Learning from Weaving for Digital Fabrication in Architecture

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ABSTRACT

This project restructures weaving performance in architecture by analyzing the tacit knowledge of traditional weavers through perceptual study and converting it into an explicit rule in computational design. Three implementations with different materials show the advantages of using computational weaving that combines traditional principles with today's digital (CAD/CAM) tools to develop affordable fabrication techniques.

Introduction: The Missing Link Between Digital and Traditional Weaving

A number of recent architectural design practices are revisiting weaving to promote the excellence of digital architecture computation [1]. Various braiding, knotting, and weaving algorithms make it possible to generate interwoven objects seamlessly with the digital model and materialize them with rapid prototyping machines [2]. However, some fundamental weaving properties seem to be missing. While traditional weaving performs both aesthetic and structural functions, some of today's digital architecture, as demonstrated by the Aranda/Larsch algorithm, use weaving mainly as surfacing pattern and not as a method of structural assembly [3]. Other promising proposals, such as Peter Testa's Carbon Tower [4] and Jenny Sabin's eBraid tower [5], apply weaving to large-scale architectural design by using carbon fiber (Figure 1d and 1e) .

In several traditional communities, where digital fabrication tools and advanced materials are not available, hands-on weaving routines are still widely exercised in craft-making and house construction (Figure 1a, 1b, and 1c) [6]. While weavers are working with the raw material, their senses and logic perform an immediate problem-solving procedure, as every knot they make constrains the next weaving step. This activity is analogous to how Donald Schön illustrates designers sketching their designs as a reflection-in-action practice [7]. In the case of weaving, the weaver's hands act as a force and stress gauge, while the weaving algorithm runs tacitly in their minds. The resulting weaving patterns are structurally durable and aesthetically contextual in their culture. In contrast to synthetic materials such as carbon fiber, natural materials such as grass, reeds, palm leaves, or rattan may offer flexibility and elasticity that might be useful in traditional architecture, but their limited dimension and lack of long-term endurance are not suitable for large-scale architectural designs, which require a certain degree of stiffness and permanence.

This research aims to bridge the gap between the absence of structural aspects in digital weaving and the lack of rigidity in traditional natural materials by analyzing structural performance in traditional weaving and implementing it using a digital computational method. In this pursuit, the following questions emerged: First, how do we frame the notion of weaving as it might be used in various fields? Second, how do weavers sense the interwoven object in order to make an assessment of its rigidity? Third, how can we explore the material behavior in relation to establishing novel manufacturing means and ensuring adequate production capacity? And finally, how can we convert traditional weaving procedures into the digital realm so that they will be

not only compatible with further computational processes, but also capable of expressing various patterns, as traditional weaving is? In exploring these questions, three projects show the conversion from and application of traditional weaving to digital weaving in designing woven shelters that combine conventional building materials (bricks and wood) with fast, easy, and cheap construction.

Weaving in Architecture

The use of weaving in contemporary architectural design as well as in this research is less about creating a new genre but more about a journey to the origin of architecture. In his "four elements in architecture" proposition, Gottfried Semper states that the origin of architecture overlaps with the creation of textiles, for people invented interwoven fences as the earliest vertical spatial enclosures, which then led to the invention of woven objects on a more domestic scale [6]. In addition, Frei Otto argues that the first human dwelling was constructed by weaving living plants (young conifers, bamboo, or branches of broad-leaved trees) because they were easy to harvest and manipulate by hand (Figure 1a) [9]. Moreover, the terms "technology" and "textile" are both derived from the Latin *texere*, meaning to weave, connect, and/or construct [10]. Given this intertwining history between architecture and woven surface, it is necessary to place the notion of weaving on a transcendental level between the fields of architecture and other disciplines that benefit from weaving (art and craft, textiles, material science) and focus more on the overlaps between those fields when weaving is used to meet a
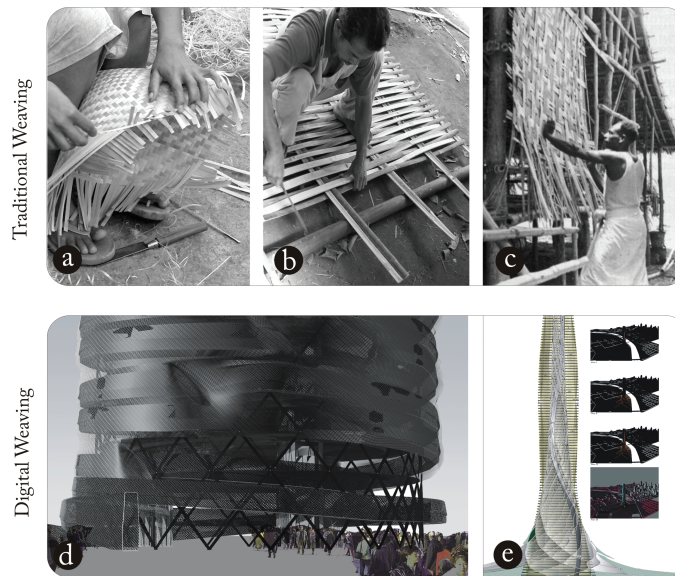

