Re-Frame:
form-finding within the constraints of mutually supporting assemblies

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Abstract

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This research is an investigation into the concept of the reciprocal frame as a means of generating sculptural architectural form within the limits of modular unit design. The development of expressive form involves a balance of various influences. One of these is the process of rationalization, where ideas and images are considered as material artifacts that must be built using available resources and technologies. The concept of the reciprocal frame presents an intriguing case for accommodating the limitations of a construction method in the development of form. This thesis explores the range of aesthetic variation available in axially connected reciprocal assemblies by means of experimentation with pattern, physical prototyping, and iterative geometric optimization. The project develops a workflow from form-finding to fabrication within the rigid constraints of this assembly logic, while striving to remain faithful to the tectonic elegance for which this structural concept has historically been valued. Conclusions of this investigation are that the state of axial tangency defines a class of reciprocal assembly which, while constrained to a distinct range of form, offers benefits in tectonic rationality and scalability over other sub-families in this area of structural design.

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Finally, my deepest gratitude to my wife and family for their unconditional love and support in this process of exploration.

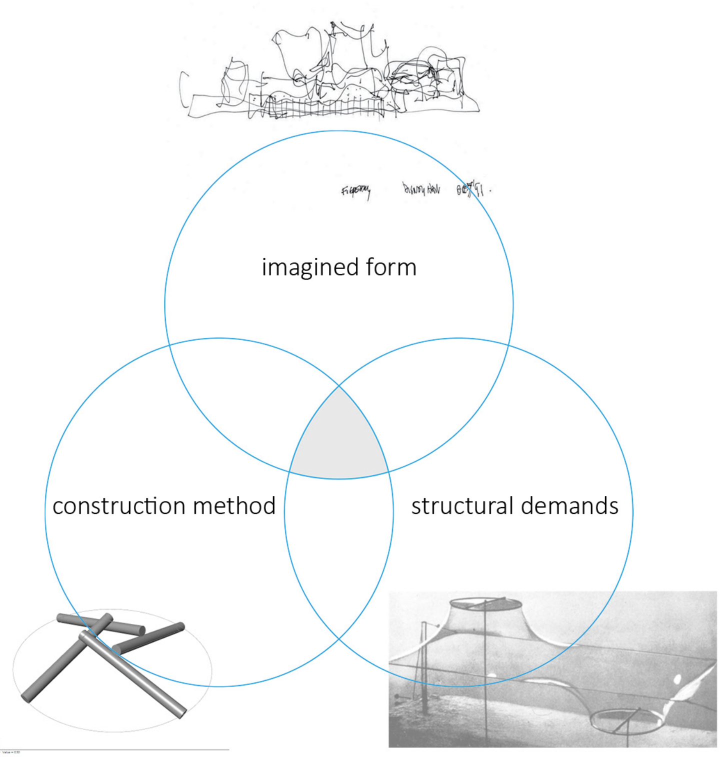


Fig. 1.1: The development of architectural form can be represented as a confluence of various constraints.

1.0 Introduction

In contemporary architecture, so-called ‘free-form’ geometry is more and more a part of the language of form available to designers as tools for managing geometric complexity become more accessible. Free-form architectural geometry offers new opportunities for expression of form and volumetric response to design program. However, added complexity in the connection of parts limits the available material palate or makes otherwise inexpensive materials cost prohibitive. In timber construction, for example, the latter is often true. It is therefore desirable to find a flexible solution that uses available materials and allows for simple joinery conditions with minimal hardware while maintaining some repetition of process in manufacturing. This thesis suggests that such a goal may be best achieved using the concept of the reciprocal frame and a process of iterative optimization.

All decision-making processes are shaped by influences or constraints. The physical form of an architectural construction is the product of a complex decision-making process which incorporates considerations of material, natural forces, and design ideation. These translate into construction tectonics, structural performance and aesthetic intent. Structural performance is dictated by natural laws and the choice of tectonic system. The tectonic system is influenced by design intent, and also by available materials and the processes by which they are prepared as building supplies. While all of these factors play a vital role in the development of form, the constraint of construction technology provides more opportunity for control in material and process, and has a proportionally greater ability to affect the cost and feasibility of a project in a given situation.

The tectonic concept of the reciprocal frame (RF) has been used in different roles throughout the centuries as an adaptation to otherwise simple design problems constrained by lack of conventionally appropriate material, labor expense, portability and other unusual circumstances. This investigation explores the value of this tectonic system as a constraint in the generation of sculptural form. The intent of this work is to find simple methods of rationalizing complex surface forms and to identify limits of the RF concept as an approach to the problem.

Fig. 1.2: The facade of Frank Gehry's EMP is an homage to Jimi Hendrix and a direct metaphor for one of his iconic performances.

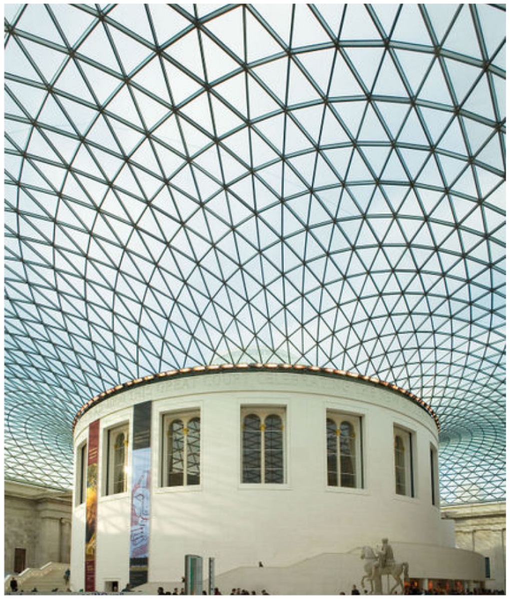


Fig. 1.3: The free-form of Foster+Partners' roof for the British Museum is developed as a response to existing edges

1.1 Balancing/Opposing: Ideation and rationalization

Sculptural geometry at architectural scale has historically been more costly and laborious to build than the conventional structures of a given era, as existing construction methods must be adapted to new ends. The motivations for these forms are varied, at times expressing artistic aesthetic, responding to design program and edge conditions, or making reference to analogue forms or concepts significant to the culture or client for whom the work is built. The expense related to sculptural form is due, in part, to the fact that developing these forms into built artifacts often involves a top-down rationalization approach, wherein conventional construction methods and materials are pushed to conform to abstracted geometric representations.

