

To minimize the risk of vertical shear in previous one, this segmentation pursues fixed-end support condition by re-routing load distribution in loop distribution. Figure 6b shows loop stress distribution among four elements on each interlaced area \((A)\)–A supporting D, D supporting C, C supporting B and B supporting A—, where the distance between knots (D) is
While segmentation A distribute the vertical load through all the member along the same axis, segmentation B distributes the vertical load just in one member for each cell, making the cell more stable in comparison with segmentation A.

Segmentation C: Two-way loop distribution

Segmentation C intends to perform the same rigidity with method B with loop distribution in each interlaced area. Yet, instead of distributing the load vertically in one direction for each member, method C distributes the load in two directions. As shown in figure 6c, element C supporting element B while at the same time supported by element D. In other words, whereas
segmentation B distributes the vertical load in one direction for each member; segmentation C gains its stability by distributing the stress in two axes for each member.

3. Pseudo-codes for interweaving rule

Based on these three reconfigurations, shape grammar is used as a converter to translate interweaving structure principle and geometric patterns into architectural computation. Shape grammar works very efficiently as a visual pseudo codes in the following aspects. Firstly, drawing the sequential interweaving rules and relationship in shape grammar is proportional with the writing of lines of code in digital scripting. Secondly, visual calculation in shape grammar is highly congruent to the logical operator in computation language [12]. Thirdly, erasing rule and multilevel relationship in shape grammar is equivalent with the concept of emergence to generate more possible weaving patterns recursively from a simple rule [11]. The following experiment practicing interweaving grammar based on the three different structural reconfigurations, three geometrical dimensions and three different types of materials.

3.1. Experiment 1: Interwoven bricks (points composition)

For the first experiment, clay is chosen as the structural interweaving material for its enormous availability in today’s construction industry. Following structural reconfiguration in segmentation A, a modified brick as a structural member is connected to the other brick in the same direction using notches and tabs as simple-support members (Figure 7b, 7c). Interconnected bricks from the other axis prevent vertical shear in each notch from the lateral load. In resembling motif in traditional interwoven craft (Figure 7a), at least there are three kinds of brick required: (1) The edge brick for erasing rule, (2) the checkered brick for the checkered motif and (3) the continuous bricks for the continued line. The shape grammar goal for this interwoven bricks is to generate point’s composition by the bricks based on the mosaic pattern of particular image or ornament similar to rules in John Conway’s game of life [13]. However, instead of analyzing the condition of the nine neighboring cells, the interweaving bricks rules intend to guide the bricks fabrication procedure by looking only at two cells, the previous and the next cell in the same axis. The rule consist as follows: (1) If the next cell is alive, use continuous brick; (2) If the next cell is dead, use weaving brick; (3) If there is no cell afterward, then use edge brick (Figure 7d). These rules can generate various points’ compositions, for instance, in applying traditional motifs into a wall (Figure 8a, 8b, 8c, 8d). Structurally, force-stress equilibrium in this interwoven brick wall is performed by the interlocking joint on each cell which makes it possible to reduce the use of mortar less than those used in conventional masonry (Figure 8e, 8f).
3.2. Experiment 2: Interwoven beams [line composition]

The next experiment uses segmentation B where every joint seeks to perform loop distribution (Figure 6b). The fact that this segmentation avoids continuous connection as in interweaving brick makes any limited size rigid material is able to perform interweaving pattern. In this case, short plywood is used as a structural member to distribute vertical load by creating an overlapping configuration of three and four members [14]. The configuration created by rotating and multiplying the first member into three or four, in which the rotation angle equals to 360 divided by the number of beams \(n, \alpha = 360/n\). This second experiment uses parametric shape grammar to generate various patterns using the rotation and two-ways force distribution. Firstly, the grammar begins by defining the labeling
rule (Figure 9a) to initiate coordinate for the center point of rotation from
the beam line’s starting point so that each member will interlock
proportionally to each other. Secondly, the rotation rule (Figure 9b) defines
how many beams will be produce to generate desired pattern in each cell
(n). Thirdly, a reflection rule (Figure 9d) will reflect every new beam on its
centroid so that the starting point will become the end point and vice
versa. That way, the next center point will be based on this new starting
point and not overlapping with existing center point. This reflection makes
the new beam ready to iterate the pattern recursively. In a free form
surface, the start point and end point of the new beam will be projected to
the surface to create curve adjacent to the surface curvature (Figure 9c).
Additionally, to prevent the new beam overlap with the existing member; a
collision rules based on the Boolean logic generate collision and dispatch
scenario (Figure 10).

Figure 8. Process of assembling
the traditional motif within the
interwoven brick into a wall.
(a,b,c,d) Load distribution in
interwoven brick wall (e) in
comparison with conventional
masonry wall (f).
Figure 9. Shape grammar and its conversion in digital scripting (Rhinoscript).

