10 NOTES ON ASSEMBLY

When the means and action of fabrication are divorced from the process of design (a particular risk of closed digital systems), aspects of the actual construction and assembly processes are placed at risk of terminating or at least compromising the integrity or intent of the design. Digital tools offer powerful ways of envisioning and directing design strategies, but they can also promote inattention to the processes required to realize full-scale work.

In our case, the entirety of the arch structure was developed alongside an additional but invisible set of construction formworks that enabled the mutable and complex aggregation of components to be physically joined (Figures 21–23).

The nature of the process is one of coordination and constant recognition of the structural tendencies and resilience of the incomplete structure and subassemblies. Within our research and fabrication, it is only at this point of the process when it becomes necessary to establish a rigid formwork or scaffolding in order to move between the gravity-free virtual world, real materials, and space.

11 CONCLUSION

Digital Steam Bending points to an expanded model of digital and material practice in which powerful computational tools extend one's capability to explore the reciprocity between digital and physical realms across a range of scales. Through this research, the authors have sought material resistance as an active collaborator in the generation of design, providing insight into the potential of materials and data to be transformed by physical processes and vice versa through a series of interconnected feedback loops. Digital Steam Bending has recovered a nearly lost art and craft and forged new ground for steam bending at an architectural scale.

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PROCESS THROUGH PRACTICE:
SYNTHESIZING A NOVEL DESIGN AND PRODUCTION ECOLOGY THROUGH DERMOID

ABSTRACT

This paper describes the development of a design and prototype production system for novel structural use of networked small components of wood, deploying elastic and plastic bending. The design process engaged with a significant number of different overlapping and interrelated design criteria and parameters, a high level of complexity, custom component geometry, and the development of digital tools and procedures for real-time feedback and productivity. The aims were to maximize learning in the second-order cybernetic sense through empirical experience from analog modeling, measurement, and digital visual feedback and to capture new knowledge specifically regarding intrinsic material behavior applied and tested in a heterogeneous networked context. The outcome was a prototype system of design ideation, conceptualization, development, and production that integrated real-time material performance simulation and feedback. The outcome was amplified through carrying out the research over a series of workshops with distinct foci and participation. Two full-scale demonstrators have so far been constructed and exhibited as outputs of the systems and processes developed.

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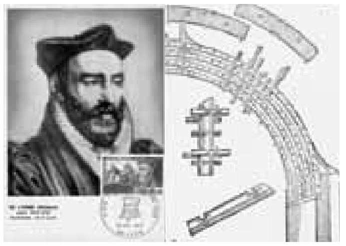


figure 1

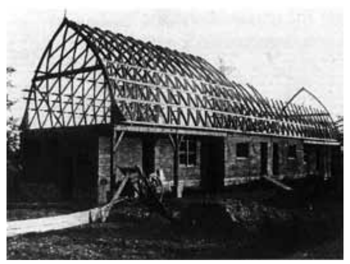


figure 2

1 INTRODUCTION

1.1 Project Aims and Objectives

The Dermoid project aimed to apply a performative approach to the modeling and simulation of built structures in the specific domain of material behavior. There has been considerable work on developing tools and feedback systems in design modeling for evaluating structural performance, energy performance, and response to climate, which include the extrinsic characteristics of material (Holzer et al. 2007; Toth et al. 2011). The novelty in this investigation was to engage closely with material as a nonhomogeneous medium that could have its properties manipulated and altered through, for instance, bending, jointing, and composite assembly, with the aim of being able to achieve digital simulation and performance feedback of these levels of difference within a complex networked structure.

1.2 Precedents

This project draws on a five-century-old design philosophy: Philibert de l'Orme's treatise on low-cost, large-span structures made from short timber lengths. In 1561, responding to the problem of obtaining long oak timbers in his part of France, de l'Orme published *Nouvelles Inventions Pour Bien Bastir et a Petits Frais* (New inventions for building well at little expense). De l'Orme researched and realized the idea of producing arches from short pieces of oak instead of producing the usual hammer-beam construction—a considered design response to a serious supply problem (Figure 1).