Figure 1. Comparison of traditional weaving and digital weaving. (a) Traditional basketry. (b) Weaving an interlacing bamboo partition (photo © Andry Widyowijatnoko). (c) Interlacing bamboo for a wall (photo © Paul Oliver). (d) Peter Testa's Carbon Tower (© Peter Testa). (e) Jenny Sabin's eBraid tower (© Jenny Sabin).

certain goal in design (geometrical composition and load distribution). For instance, we could compare knots in basketry to joinery in traditional grass roofs. By associating various aesthetic and functional values between these fields, we might gain valuable inspiration on the versatility of weaving in different applications. Based on this rationale, the term "weaving" in this research is framed as a system of interlacing objects into a structurally interdependent pattern, in which the object can be parameterized with various material properties, the structure can be reconfigured with different loading configurations, and the pattern may be embedded with other adaptable geometry for given material properties and structural configuration.

Haptic System in Traditional Weaving

In reference to Gibson's definition, "haptic system" could yield information about solid objects in three dimensions, whereas "sense of touch" does so in only two dimensions [11]. Thus, we might imagine that Aristotle's "sense of touch" evaluates weaving structural behavior by pressure and tension on the skin along a single axis (lateral or axial), whereas the Gibsonian "haptic system" assesses the higher dimension of weaving activity in three main weaving procedures:

First, the weaver's hand has both a passive role to feel the stress and strain of each knot and an active role as fabricator of the weaving (Figure 2e). Second, for weavers thread is not merely a construction material but also something that performs as cutaneous appendages and receptive units to transmit structural data from the woven object to the weaver's hand as the thread is stretched and pulled (Figure 2f). Third, the weaver's body performs dynamic touching as skin, joint, and muscle act together with different degrees of sensitivity. The stretching muscles transmit stress and strain data, the joint rotation transmits the angle and position coordinates, and the skin pressure provides contact information. In combination, they project a vector space in the surrounding environment to provide information regarding the weaving surface's stiffness (Figure 2g) [12]. This study argues that the above perceptual apparatus helps weavers to analyze the interwoven object in two scales: first in the knots and second in the plaiting surface [13]. In the knots scale, the weaver's sense of touch informs the way force and stress are distributed and creates structural interdependency at each intersection, by which the yarn in the X axis is being supported by vertical stress (sV) from the Y yarn on the interlaced area (A) (Figure 2c). In the plaiting scale, the weaver's haptics system can tacitly perceive pressure and tension stress along the surface by pulling the woven thread in vector space (Figure 2d). This is the point where material properties play a significant role in the weaver's perception of the weaving's structural properties. Elastic materials (reeds or coconut leaf) can transmit stress and strain information of the knot bending stress to the weaver's hand as it feels the distance (D) and coordinate changes (X_i, Y_i, Z_i).
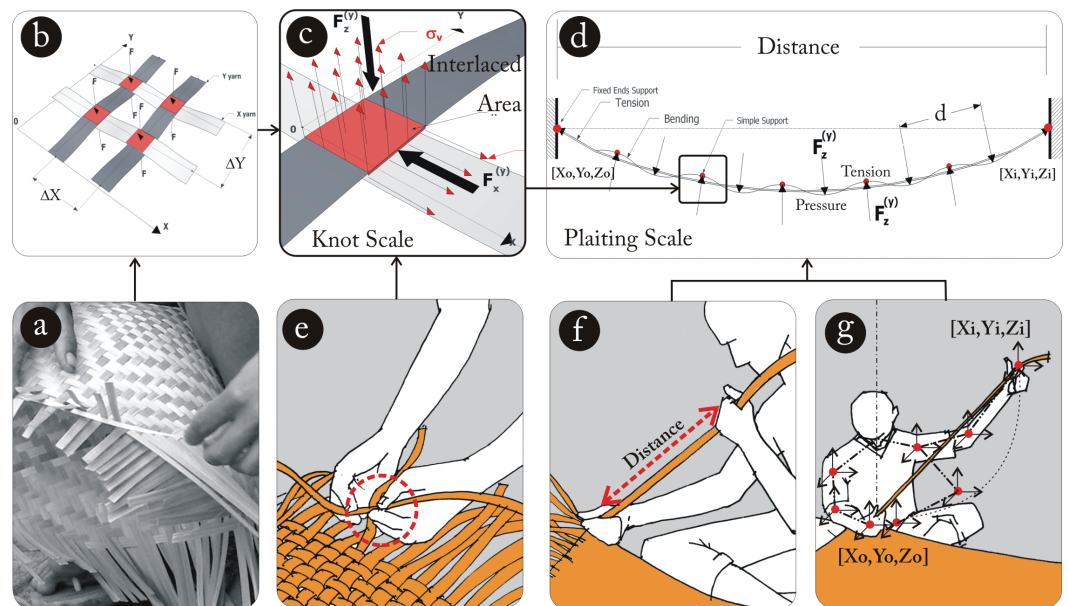