In any process of design rationalization, material properties and construction methods push back against the imposed notion of abstract form, resulting in a final artifact that represents the interplay of these constraints. Since the adoption of CAD/CAM workflows in the architecture and construction professions, this process of top-down form rationalization has become more economically feasible (Kolarevic 2003), but does not necessarily represent an efficient use of materials or construction labor. As tools of representation have become more capable of communicating the designer's vision, and methods of construction adapt to meet the demands of increasingly ambitious projects, it is worth considering the importance afforded to various factors influencing the final rationalized design.

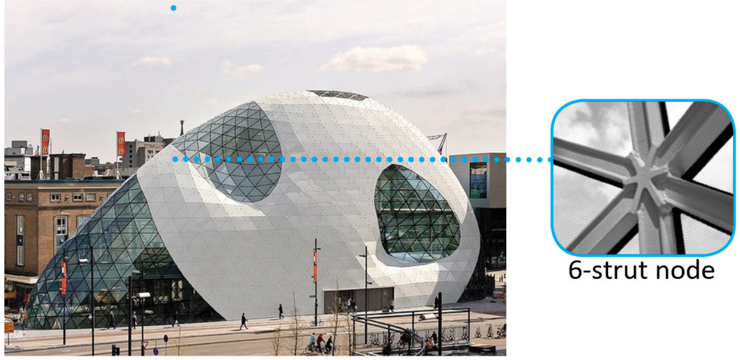


Fig 1.4: Free-form facade of the “Blob”, Fuksas Architects

Fig 1.5: revolved facade of the Sage Gateshead, Foster + Partners

Enlightened practices involved in complex geometric projects have made effective use of rational architectural geometries during the ideation phase of design, acknowledging the tectonic benefits of forms that can be built more simply and perform aesthetically and architecturally as well as more abstract ‘ideal’ design forms. Two notable projects by Foster and Partners, the Copenhagen New Elephant House and Sage Gateshead, both take their facade forms from surfaces of revolution. The use of geometries in this family allows the facade to be broken down into quadrilateral panels with some repetition of elements (Peters 2010.) This equates to dramatically reduced cost in fabrication when compared to triangular paneling techniques, as surfaces of revolution provide simpler node connections in construction and a greater degree of uniformity in the production of panels and structural members (Pottman 2007.) While triangular rationalizations can be applied more generally to arbitrary complex surface geometries, the added expense in fabrication and assembly must be warranted, usually by aesthetic demands on the design.

In the design of so-called ‘free-form’ architecture, there are many motivating factors at play. Often the building or element is intended to act as an icon of a place, an advertisement to draw outside attention. The extreme expense of these projects demands a driving motivation with some promise of return on investment. However, there are other reasons to build non-standard or sculptural architectural forms. In situations where transportation of material and unusual site conditions provide atypical constraints, the designer may look to atypical geometries for a solution. Like the decision to use a revolved form over a true free-form for tectonic simplification, other forms of efficiency have pushed designers to build sinuous vaults and other non-standard forms over the more conventional or straightforward building geometries available at a given time in history.


Fig. 1.6: Elegant architectural tectonics derived from traditional ajiro wickerwork.

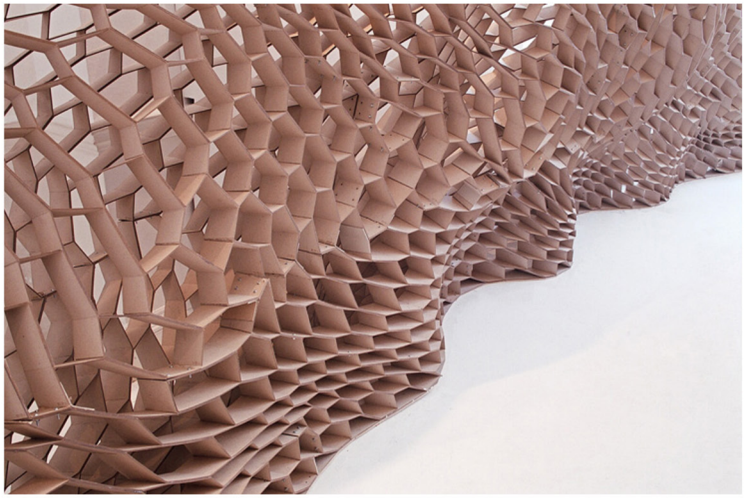


Fig 1.7: Honeycomb-inspired structural installation, MATSYS

In the development of non-standard surfaces in architecture, one must decide to deviate from conventional building geometry, and decide how to go about constructing the form. These decisions need not follow in a prescribed order, as each of these decisions carries implications of motivation, and motivations are likely to differ from project to project.

1.2 Common Patterns : Nature and Artifice

The search for elegant form in architecture, as in other fields of design, looks for inspiration in the geometry and processes of nature. Naturally occurring forms, particularly biological forms, are often developed using minimum energy of one type or another to maximum effect or performance. It is a pattern of economy that exists at various scales, from molecular interactions to cellular structures to the behaviors of animals. Across this range of scales, the rules of economy are interpreted differently, as the constraints of the environment act differently on one process than on another. However, when considering the development of architectural forms, the available material palette imposes further constraints. Here, we may look to other forms of evolution for inspiration. Both nature and technology develop and progress on the fundamental principles of evolution. More fit forms survive while less fit forms are abandoned. Traditions of vernacular craft, based in utility and inspired by efficiency or scarcity of material, provide an intriguing counterpoint to contemporary bio-mimetic design.