More recent research has taken as a point of departure the wooden roof system of Friedrich Zollinger (1880–1945): a traditional structural lamella system using a woven pattern of interconnected beams to produce a strong spanning vault from short-length timber (Figure 2). While this system had a small repertoire of achievable geometries, the recent research investigated the application of flocking, agent systems for self-organizing generation of a much greater variety of freeform outcomes conforming to a structural rule set, or set of agent behaviors derived from the history of Zollinger's lamella system (Figure 3) (Tamke et al. 2010).

As an alternative to this bottom-up approach to achieving structures for "difficult" geometrical or free-form surfaces from small timber components, another approach is to program the population of predefined surfaces (Peña de Leon and Shelden 2011). An example using timber in a similarly structurally indeterminate way is the Shigaru Ban Centre Pompidou-Metz roof (Tristan et al. 2007).

The novel emphasis in this project was to explore—through modeling, prototyping, and empirical testing—ways to develop a design process that brought the feedback regarding shape, deformation, and structural performance live into early and potentially responsive design modeling and simulation, rather than testing and adapting geometrical design iteration outcomes after the fact. This involved open experimentation and mapping of empirically observed behavior back into the computational systems developed. The larger aim was to develop comprehensive design and production systems and procedures that exploited the round trip between physical and digital modeling and simulation to achieve more materially responsive architecture. These systems for bringing new material knowledge and responsiveness into design practice were the primary focus of the research.

1.3 Timeframe and Context

This question of how material properties can be introduced into contemporary design practice was the focus of a 2009–11 Velux Visiting Professor invitation to Mark Burry from the Centre for Information Technology and Architecture (CITA) at the Royal Danish Academy of Fine Arts. Over the 18-month period of the project four intensive workshops were held, each building on the work of the earlier ones and based on four phases: ideation, concept development, design development, and fabrication. Two research groups collaborated, with student cohorts engaged in two of the workshops.

figure 1

Philibert de L'Orme, from Nouvelles Inventions.

figure 2

The roof structures of Friedrich Zollinger (1880–1945).

1.4 Project Plan: Criteria and Ground Rules

The first consideration for the project was that small elements should work collectively within a network or an interdependent matrix that could include cyclic relations. The aim was to set structural challenges in which the computational modeling, performance analysis, and structural and geometrical feedback would ultimately be both nontrivial and highly generalizable to different designs and geometries.

The second was the exclusive use of small-section wood and wood products. Initially the first workshop experimented with thin ash strips. In subsequent stages this became knot-free pine in combination with birch-faced 4 mm and 6.5 mm plywood, and finally just plywood.

The third was to permit formal license in terms of both shape and the degree of custom design needed for the individual elements and their nodes and connection point details, but to find systems to accommodate this in streamlined fabrication and construction.

A fourth was to avoid secondary non-wood-based products, materials, fixings, or adhesives that might introduce other local strength and behavior characteristics.

1.5 Methodology

Each of the four workshops had distinct research and pedagogical ambitions. Each had a different mix of researchers, external collaborators, and in three cases undergraduate or graduate students. While each produced outcomes and knowledge that could be redeployed in the next, each also exploited the opportunities of returning to a fresh point of departure in the iterative spirit of both discovery and design. In this way each contributed to the design and development of the overall system as much as to the design of the ultimate demonstrator. Work continued for the core research team on the development and refinement of the systems for modeling, simulation, design development, and fabrication between and outside the staged workshops.

2 SYNTHETIC DEVELOPMENT AND COMPREHENSION OF THE DESIGN ECOLOGY

2.1 Workshop 1: Developing Design and Performance Intuition

In the first workshop a group of students explored the properties of thin wooden strips through physical experimentation, including exposure to water and heat (Figure 4).

2.2 Workshop 2: Developing Systems—Reciprocal Framing

The second workshop brought together members of architectural and computational research teams at CITA, including engineering participants and the Spatial Information Architecture Laboratory (SIAL) at RMIT University for three weeks of intensive physical modeling, testing, and trial digital simulation environment development. A number of new and enduring ideas were introduced at this stage, and the aim was to have a first prototypical extensible structural system developed by the end of the workshop.