Figure 2. Sensing the structural behavior of a woven object. (a) The interwoven surface. (b) The surface translated into a structural grid. (c) Structural analysis of the knot scale. (d) Structural analysis of the plaiting scale. (e) The weaver's sense of touch. (f) The weaver's use of threads as cutaneous appendages. (g) The dynamic touching of the weaver's movements. © 2010 Rizal Muslimin.

Weaving Materialization

The challenge for this research is to answer how rigid material can perform weaving configurations based on perception studies of traditional weaving. The preceding assumption of the weaver's touch and haptic apparatus enlightens us that, structurally, weaving configuration balances the stress among tension, bending, and shear of the plaiting surface and the knots. Therefore, by applying this structural equilibrium in rigid materials, one can gain the benefit of traditional weaving within the more stiff and reliable materials, even with non-continuous

material [14]. The demonstration in Figure 3 shows the conversion process from traditional elastic materials to rigid materials through computational reasoning as follows:
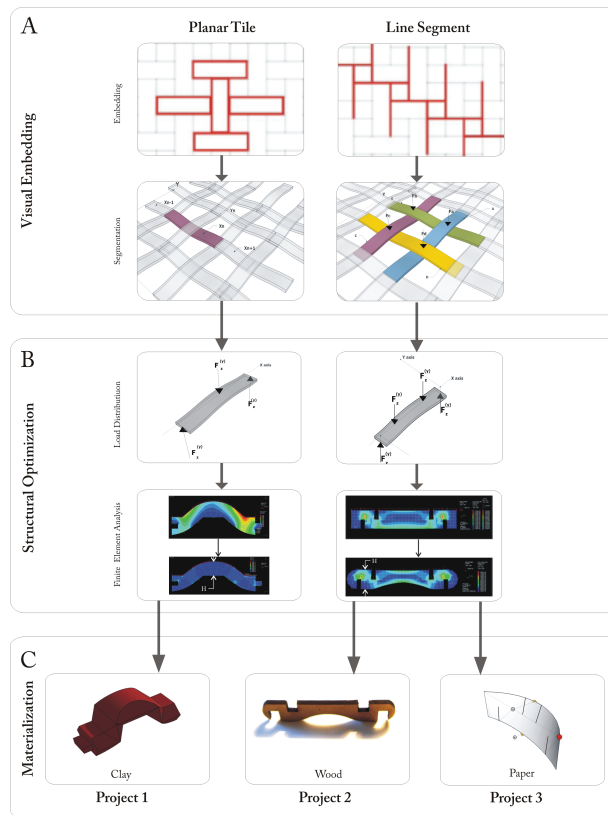
Visual Embedding. A geometrical pattern is visually embedded into the plaiting pattern to discretize weaving continuity based on the structural configuration from the sensing experience. For the first project, the segmentation literally subdivided the long yarn into a planar composition at each knot (planar tile), while for the second project the pattern is embedded by linear composition using the edge of the weaving pattern (line segment) (Figure 3a) [15].