Adaptation to Material Behavior

Beginning the 1950’s, architect and engineer Frei Otto made a thorough and systematic effort to harness the economy of energy and material found in natural forms. By observing the physical morphology of soap films under controlled conditions, Otto was able to push the boundaries of design in membrane and tensile net structures (Barthel 2005.) This process of form-finding is based on the idea of an analogue between two sets of materials and processes. The tendency of fluid soap films to reach an equilibrium at which tension forces are evenly distributed across the surface makes them ideal modeling tools for membrane structures and tensile cable tents, in which the material must perform in pure tension.

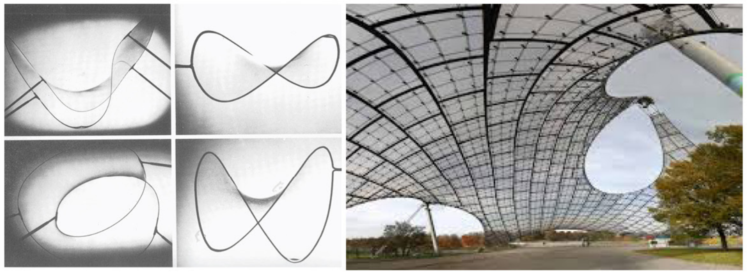


Fig. 1.8: Otto's experimentation with soap film behavior is directly responsible for the anticlastic forms of the 1972 Munich Olympic Stadium.

In designing for different tectonic systems, different categories of analogue forms are explored. A similar logic is applied in the design of catenary suspension structures and inverted catenary vaults, where a slack chain or weighted line can be used to find the form in which forces are most evenly distributed through the material most directly transmitted to the supports. This method of form-finding for arch design was formalized as early as 1675 (Jardin 2001) and has been developed further in the work of Antoni Gaudi, and later again by Otto.

Harnessing Biological Adaptation

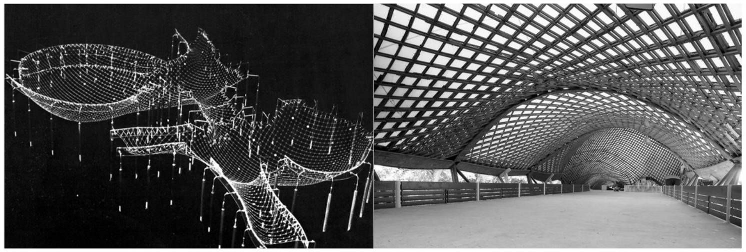


Fig. 1.9: A hanging-chain model is used to develop the form of the Multihalle gridshell.

The designer can experiment directly with inert materials to find efficient and economical forms, but often may find that much of the experimentation has already been done by evolution. Any of the forms found in biological structures can be interpreted in some way as a finely tuned response to the forces of the environment. The most easily generalized forms are those that respond to constraints similar to the demands of the design problem. Bionics, the field encompassing this type of formal inquiry, looks to naturally evolved geometries for both performative and metaphorical ends. Architectural works may make symbolic reference to natural form as a way of expressing design values or intent, as demonstrated in the soaring forms of works by Santiago Calatrava (Motro 2009.) At this scale, metaphor may take some of the performative quality of the inspiration, but relies heavily on traditional analytic processes for optimization. Space-filling structures

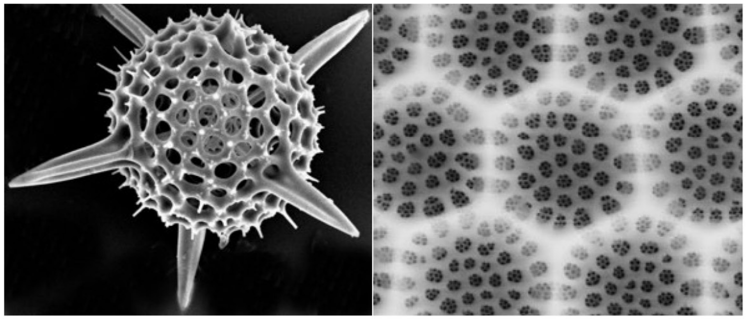


Fig. 1.10: Radiolarian (left) and diatom (right) skeletal structures

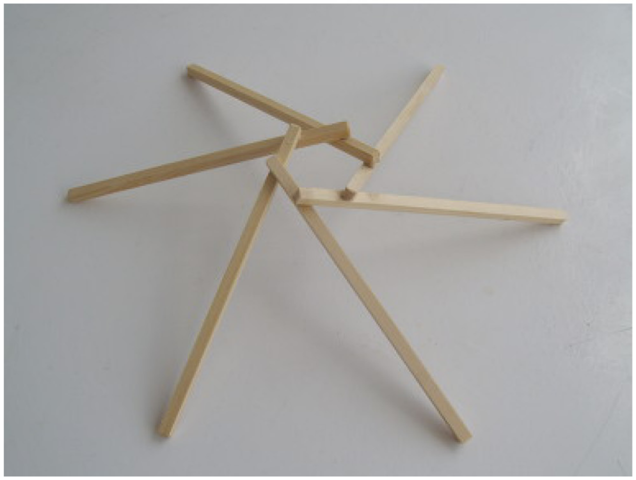


Fig. 1.11: 6-beam reciprocal frame assembly

are common in nature, particularly at small scales, where gravity is less dominant over other forces. The skeletal structures of hard-shelled algaes and planktons, particularly species of free-floating Radiolaria have provided geometric inspiration in the design since the nineteenth century (Beukers, Van Hinte 2005.) When used at architectural scale, these configurations are able to resist forces with an efficient distribution of material, the precedent being formed by a balance of forces similar to the example of an inverted catenary model.

In addition to scientific experimentation and observation or naturally-occurring forms, craft tradition can be used to great effect as an inspiration or precedent in developing efficient structural systems (McQuaid 2003.) The same scalability of geometric efficiency that allows an architect to draw inspiration from microscopic plankton also applies to handicrafts such as weaving, knitting and paper-folding. Textile and basketry techniques, in particular, are applicable at larger scales than ever before due to the increased range of materials available to designers. These arts represent an evolution of technique, culminating in an optimized system for using available material to a particular end. A great benefit of working from a craft inspiration is that the geometry brings with it a tectonic logic, a system of implementation, some knowledge of the forms one can create, and the known failure modes of the system. This study investigates the merits of such a system, the reciprocal frame (RF).