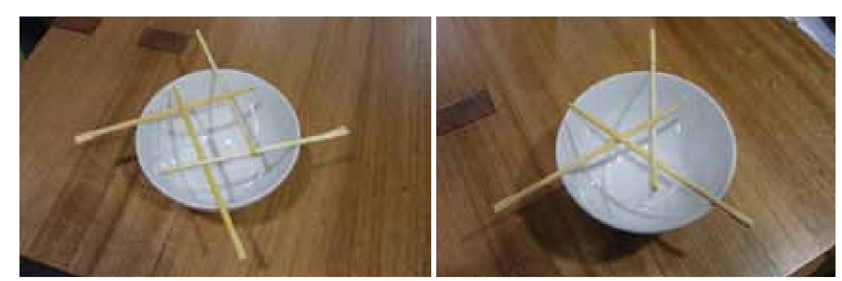


figure 5

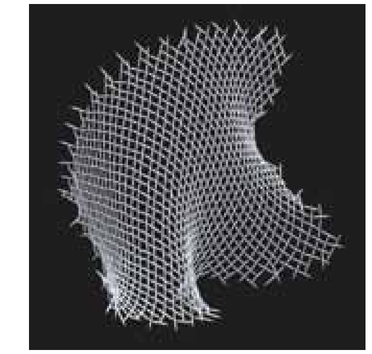


figure 3

figure 4

figure 3

Agent-based flocking system used to generate a lamella system of small timber members over a freeform surface.

figure 4

Workshop 1.

figure 5

The theory of the reciprocal frame truss.

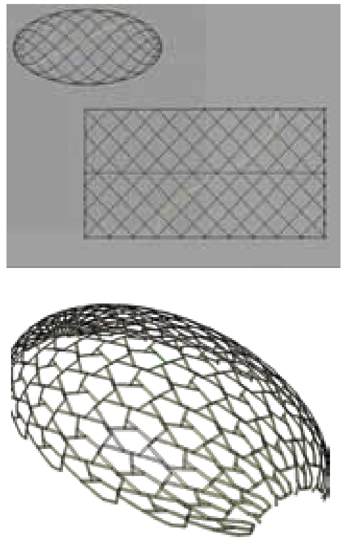


figure 6

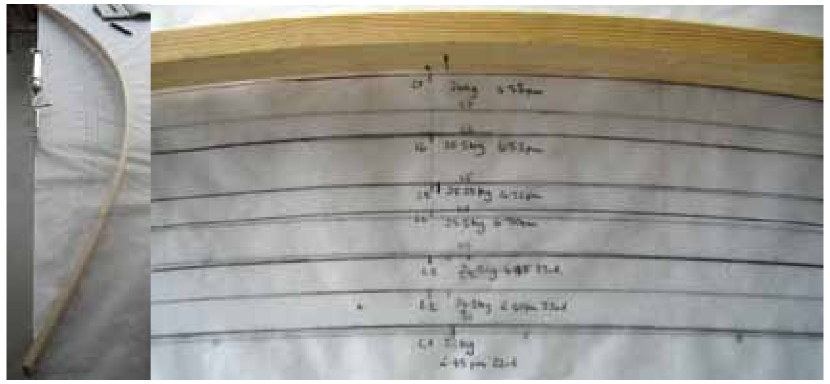


figure 7

figure 8

The first idea was to further investigate the application of the reciprocal frame as the basis of the interdependence within the structure at the unit level (Popovich 2008) (Figure 5). The team had access to expertise in this structural approach, and it was an interesting and challenging way to commence the investigation into the use of short wood lengths for longer spans.

The second new idea was to adopt the ellipsoid as the starting point for the dome of the whole structure, which was conceived as an enclosure rather than a spanning roof. The ellipsoid with aspect ratio not equal to 1 in any dimension is notoriously difficult to tile, with its continuously changing curvature in all dimensions, but it has positive curvature everywhere so engages the traditional problem of the long spanning arch. It has the problem of its "poles" or areas of very high curvature and no obvious geometry for the creation of openings (Figure 6). It is very difficult to closely approach a true ellipsoid with any limitation on the number or dimensions of different tiling units, so it leans toward a high level of customization and differentiation across the surface. How would this be accommodated economically in the structural design and performance of small structural units optimizing material performance?