Structural Optimization. The load distribution of the discrete elements guides the translation from two-dimensional pattern into three-dimensional shape. Areas where X and Y yarns interlace point out the location for notches and tabs as well as the increased height (H) of the area that supports the vertical forces. The three-dimensional shape is then digitally optimized using finite-element analysis to find the effective loading distribution. In finite-element analysis, similar sensing mechanisms do occur, albeit in an opposite way: the tactual sense happens in the woven object, while human hands act as instruments for applying the external forces and controlling the degrees of freedom. In other words, the sensing agent is embodied in the thread instead of in the external force (Figure 3b).

Figure 3. Conversion from traditional weaving to digital weaving through computational reasoning. (A) Visual embedding. (B) Structural optimization. (C) Materialization. © 2010 Rizal Muslimin.

Materialization. The optimized shape is then converted to a building component for architectural construction: the planar discrete element materializes into a brick, while the linear element transforms into a beam. For the first project, clay was chosen as the material because it is renewable, decomposable, and abundant in nature. The second project uses plywood for its light weight and its wide use in framing of structures. The third project uses paper to simulate the behavior of the weaving pattern, using elastic material as a comparison to rigid material (Figure 3c).

Rule for Assembly

An assembly rule is assigned to the discretized building component so that it becomes programmable to generate various geometric patterns from a few modules while retaining the essential structural properties of weaving. In this case, the rule assignment uses shape grammar not only because it is parametrically compatible with other computational algorithms (L-systems, cellular

automata, fractals), but also, more importantly, concerning the limitless variety of weaving configurations, the labeling system and shape relationship in shape grammar can manage and elaborate different emergent behavior [16]. Moreover, shape grammar is capable of translating abstract logical propositions into a concrete functional feature [17]. The following applications with different materials (clay, wood, and paper) demonstrate the way shape grammar's label and shape relationships mediate computational algorithms, generate programmable components, and accommodate weaving structural behavior.

Project 1: Weaving as Brick Assembly

In this project, points in the pixelated pattern correspond to the surface of a brick module (Figure 4a). Shape grammar analyzes the original pattern as a two-dimensional array of red and white cells, and tracks the pattern linearly, cell by cell, along the same axis, similar to the rules in von Neumann's cellular automata [18]: red means the cell exists, and white means the cell is empty (Figure 4b). More specifically, the rule reads the current cell as a labeling point and its connection to the next cell as the shape relationship. Then, for each iteration, shape grammar looks at the next cell to see whether it exists, is empty, or is not detected, and assembles the corresponding brick on the projected grid based on the following rules (Figure 4c):

Continuous Rule to form a continuous line: IF the next point exists, THEN use a continuous brick;

Checkered Rule to form a checkered pattern: IF the next point is empty, THEN use a checkered brick;

Edge Rule to stop the iteration at the edge of the surface: IF there is no point afterward, THEN use the edge brick.

Each brick is connected to the other bricks through the same axis using notches and tabs as the joint elements, creating both a self-supported surface and a mosaic of the pattern with little cement or mortar. Structurally, the checkered composition is more rigid than the continuous one, so the more the checkered rule is used, the firmer the surface will be. Also note that in this project the brick module uses a rectilinear grid, which causes the surface to be generated in rectilinear fashion. Likewise, different brick modules with diamond, circular, or triangular shapes will create different geometrical expression.
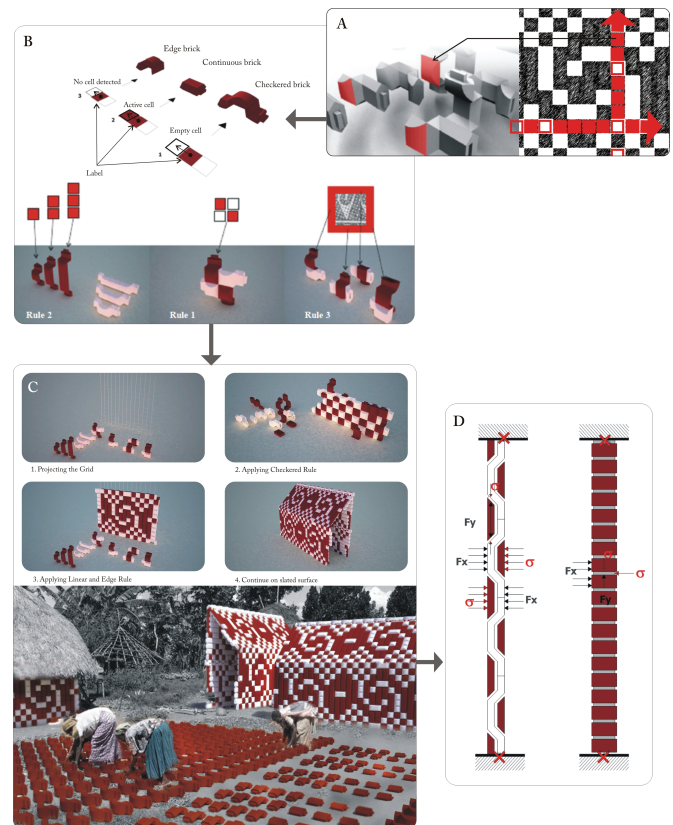