Even when beginning with a strong knowledge base, it is inevitable that one will find new questions and new constraints when experimenting with an existing construction system. It is the goal of this study to illuminate some of the benefits and shortcomings of the RF as a concept and to explore an aspect of the system that promises to deliver on the basic motivations that created this family of structural forms.

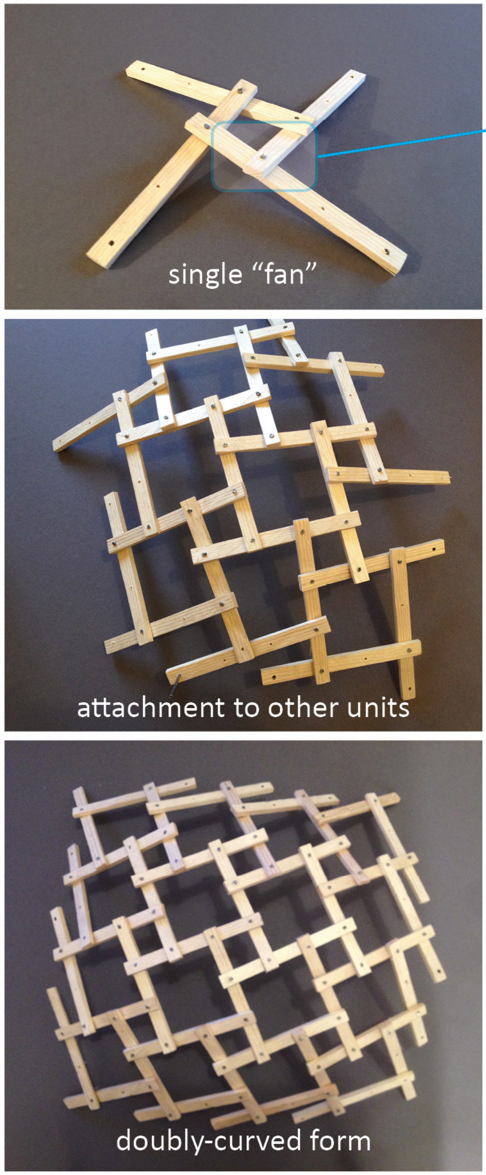
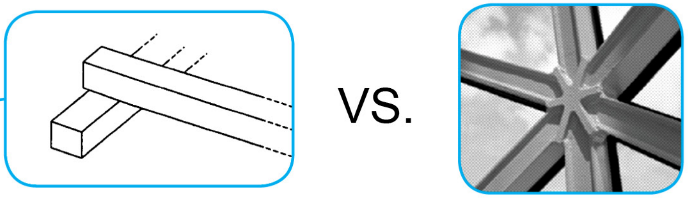


Fig. 2.1: A vaulted form is created by compounding the basic reciprocal unit.



2.0 Reciprocal Frame Assemblies

The concept of the reciprocal frame has deep precedents in historic and prehistoric building forms, but remains an esoteric area of architectural discourse today. Its basic mechanism is represented in the simple ‘fan’ arrangement shown in figure 2.1. Beam or strut elements are overlaid in a non-hierarchic arrangement, such that each supports and is supported by a neighboring element. Fans can be compounded, attaching one to the next to form a rotated grid pattern. In this way, small pieces of material are able to span significant distances with minimal complexity at joint conditions. The incline of the base unit directly informs the local surface curvature in a compound grid, and this incline is subject to the effects of other values present in the geometry of the assembly. The intertwined nature of these parameters is both a strength and a shortcoming of the reciprocal attachment. The parameters of this system have been explored analytically and well documented, most notably in the work of Olivier Baverel. This typical overlaid joint defines the most studied form of the RF, in part due to its adherence to the simple tectonic motivations of the system. A benefit of this simplicity is that overlaid RF structures are more easily constructed from simple materials with simple joint conditions. These joints, being variable in rotation and translation, are easily manipulated in the field to produce different frame geometries, making them ideal as study models and promising as deployable structures.

2.1 Logic and parameters

In recent years, research in the fields of structural engineering, geometry, and computer science has made great advances in understanding the information structure and relationships that govern reciprocal frame geometry and structural performance. In geometric abstraction, the units of a frame are often represented as cylindrical struts, as this geometry clearly portrays the inter-relation of parameters present in these systems. Many repeating tessellation patterns have been identified as capable of accommodating reciprocal beam geometry (Song 2013), and in all cases, the inter-relation of parameters at the 'fan' level is consistent.

The fan unit can be considered as a standard truss node in which all of the members are rotated by some amount, producing an open cell at the location of the node. The ends of these members are then overlapped to create a mutually supporting frame. This transformation has been described as 'system turbining' in the design of rigid tensegrity structures (Fuller 1975.) Overlapping creates an incline in each of the members, and now the fan is defined by a set of interconnected parameters. Unit incline is controlled by the radius of the members (eccentricity), the degree to which they have rotated away from the node center (engagement length), and the number of members in the fan. Any one of these parameters can be determined by changes in any of the others. Depending on the initial configuration of the frame, more or less freedom is allowed in the parameters of individual fans (Douthe & Baverel 2009.)

Frame geometries can be developed both by direct manipulation of base parameters or by iterative relaxation processes (Baverel 2000.) The choice of method may be determined by design geometry (i.e. regular poyhedra vs. free-form surface) or by the pre-selection of a material or building unit geometry. Many approaches have been used to rationalize these systems for construction, and all have both strengths and weaknesses.