At the same time the group worked on research into the behavior of the material and how this might be mapped into specific base units, beams, or trusses at the unitary level.

At first, bow-string trusses were investigated for:

1) plastic creep in the wood over an extended period (Figure 7);
2) consistency of mathematically definable shape for different lengths, tensions, etc., and how this might be modeled, predicted, and affected under load.

Simultaneously, experimental models creating assemblies of reciprocal truss trefoils or hexagonal

figure 6

Geodesics: Wrapping straight lines onto an ellipsoid; wrapping reciprocal frames onto an ellipsoid.

figure 7

Bow-string truss passive deflection over several days, for which the partial reverse was also charted.

figure 8

Early assembly models testing patterns of tri-member reciprocal frames and web introduced for stiffness.

figure 9

figure 10

figure 11

tilings of bow strings quickly identified the need for increased stiffness in the individual elements if the design strategies were to progress to large span self-supporting structures with a highly controllable shape under dead load (Figure 8).

This led to prototyping variants on a T-shaped arched beam, initially with an ash flange and birch ply web slotted into it (Figure 9). Attaching the two components became a challenge that was resolved later by switching to a ply flange also. In this version perforations were introduced into the flange, and matching teeth protruding from the web allowed them to be "zipped" together, literally rolling the flange onto the web from one end to the other (Figure 10). Extensive experimentation with fitting together many versions of such assemblies led to refinement of the tolerances in sizing and spacing of teeth and perforations, and also discoveries about the difference in loading point at which the flange and web would separate according to the relative proportions, dimensions, and intervals for

figure 9

Examples of an early T-shaped beam of timber flange and birch ply web slotted into it, and loading to measure deflection up to failure.

figure 10

The zip truss: birch ply flange and web with matched perforations in the flange and teeth on the web for a dry friction joint.

figure 11

Load testing variants of the zip truss for deflection and failure.

figure 12

the zipper (Table 1/Figure 11). Other parametric variations tested were variable resting curvature of the beam, plywood thickness, depth of the web, and extracting material from the web through different window cutting patterns. The dry friction fixing and truss configuration were found to be novel and outside the range of existing load tables or accessible structural data by the engineering participants and hence worthy of extensive empirical load testing for deflection and ultimate failure. An initial pass identified the best performing configurations; this was followed by much more systematic testing selectively varying the depth of the web, ply thickness, and zipper configurations.

In the early assembly models of the tripartite reciprocal frame, each individual member overlapped with others in convex curvature at one end and concave curvature in another triad of joints at the other, so initially had to be constructed from two co-tangential T-profile arched beams. The jointing presented problems that were solved through developing an S-shaped prototype, with the web transferring midspan from one side of the truss to the other with an overlap for stiffness (Figure 12).

2.3 Workshop 3: Developing a Design

A third workshop with Royal Danish Academy of Fine Arts students followed a period of intensive follow-up work on the project after workshop 2. Researchers had developed a number of tools and digital environments in which the students could start to explore parametric variations of a schematic design system (Figure 13).

The physical modeling aspect of the workshop focused on developing the systemic design for the final prototype construction. At this stage the idea of doubling the reciprocal frame units emerged during early design exercises, drawing on the structural metaphor of the wishbone,—so light, strong, and essential to the mechanics of flight in birds. This greatly increased the potential stiffness of the structure through the combination of positive and negative curvature all over the structure (Figure 14).