Figure 10. Collision Rule to anticipate new member overlap with existing member. Collision and dispatch scenario using a Boolean logic (b). A tag on each connection indicates the rules of each iteration (a).
In this experiment, the grammar is applied in two different angle variables for the rotation rule: 120 degree (Figure 11a) and 90 degree (Figure 11b), and two different materials, wood and paper to analyze how the material elasticity will affect the iteration. The interweaving wood beams as structural framing system component (Figure 12c, 12d) represents the possibility of reducing the number of lumber layer, for instance in conventional roofing system, which could eventually minimizing the amount of material (Figure 12a, 12b). Unlike wood, paper elasticity not only allow a flexible shape for each member but also exhibiting shape memory behavior as each component contracted back from a bent shape to its flat form, which make the surface bending (Figure 13c, 13f) from its initial intention (Figure 13b, 13e). This segmented paper experiment also applied the grammar in multilevel iteration where each resulting pattern from the previous iteration becomes an initial shape for the next iteration (Figure 13d).

3.3. Experiment 3: Interweaving plates [Plane’s composition]
Interweaving plates combine loop distribution from interwoven beams and pattern composition from interwoven bricks. Creating loop distribution in
Figure 12. Interweaving beam applied as a wall and roof (c,d) as single-layer framing system with short pieces compared to conventional roofing system using multilayer framing system with long-size beams (a,b).

Figure 13. Application of interweaving beam grammar using paper with single level grammar (a) and Multilevel grammar (d), where pattern resulted from 3 rotations becomes an initial shape for 6 rotations, and then the resulting pattern from 6 rotations becomes initial shape for 3 rotations. The bent paper contracted back from its initial design (b,e) to its original flat shape bending the whole interweaving surface (c,f).
two axes, as illustrated in segmentation C, allows the joint to widen the component surface in two axes instead of one linear direction. This wide surface allows interwoven plates to accommodate various shapes to perform two dimensional compositions. Shape grammar defines transformation rule for this edge based on the X and Y axis in each member (Figure 14). Rule 1 defines the length of the side (L) and shapes for the joint. To avoid overlapping of each joint, the total height of the joint should be lower than L/2. The joint then reflected based on the axis line offset L/2 in +X direction. Here, rule 1 and 2 perform a reflection of the copied joint based on the new axis line offset L/2 in +X direction. Both rules also work for the Y direction in order to generate cutting for plate modules. As an alternative, Rule 3 and 4 create similar surface using both rotational and reflection transformation where each iteration shifting the role of the shape from supporting tab into supported notches back and forth (Figure 14c, 14d).

The fixed-end joint in this interweaving system resulted from the angle of the side surface, where they are connected to each other. Figure 15
shows the edge for supporting sides have 45 degree interval, and the supported side has 135 degree, which basically act as a notches and tabs. This requires each edge to be identical so they can be fit together in larger surface.

4. Conclusion

At the beginning of this paper, interweaving was introduced as a celebrated yet little used in architecture. This study has applied the promising feature of interweaving as an active structural element in the building exploiting its Geometrical compatibility and Shape Grammar generativity.

Geometrical compatibility

The shape characteristic of each interweaving system, Points, Lines, and Planes, can be easily translated into the language of architectural geometry. In ornamentation purpose, these geometrical elements can be defined as the module or shape that can be expanded later into more complex patterns and structural configurations. For other construction purpose, this interwoven structure may be extended further to act as a column, a wall, a floor, or a window by applying the rule into a different scale and function.

Generative grammar

Labeling system in shape grammar has proven to be powerful in generating many complex patterns within a simple rule by just manipulating the label and the variable. This study shows that shape grammar not only works for generating a novel interwoven pattern but also very useful in analyzing existing woven objects to reveal the rule of its pattern. Note that all pattern from the three experiments were generated from the ordinary plating surface while there are various interwoven pattern remain untouched, either from the past or those that are currently in progress. In other words, there are numerous prospective rules remain uncovered for further architectural design studies.

This structural insight on the interwoven object illustrates the significance of computational rules behind the traditional artifact. Moreover, further computational studies on this object might reveal more benefits for

▲ Figure 15. Translation from line (a) into a plane (b,c). Interweaving plate’s module becomes a structural planar element with integrated notches and tabs with no additional binding component required.
other multidisciplinary studies, such as: environment sustainability and human-machine collaboration.

**Pursuing environmental sustainability**

The three experiments: weaving brick, beam and plates show how architects may use interweaving methods to minimize the use of additional binding component such as cement, nails or steel bracket. This reduction may not only reduce construction cost but also minimizes the impact of the binding material, such as steel and cement which require large scale of mining and manufacturing. In fact, types of materials used in this experiment, clay and woods offer more options for architects to use the local material.

**Enhancing human-machine collaboration**

The issue of applying computational design in traditional communities is not merely about the cost of the machine but instead, it’s about reconfiguring a mutual collaboration between the labor and CAD/CAM technology. This research shows a promising synergy between human and the machine, where the fabrication process is suitable for CAM and the assembling process could be enhanced by the intrinsic interweaving techniques as part of the traditional culture.

**References**