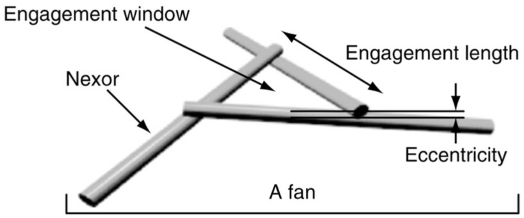


Fig. 2.2: The parameters of an elemental RF 'fan'

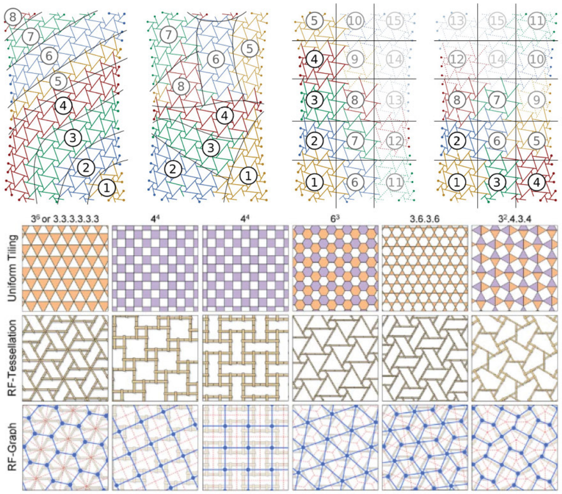
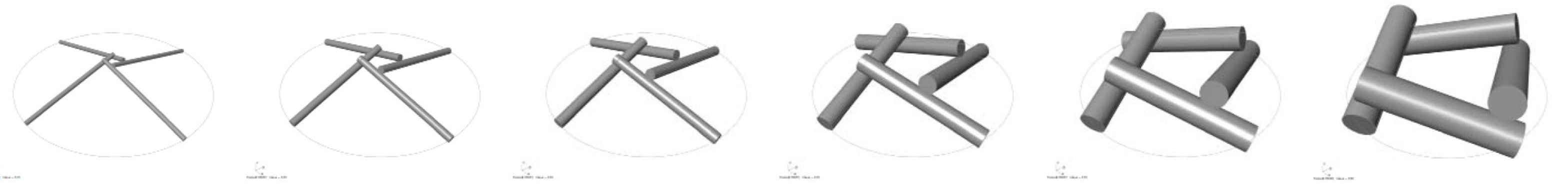
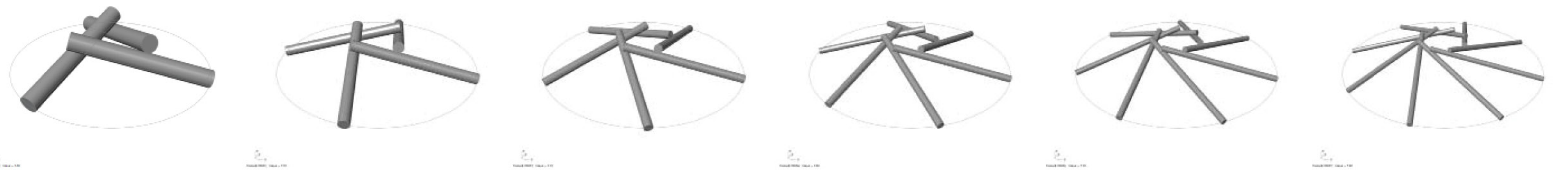


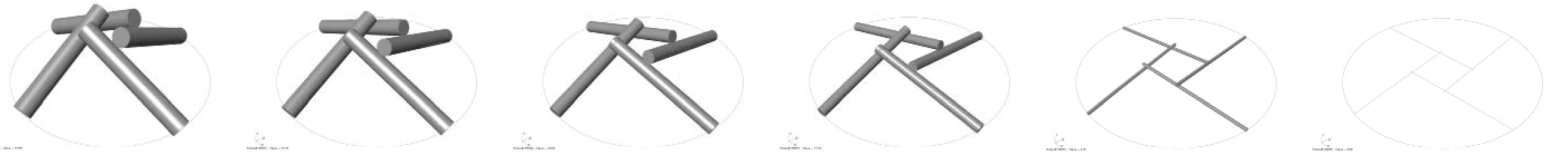
Fig. 2.3: Recent research has focused on tessellation options and assembly sequence for overlaid assemblies.



increase in **engagement ratio**: 5% to 90%



increase in **number of members**: 3 to 8



decrease in **angle of incline**: 30 to 0 deg.

Fig. 2.4: There is a set of interdependent parameters that need to be understood in the design of reciprocal frames. These are the engagement length (the distance at which members join to one another), angle of incline, which determines the pitch of a single fan structure or local curvature in a complex grid, and the axial eccentricity (the distance between centerlines of adjacent members.) In a geometrically pure RF system these parameters are inextricably linked to one another. If we change only the engagement ratio, but maintain angle of incline, member cross-section must increase to maintain contact as does the distance between centerlines. Similarly, if the number of members in the assembly increases, the cross section of overlaid bars must decrease. And if we change the angle of incline, member cross section is again affected, until at 0 incline the unit effectively becomes a flat line drawing.