Figure 4. Weaving with bricks. (A) Bricks corresponding to the pattern of pixels. (B) The label and spatial relationship rules resemble the motif of the original pattern. (C) The process of assembling the shelter structure. (D) Comparison of a conventional brick-and-mortar wall and a woven brick wall. © 2010 Rizal Muslimin.
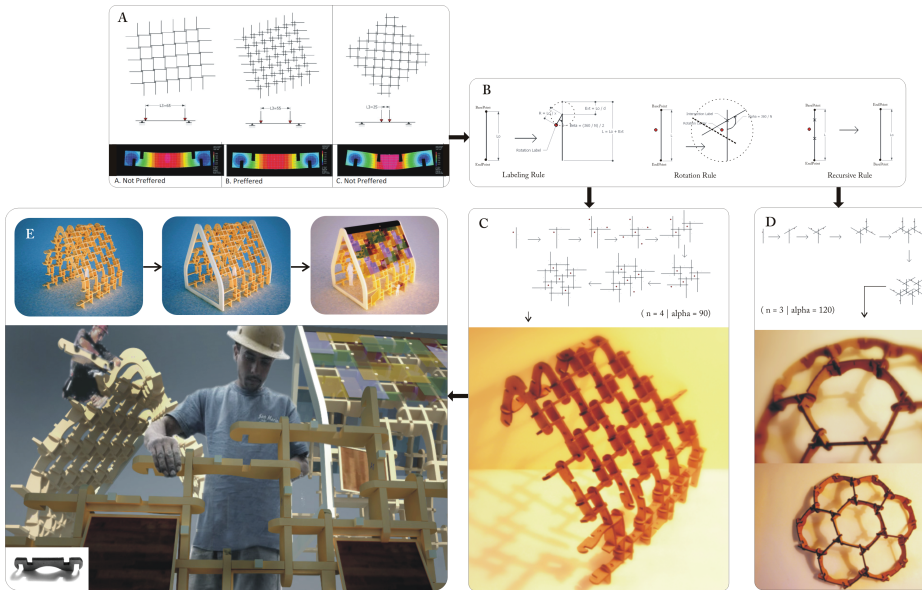
Figure 5. Weaving with wood for shelter construction. (A) Finite element analysis optimizing the distance between notches for each beam. (B) Parametric rule for overlapping plywood. (C) Application of the rule using a 90° angle for four beams. (D) Application of the rule using a 120° angle for three beams. (E) Application of the interwoven beam grammar in shelter construction. © 2010 Rizal Muslimin.

A similar approach to eliminating the use of mortar to create low-cost patterns using self-consistent rules has been implemented in Larry Sass and Terry Knight's meandering bricks. The components of meandering bricks have integrated alignment features (two horizontal and vertical notches as aligners) so that they can be easily matched and locked together manually without binding materials [19]. The difference between these two methods is that in this project, the interwoven arrangement between bricks establishes a firm alignment capable of supporting the axial and lateral forces. Connections with neighboring bricks along the perpendicular axis prevent vertical shear that might be caused by lateral loads at each joint. In this way the wall's thickness can be significantly reduced (Figure 4d).

Project 2: Weaving in Wooden Structure
In contrast to the brick assembly, which continuously distributes the load in a single axis, the overlapping load distribution along both the X and Y axes in wooden-beam weaving makes it possible to use short plywood as a structural member. Here, the label and shape relationship grammar were determined parametrically by the rotation center point and the number of beams to copy and rotate the first beam, as the initial shape, into three or four pieces at each knot using the following rule (Figure 5b):

The Labeling Rule locates the rotation center point based on the distance between notches and tabs from the finite element analysis (Figure 5a) so that each member will interlock in a proportionally stable manner.