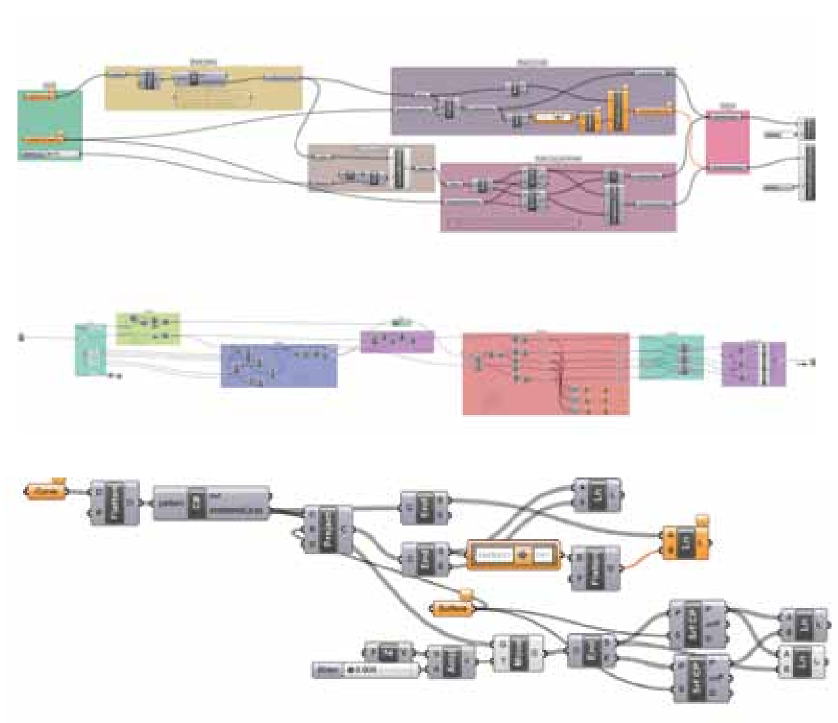


figure 13

figure 12

The first S-shaped prototype beams with the web switching from one side to the other.

figure 13

Digital explorations for students developing their parametric modeling skills.

figure 14

figure 14

The wishbone added reciprocity: doubling up the reciprocal frame to give it positive and negative curvature.

Intense physical prototyping explored the potential for the wishbone system, optimal jointing for the flange and web, and particularly the resolution of the point of inflection between adjacent elliptical beams and jointing between beams that would accommodate the unique combined angle of each joint in three dimensions and unique beam length in each unit populating the surface.

A project-specific tool or routine was developed in Grasshopper as the basis for the 2D cutting and identification of elements for efficient fabrication of the units and assembly of the future demonstrator—the detailed overall form of which was still in negotiation.

2.4 Workshop 4: Developing a Production System

A final workshop involved a smaller team to finalize the form of the full-scale demonstrator and the automation system to translate the design into a system of components that could be cut, assembled, and fabricated into the large enclosing structure in a relatively short time by a few final participants.

figure 15

3 STRUCTURAL ANALYSIS AND EXPLORATION

3.1 FEA Structural Testing

Tests conducted with finite element simulation incorporated detail such as the plywood layering. They showed the overall structural behavior but through an analytical approach that was labor- and time-intensive and required a static set of boundary conditions. The computing time for the analysis, while rapid, was still of an order that ruled out real-time feedback and interaction with the model.

Parametric systems and finite element analysis (FEA) can be linked (Maher and Burry 2003; Burry et al. 2005). But the question of how and where feedback from FEA should be fed back into a parametric or recursive design process remains an open one. In order to develop any kind of automated or optimizing loop between the analysis and design, the nature of the response must already be determined. For instance, Arup developed a tool to optimize the size of individual steel members contributing to a complex structure through iterative analysis and feedback, but in this case the response was limited to selecting from a finite number of possible member sizes. In this project there were at least four mutually implicated levels of engagement in the design of the demonstrator: (1) material thickness; (2) element cross-section and joint details; (3) overall structure; (4) overall topology (Tamke et al. 2011). In this design process the choice of response was left open to the designer: to experiment with change and further analysis and to some extent design intuition about how best to respond. For instance, the structural performance following FEA was improved by increasing the overall height and arching of the Dermoid structure, altering the lengths of the members and angles within the nodes but not the topology or thickness of any of the members. This was effective both structurally and in terms of avoiding rework in the node design that variable member thickness would have necessitated.