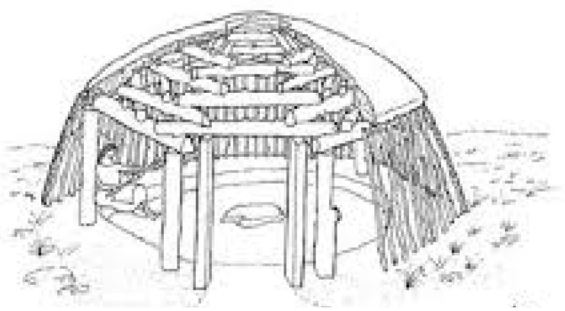


Fig. 2.5: Navaho Hogan Dwelling

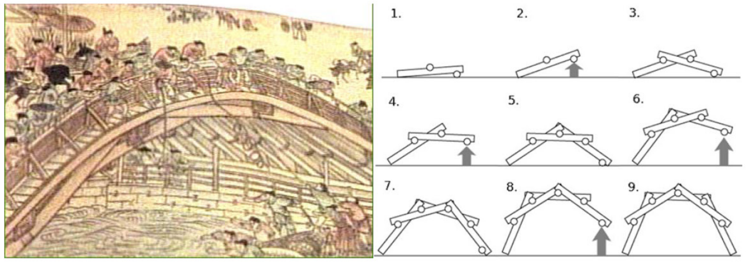


Fig. 2.6: Reciprocal bridge design

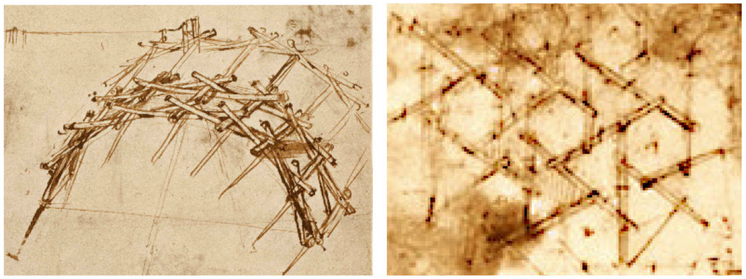


Fig. 2.7: Da Vinci's sketches depicting bridge and grid configurations

2.2 Historical Development

The concept of the reciprocal frame can be traced to prehistoric building types, though the archaeological record and observations of surviving traditions. Similar systems appear in archetypes such as the tepees built by the native peoples of North American plains, the hogan dwellings of the Navaho (Larsen 2008) and yurts and gers of the northeast Asian steppes. These simple structures have in common the design approach of enclosing space with many, relatively small pieces of structural material, arranged in an interdependent system. This efficiency in design appears to have been driven by factors such as the demands of a nomadic lifestyle and scarcity of available local building material, conditions often correlated to one another.

In the historical record, the earliest known description of a reciprocal frame structure comes from Song dynasty China. A depiction of the "Rainbow Bridge" by Zhang Zeduan dates the concept to the twelfth century or earlier (di Carlo 2008). Bridge designs of this type also appear in the sketchbooks of Leonardo da Vinci (1452-1519c.e.), suggesting that the idea of overlapping deployable reciprocal structures may have migrated from Asia to Europe during the Renaissance. Da Vinci expanded the concept seen in bridge sketches to depict multi-unit tessellation patterns which appear to provide a datum for the modern concept in western research. Designs by architects Villard de Honnecourt (ca. 1250c.e.) and Sebastiano Serlio (1537c.e.) describe planar systems with a similar type of interdependent structure composed of rectangular-profile beams attached with mortise and tenon or bridle joints (Baverel 2000) but it is doubtful that these examples share any conceptual lineage with the designs of da Vinci, being instead developed as responses to inadequate material for typical timber framing of floors, walls and other planar assemblies.

The concept of reciprocal support in architectural structure arises repeatedly throughout history. This occurs sometimes as a revival or development of a precedent type and sometimes as a re-invention of the basic concept.

Fig. 2.8: the ‘Spinning Roof’ by Kazuhio Ishii, a compound radial RF structure

One of the most well-developed traditions in reciprocal frame construction exists in Japan, where a small number of architects and builders maintain a construction tradition developed for temple roof reconstruction in the 12th century c.e. The same construction system now flourishes as an experimental building practice in the United Kingdom, having been introduced by designer Graham Brown in the mid-1980’s (Larsen 2008.)

3.5 Relation to other structures

The term ‘space structure’ refers to structural forms that cannot be idealized in a single plane, but must be considered in three dimensions (Baverel 2000.) This includes shells, truss space-frames, membrane structures, and masonry vaults, among others. Within this family, instances can be grouped by the action employed in transferring loads from one member to another and to the foundations. Here, the reciprocal frame is unusual. In contrast to membranes and net structures, designed to operate in pure tension, and masonry vaults, which rely on pure compression, reciprocal frames are predicated on the transfer of loads through bending. In terms of form optimization, this class of space frames can be described as ‘levery’ structures in contrast to catenary (tension) and inverted catenary (compression) forms (Di Carlo 2008.) There are notable exceptions to this categorical association with bending action. Lamella vaults, which can be described as a subset of the RF concept, for example are traditionally designed to act primarily in compression.

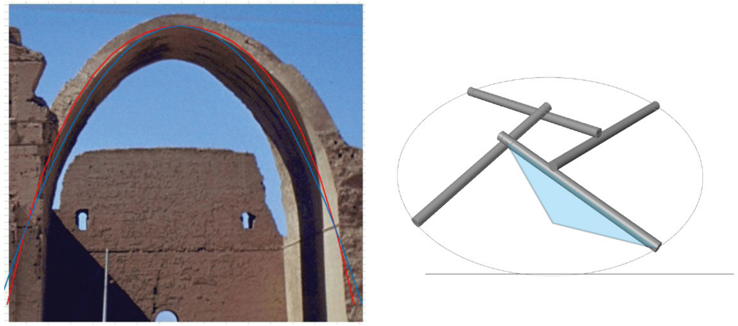


Fig. 2.9: In contrast to compression vaults, reciprocal frames act as ‘levery’ structures, whether in simple units or compound grid shells

Quadrilateral permutations of the reciprocal frame bear resemblance to pantographic grid structures, or scissor frames. These folding structures are used to create deployable infrastructure at various scales (Hanaor 2009.) In a static reciprocal frame, the joint freedom typical of a pantograph may allow the structure to join without requiring unique joint customization. Other deployable structures predicated on prismatic joint releases provide clues as to the variability of form possible within a particular RF topology.

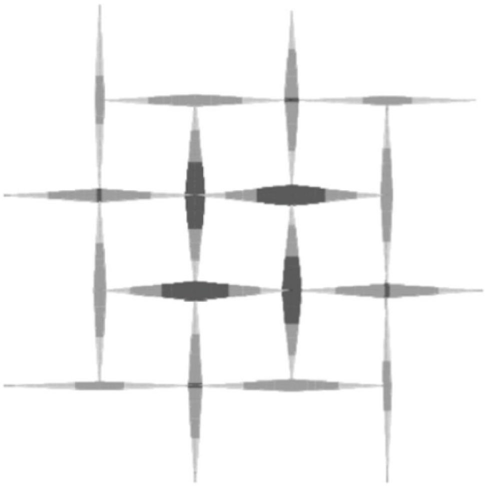


Fig. 2.10: Bending moments in a statically determinate nexorade grid.