The Rotation Rule defines the type of shape relationship based on the rotation angle (a, alpha) and the number of beams (n) that will be produced on each knot (a = 360 / n). In this example, three beams rotate by 120 degrees to create a triangular pattern (Figure 5d), while four beams rotate by 90 degrees to express a rectilinear pattern (Figure 5c).

The Recursive Rule mirrors the new rotated beams so that its new center point can be used as a label to create other new beams recursively. Once the rotation center point label and
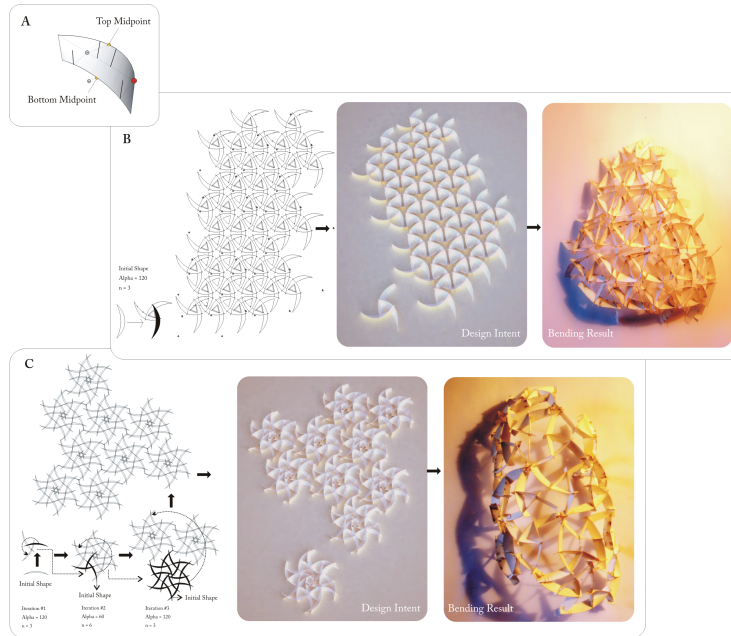
Figure 6. Material behavior in the interwoven paper beam. (A) A piece of the bent paper beam. (B) Shape grammar rule (left and middle) and the result (right). (C) Parameterized rule application results in a new initial shape for the next iteration, including surface deformation caused by the bending moment of the paper. "Moment of force" (or simply "moment") is the tendency of a force to bend, twist, or rotate an object. © 2010 Rizal Muslimin.

shape relationships are defined, shape grammar generates the woven beam surface analogous to an L-system generation of various plant geometries [20].

The resulting woven plywood creates a strong rigid structure that can support loads along the axial, lateral, and vertical axes with different patterns (Figure 5e).

The same intention to reduce and simplify joinery components has been demonstrated by Axel Killian in his puzzle-like adaptable detail (3D puzzle) of a curved surface by combining computer-controlled fabrication and generative modeling in order to generate cutting geometries [21]. But dependence on advanced fabrication machines is not critical, as simple rectangular notches and tabs in this beam can be easily cut using traditional woodworking tools. Therefore, this woven beam is more like the work of Cecil Balmond, Eduardo Souto de Moura, and Alvaro Siza in their 2005 Serpentine Pavilion Gallery [22]; Kenneth Snelson's tensegrity [23]; Frumar et al.'s tensegrity structures with 3D compressed components [24]; Studio Weinand's textile applications on building scales [25]; Shigeru Ban and Arup AGU's Centre Pompidou [26]; and many other remarkable strategies for pursuing integrated joints for cheaper and more efficient construction.

Project 3: Weaving the Paper Beam
In exploring paper flexibility, I bent the rectangular surface by shifting the midpoints of its side length (Figure 6a). To this bent paper I then applied the same rules from the second project using 120-degree angles to create a two-dimensional triangular pattern. However, the woven bent paper beam demonstrates unexpected behavior, as the pattern blossoms from a flat into a round surface as it is assembled. This effect is caused by the bending moment on each module, which tends to twist the shape back to its original flat surface (Figure 6b). Furthermore, this project exercises the parametric feature of the rotation rule by changing the value of the angle and the number of beams in each generation. The first iteration rotates the paper beam 120 degrees to create triangular relationships. The composition from this iteration then acts as an initial shape for the second iteration, which uses a 60-degree rotation, creating another shape relationship: a hexagonal star (Figure 6c). This hexagonal star is then used as an initial shape for the third iteration that goes back to 120-degree angles, and the process continues to populate the surface with the same values afterward. Similar to the previous design, the bending moment in each knot causes the surface of the whole pattern to bend.