3.2 Building Structural Intuition

Based on experience from former projects (Tamke et al. 2011) the physics solver incorporated in the nucleus engine of Maya™ was used to establish a time-based process giving real-time intuitive feedback on many different and interrelated parameters. Based on the abstraction of the hexagonal distribution system, a particle/spring-based system used the underlying polygon mesh as an input. This created a different geometric understanding of the constraints and their interdependency and relation to the overall system, including spatial design; functional constraints, mesh density, and appearance; angles in the nodes; minimizing beam lengths; size and distribution of cells; curvature; cutting plate size constraints; and staging and accessibility during construction. In this way the mutual dependency of the parameters could be modeled digitally, solving several layers of constraints in parallel.

4 DIGITAL MODELING TECHNIQUE, SIMULATION, AND FEEDBACK

4.1 Synthetic Tectonics—Digital Tools

The leading role of synthesis in the design research discovery in this project is illustrated through the description of the physical modeling–informed decision-making. The project proceeded through an iterative design process of physical and digital prototyping. Physical material experiments led, and the development of bespoke design tools was continually tested in response to the physical performance of the material models and prototypes. The tools were evolved through a mashup of Grasshopper™, Digital Project™, C++ with Open Cascade object library, Processing, and Maya™, with extensive scripting overlays.

4.2 Adapting the Reciprocal Principle

The exploration started with ideation based around the construction of physical models that introduced "material bendiness" in a reciprocal frame system. This was subsequently referenced back to the question of simulation in the digital environment. Traditional reciprocal structures utilize gravity for their stability, which means they ideally need to align horizontally (Popovich 2008). The aim in this research was, however, to achieve enclosure by a continuous surface. A structural system had to be developed that could operate in the vertical as well as near-horizontal plane. This involved a wider understanding of reciprocal systems. Where these are typically made from layered beam systems, we introduced a secondary stabilizing level to accommodate the vertical components of the dome. The system remains reciprocal in the jointing where the three beams connect in a circular manner (Figure 15).

figure 15

The circular (reciprocal) relationship of the joints.

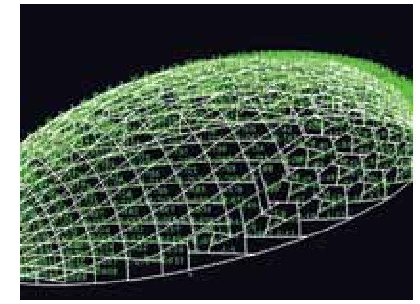
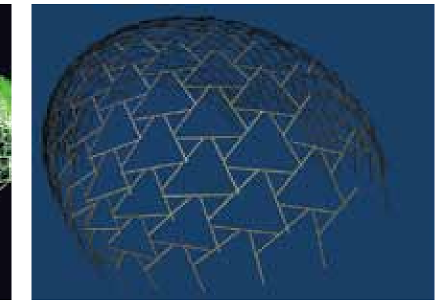


figure 16



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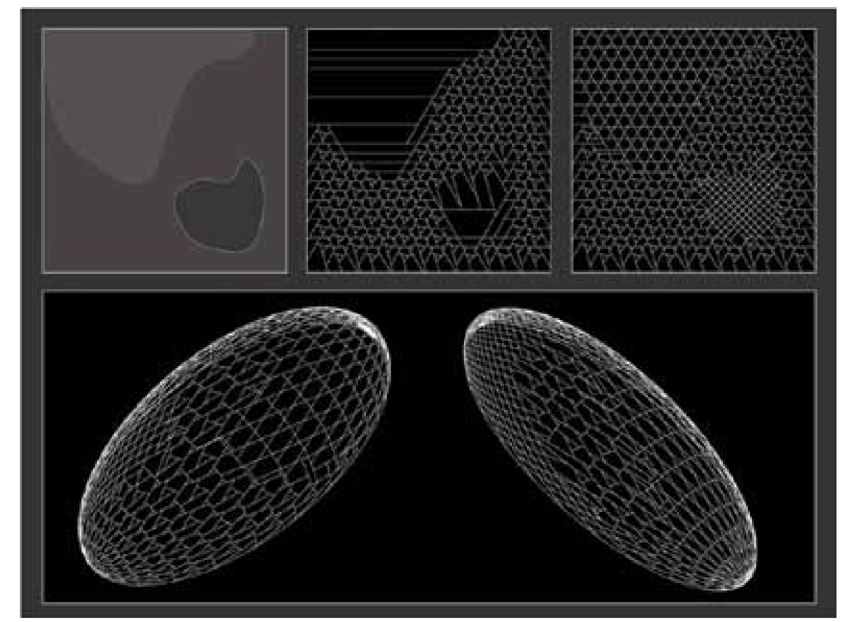