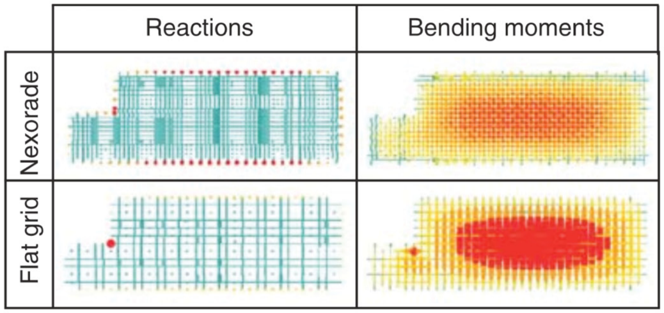


Fig. 2.11: Comparison of an axially joined nexorade and a conventional square grid structure.

The value in applying these mechanical linkage principles to the concept of the reciprocal frame is in the opportunity for geometric variability without the need for unit customization. A modular system with multiple forms is more versatile on site and requires less consideration of situation specific constraints.

2.3 Structural Behavior

The structural performance of reciprocal frames (also known as nexorade assemblies) is an area of ongoing research, due in part to the geometric constraints of the assembly strategy, and in part to the non-hierarchic transfer of forces between elements. The primary transfer of loads through bending makes these structures unusual in the category of lightweight structures, but research continues due to the promise of tectonic simplicity, among other benefits.

Analytic methods have been explored in the structural evaluation of these assemblies (Baverel 2000, Nelson & Kotulka 2007), but in most cases, numerical finite element analysis is more feasible for complex forms and non-uniform loading cases. These systems are unusual in that they operate as one-way beam systems at a local level but must be evaluated using tools adapted for two-way structures.

It has been demonstrated (Gelez et al. 2011a) that in the design of a nexorade grid, joinery design plays a strong role in the robustness of the structure and that this robustness is inversely related to the geometry's ability to adapt to changing edge conditions. If the joints are designed as hinges (1 degree of rotational freedom) the structure will account for movement at free edges by developing torsional resistance along the axis of members near the unsupported edge. This capacity to resist moment forces acts as a safeguard against cascading failure in the structure, but means that in a rotationally fixed system, the ideal form of the structure, wherein members

Fig. 2.12: Friction-dependent clamp fittings are highly adaptable to changing geometric demands, but are not well-suited to resisting axial loads.`

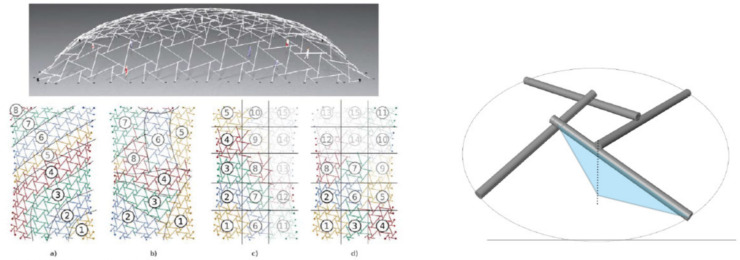


image credit: geometry.cs.ucl.ac.uk

Fig. 2.13: Internal moment and axial forces vary in a complex RF assembly, but the tectonic system does not easily allow member cross-section to be adapted to demand.

have no internal torsion on axis, is determined by the shapes of members themselves. In this case, there can be little or no variation in the form of the structure without deforming the members through bending or placing undesirable moment forces on the joints between members. In the case that all rotations are released at the joint, variability in the overall form of the structure should be possible without placing undue stress on the units. The consideration of stresses at the joint condition brings to light disadvantages of the commonly seen overlaid strut assembly technique. In a curved or vaulted RF system, many elements are required to bear both bending and axial stresses. This combination has the potential to compromise many types of joints commonly used to connect stacked members. In the case of a friction fitting (e.g. cord lashing, scaffold connectors) any force placed normal to the joint (bending) will significantly detract from the ability of the joint to resist axial loading by friction (Brocato 2011.) This suggests that in complex configurations of the RF pattern, it is desirable to use a pin or other translationally fixed joint design not reliant on friction resistance.

While an RF grid may be tectonically non-hierarchic, the transfer of loads has a hierarchy as forces are passed from one element to the next. Especially in a system dependent on moment resistance, it is desirable to have variable control over the cross-section of elements on an individual level. This is a drawback of the overlaid joint.

3.0 Case Studies

3.1 Tectonic Rationality vs. Structural Demand : Forest Park Pavilion


Fig 3.1: Proposed (unbuilt) design for Forest Park Pavilion

The performance of a structural system will at times be at odds with the designer's vision of form and pattern. This is particularly true in reciprocal assemblies, where cross-section dimension is critically important to both the development of surface curvature and the performance of discreet elements in bending. A collaboration between designers at Shigeru Ban Architects and Arup Engineering demonstrates the difficulty in navigating these converging constraints.

The design for the Forest Park Pavilion was originally developed as an adaptive re-scaling of a traditional Japanese weaving technique using discontinuous lengths of material. However, the length constraint of laminated bamboo led to a further segmented tectonic system (McQuaid 2003), effectively a quadrilateral reciprocal-frame grid. Like Zollinger, the designers used the reciprocal pattern in response to limited options in the chosen building material. The canopy structure was to be composed of 8-foot boards, uniform in length and in the location of connections. Variation in curvature was generated by the lap pattern of boards in adjacent cells. Consistent overlapping creates areas of positive Gaussian curvature (concave/convex,) while an alternating lap pattern leads to transitional areas of zero Gaussian curvature (cylindrical.)


Fig 3.2: Tectonics of an overlaid RF act in opposition to structural demand

While the full-scale pavilion has yet to be constructed, a half-scale experimental prototype structure was commissioned and built at Rice University in 2002. This project uses 4-for lengths of the same laminated bamboo material, scaled accordingly in thickness and width.