Conclusions

Essentially, this research has incorporated weavers' tacit knowledge into an explicit algorithm in computational design by combining the benefits of digital computation with hands-on experience in weaving through the following contributions:

> I justified J.J. Gibson's haptic system in looking at weavers' perceptual experiences to understand the structural mechanism of traditional weaving.

> I developed a new, faster, and cheaper assembly system in brick construction by using the principles of weaving, as well as a new joint system in wood assembly that does not require additional joint components such as nails, screws, and bolts.

> I generated a rule for weaving brick that makes it possible to create various pixelated patterns and one for weaving beams that makes it possible to express ornamental structures by parametrizing the angles and the number of beams.

Further studies and experiments are required in order to improve the habitability standard of such woven shelters. Some of the questions that need to be addressed in future work are: How do we make the interwoven brick waterproof so it can be used as a roof and strong enough to be used as a horizontal woven floor plate? What is the best depth-to-height ratio of the module? What is the span limit? Can it be assembled in linear fashion to form a column? In the extreme case, consider: How can we construct the interwoven beam using wood pieces of unequal dimensions, allowing us to use wood from rubble to build temporary shelters after an earthquake, for example?

This research is a preliminary inquiry into one of many approaches to weaving in architecture. It takes into account the role of perception in design and a computational design framework. The following are a few suggestions for further studies on weaving in architecture:

> ***Examine other perceptual apparatuses:*** This perceptual investigation on traditional weaving activity has been focused extensively on the weaver's tactual experience rather than other perceptual apparatuses. Thus, further investigation (for example, on how weavers' visual perception works as they decide which pattern or what type of knot to use, and how it is related to their haptic system) would provide a significant continuation of this research.

> ***Extend the geometrical language:*** For a practical reason, the case study used in this research is a simple plaiting surface that has a standard rectilinear pattern, while there are many other varieties of patterns in traditional weaving that remain unexamined so far. This opens enormous possibilities for more geometrical exploration in this traditional-digital weaving conversion, at the knots level and/or at the surface level.