figure 18

4.3 Populating the Dome

The nature of the shape of the dome surface required an independent system to control the distribution of the reciprocal units over the surface. In parallel to the physical prototyping development of the tri-member, hexagonal-ocular system, other surface population patterns were also instantiated adopting the beam system as it became more established. This patterning deployed a sphere-packing algorithm starting from a three-dimensional geodesic curve path of spheres across the

figure 16

Pattern 1: Identifying lengths.

figure 17

Pattern 2: A variation on the hexagonal layout.

figure 18

Pattern 3: Self-organization.

Figure 19

Patterns 3 and 4: Identifying joint angle challenges and using dynamic relaxation

figure 20

The resolution of the lapping of the joints and notching in the first demonstrator, Dermoid 1.

figure 21

Automated production of two-dimensional cutting patterns from the model.

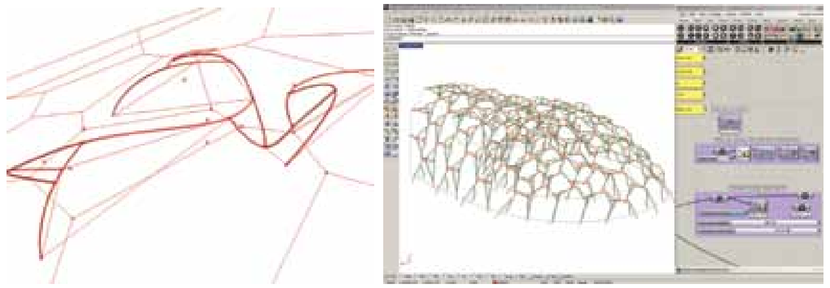

figure 19

figure 20

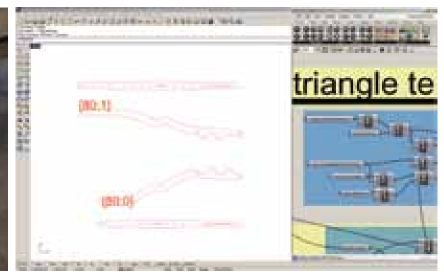

figure 21

surface. The sphere intersections on the surface were used to control the distribution, size variation, and edge conditions for the surface patterning. The local pattern of reciprocal elements could be instantiated onto the basic "hexagonal" intersections created by the spheres intersecting the master surface. The patterning routine was implemented using VB. Net with Open Cascade object library (Figures 16–19).

4.4 Lapping and Jointing

At the same time another digital modeling preoccupation was the custom nature of the joints or nodes in the structure in which the members would meet at different and unpredictable angles of incidence. Preliminary modeling used Digital Project™ to explore a series of custom instantiations, but this was not extended to full simulation for different versions of the demonstrator. The principles of the detailing were resolved as the final system of slotting and lapping flanges and webs through the iterative use case modeling and physical prototyping. The system was instantiated into the final Grasshopper model for unfolding and component cutting and assembly (Figures 20–22).

5 DISCUSSION

Designing a system for the representation, simulation, and understanding of material properties throughout the stages from early design iteration to design for construction in a way that transcends the standardization of materials and their standardizing impact on design is an open challenge. In particular, the integration of real-time feedback in digital design modeling with an appropriate level of rigor for the design stage is difficult. The Dermoid project offered a theater in which design research into real-time material performance could be undertaken.

How close did the project get to being able to modify the design "on the fly" in response to material performance feedback? At an early iterative and schematic design level, it succeeded well. It also maintained model flexibility into the final stages of producing the demonstrator. The FEA gave a good indication of the distribution of stress in the near final demonstrator. It could be linked very effectively to nontopological change in the model—for instance, to macro shape change with updating

figure 22

figure 22

Demonstrator 1.

distribution of nodes across the surface (increasing the arch) or to changing the material thickness in particular members. The challenge was to initiate the appropriate response, determining at which scale to intervene to optimize the structure. For instance, one trial response that improved the stress distribution significantly was to reverse the rotational symmetry in each tri-member reciprocal node. The computation time meant that the analysis was not responding in close to real time, but analysis feedback could be accomplished in as little as half an hour. The physics engine, by comparison, builds structural intuition about comparative performance of different configurations and provides a parametric design exploration tool ahead of providing robust performance feedback. The detailed local structural impact on the material behavior of notching, lapping, and jointing techniques, for example, would require another level of computational modeling to furnish good feedback and relied heavily on analog testing at this stage.

6 CONCLUSIONS

The project focused on structural performance and gathered novel feedback on particular new structural assemblies and configurations. It met its own synthetic design challenge to create an enclosure with a large span using small, lightweight timber components, and to do this with a high degree of customization among components and highly variable possible shape and design. More significantly, it developed systems for designers to better understand the implications of accessing real-time design computation to aid their decision making. Moreover, the computational systems were very successful in deferring traditionally pivotal decisions like the overall form of the demonstrator at little final cost.

We learned through the research that, while we are not yet able to reach the desired levels of real-time computed feedback on material performance for complex structural arrangements, we are nevertheless getting much closer than we have been in the past. We can declare that the combination of empirical analog testing and dynamic input into our various bespoke digital tools gave us a very different result than we would have arrived at if we tried to "solve the problem" through optimization alone. This will now be taken further in the development of the third demonstrator.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of the Villum Foundation Velux Visiting Professor Program 2009–10 and the Australian Research Council through the Discovery Project Challenging the Inflexibility of the Flexible Digital Model.

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UDK: Elisa Lafuente Hernández, Christoph Gengnagel

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EMERGENT REEFS

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ABSTRACT

The Emergent Reefs project draws on the potential that emerges from a coherent utilization of the environment's inherent ecological structure for its own transformation and evolution, using an approach based on digitally simulated ecosystems and sparked by the possibilities and potential of large-scale 3D printing technology. Considering tourism as an inevitable vector of environmental change, the project aims to direct its potential and economic resources toward a positive transformation, providing a material substrate for the human-marine ecosystem integration with the realization of spaces for an underwater sculpture exhibition. Such structures will also provide a pattern of cavities which, expanding the gradient of microenvironmental conditions, break the existing homogeneity in favor of systemic heterogeneity, providing the spatial and material preconditions for the repopulation of marine biodiversity.

Starting from a digital simulation of a synthetic local ecosystem, a generative technique based on multi-agent systems and continuous cellular automata (put into practice from the theoretical premises in Alan Turing's paper "The Chemical Basis of Morphogenesis" through reaction-diffusion simulation) is implemented in a voxel field at several scales, giving the project a twofold quality: the implementation of reaction-diffusion generative strategy within a nonisotropic three-dimensional field, and integration with the large-scale 3D printing fabrication system patented by D-Shape®.

Out of these assumptions, and with the intention of exploiting the expressive and tectonic potential of such technology, the project has been tackled exploring voxel-based generative strategies. Working with a discrete lattice eases the simulation of complex systems and processes across multiple scales (including nonlinear simulations such as computational fluid dynamics), starting from local interactions using, for instance, algorithms based on cellular automata, which then can be translated directly to the physical production system. The purpose of Emergent Reefs is to establish, through strategies based on computational design tools and machine-based fabrication, seamless relationships between three different aspects of the architectural process: generation, simulation, and construction, which in the case of the used technology can be specified as guided growth.