> ***Explore the computational methods:*** Through the use of shape grammar in this research I have applied other computational algorithms such as L-systems and cellular automata to the labeling and spatial-relationship system. However, the most powerful feature of shape grammar is its capability to generate many different designs using just a few simple shapes by visually embedding several geometrical properties and parameterizing various label positions and shape relationships. Thus, as an alternative to using other patterns or other algorithms, one can just continue exploring different labeling and shape relationships using the preceding shape from the interwoven brick walls, wooden beams, and bent paper to achieve other novel assembly techniques in architecture.
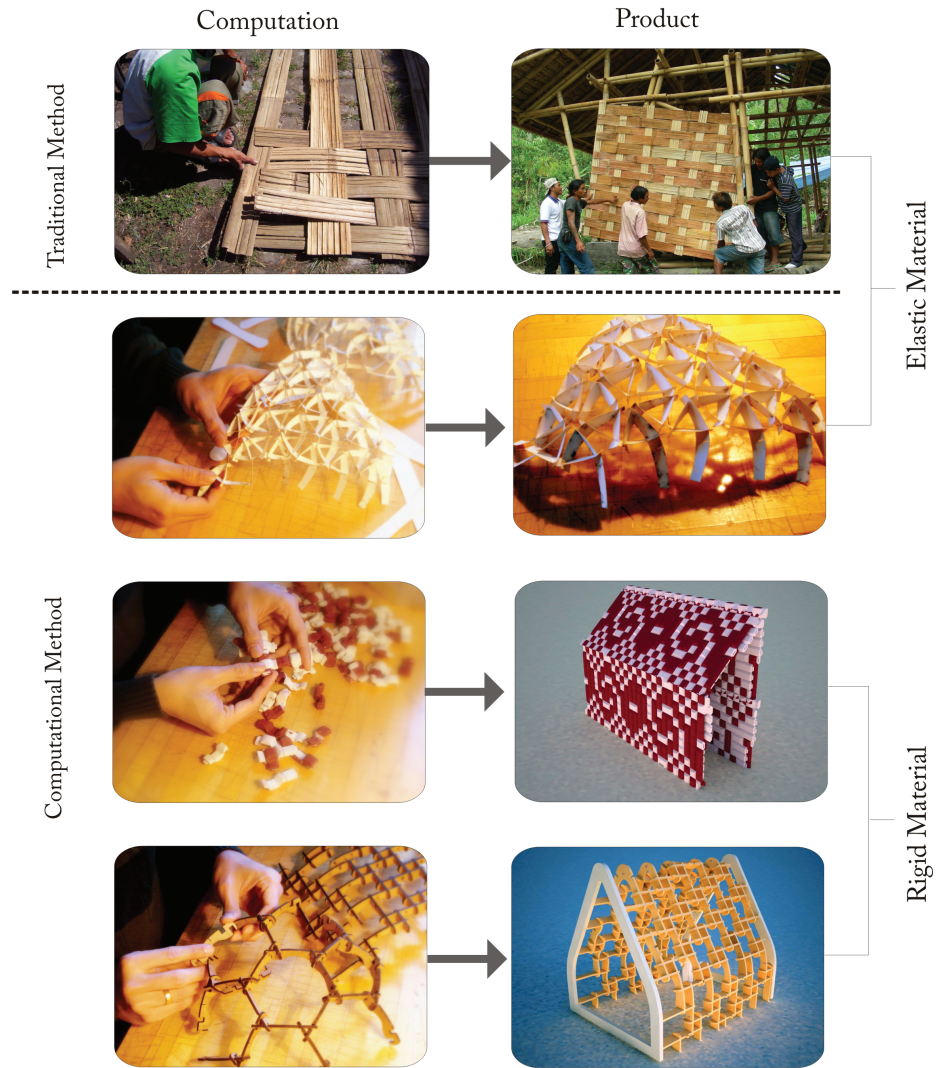
Computation   Product

Traditional Method

Computational Method

Elastic Material

Rigid Material

Figure 7. Comparison between traditional weaving using continuous materials (top left and top right) (photos © Andry Widyowijatnoko) and computational weaving using segmented materials. © 2010 Rizal Muslimin.

In conclusion, algorithms in general should not be perceived as applicable only to modern, state-of-the-art digital technology. Instead, we should begin to appreciate many of the built-in algorithms in existing traditional production techniques. By recognizing and incorporating such algorithms, designers might be able to make the intuition behind their own perceptual modalities more explicit and optimize their use of computational aids (Figure 7).

References and Notes

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3.   C. Lasch and B. Aranda [1].
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5.   Sabin's eBraid tower proposal uses two interconnected braids: an external braided carbon fiber diagrid superstructure and internal conducting braids with the capacity to absorb, collect, and deliver energy and light. J. Sabin, <www.jennysabin.com/>.

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8. For textiles, Semper uses the term "plaiting" to mean interwoven objects. He uses the term "weaving" to criticize the contemporary practice of industrial weaving as lacking a practical aesthetic and drowning in its excessive resources, in comparison to traditional weaving (by the Hindus and Kurds), far simpler and less industrial but with a greater understanding of art. Furthermore, Semper stratifies textile art into the following: 1) bands and threads, 2) spun yarn, 3) twisted yarn, 4) the knot, 5) the loop stitch, 6) plaiting, and 7) felt. To analyze structural performance in plain interwoven surfaces, this research uses knots and plaiting. The yarn and how it is twisted plays a significant role in further analysis of material performance of interwoven surfaces. G. Semper, *The Four Elements of Architecture and Other Writings*, trans. Mallgrave and Herrmann (Cambridge: Cambridge University Press, 1989).

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11. Gibson refers to the haptic system as an apparatus by which the individual receives information about both the environment and his body. In addition, Gibson warns that what is simple for mechanics is not simple for human mechanoreception—a tactual receptor of mechanical energy in all of its manifestations, including vibration—and that biomechanical stimulation is not reducible to physical magnitudes. However, information about stress/strain, forces, vector direction, and coordinates are compatible enough with digital computation, enabling it to perform the weaving of the structural configuration but not the total sensory experience of the weaver. J.J. Gibson, *The Senses Considered as Perceptual System* (Boston: Houghton Mifflin, 1966).

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