Two important geometric limits can be inferred from observing this

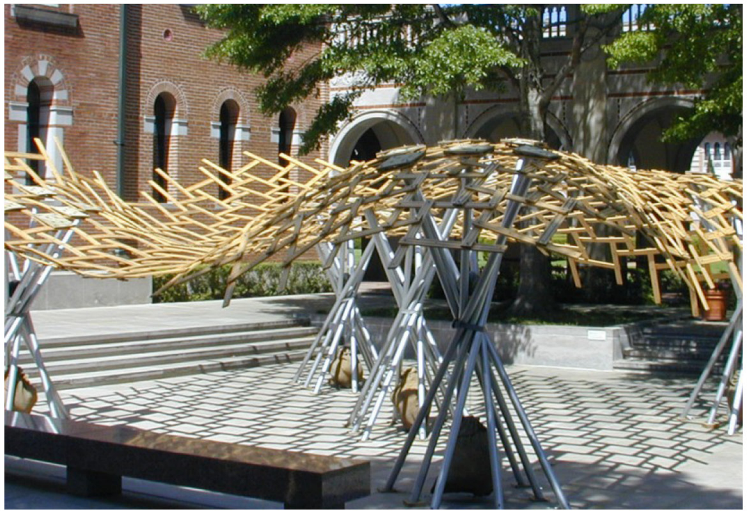


Fig 3.3: Supports of prototype structure built at Rice University

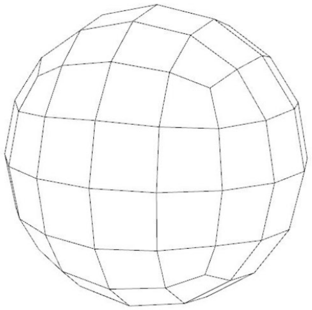
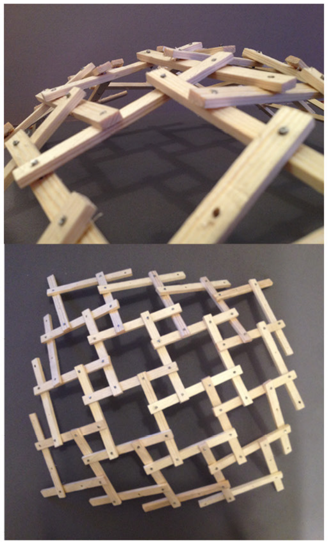


Fig 3.4: The varied edge lengths of a geodesic cube represent one of the struggles in developing modular RF systems for curved forms.



experimental work. First, the relationship between shallow curvature and thin material is a rigid one, and structurally counter-intuitive. As a grid shell becomes less vaulted, we would ideally see the members become heavier to bear the moment forces placed by adjoining elements. This conflict is one of the greatest shortcomings of the RF as a spanning system. In order to overcome this limit, a more complex joint is necessary, as in the case of heavy timber reciprocal roofs built in Japan and the UK. In a complex grid assembly, this begins to erode the simplicity and modularity for which the system was chosen in the first place. In this case, the designers accounted for this structural shortcoming in the spanning structure by supporting it on widely distributed columns, reducing the localized forces on individual elements.

Second, we can see that the variation in curvature available in a uniform-length assembly is rigidly defined by the material thickness and length parameters. Further, it is impossible for the pattern to extend more than a few cells from the center of curvature before it begins to distort. Observing the geodesic subdivision of a cube as it approaches the geometry of a sphere, it is clear that without varying the length of members, it is not possible to continue the pattern around a convex surface. The reverse in curvature seen in the pavilion roof is not only an aesthetic design decision, but a necessary response to the modular construction technique. The process is not unlike stretching woven material over a domed surface. The pattern of the weave will distort comfortably to a certain point, but beyond this a pleat is required. As pleating is not an option in an RF grid, the structure can either end, or as in this case, the curvature can reverse, starting the process of distortion over in reverse. It is an usual confluence of constraints that creates such a form, and this project does an excellent job of illustrating the relationship between tectonics and overall form in an RF grid assembly. This is effectively the limit of a specific modular RF system, defined by material properties and unit dimensions.

3.2 Evolution of Lamella Framing: Zollinger to Serpentine

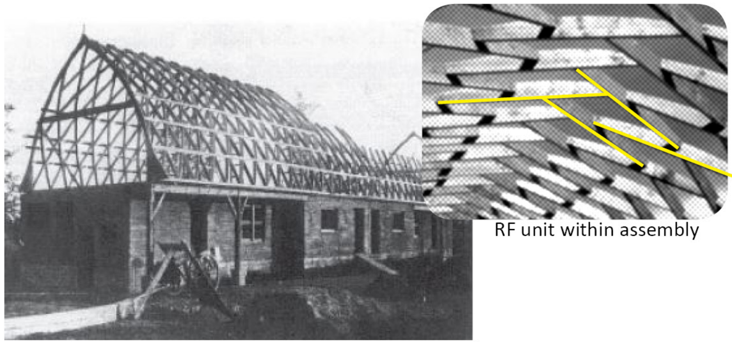

RF unit within assembly

Fig 3.5: Zollinger roof under construction, Merseberg Germany


Fig 3.6: Dalhousie Coastal Studio (left) and Rural Studio (right) lamella vaults


Fig 3.7: Serpentine pavilion, Alvaro Siza, Eduardo Souto de Moura, Cecil Balmond

The lamella roof framing system is arguably the most successful variant on the tectonics of the reciprocal frame. The technique was developed by German architect and builder Freidrich Zollinger as a response to material shortages and labor surplus in the reconstruction era following the first world war (Tamke et al. 2010.) The technique was developed further in the U.S. for the construction of large halls and aircraft hangars, but eventually fell out of favor in the mid-20th century as timber construction was replaced by concrete and steel for large civil and commercial projects (Lowenstein.) These early forms are structurally analogous to masonry vaults, being composed of discrete elements acting in nearly pure compression.

In recent decades, emphasis on sustainable building practices had led to renewed interest in timber as a structural material for large pr, and with it renewed interest in the innovative building practices of eras in which timber construction was actively developed. The lamella roof has been revived in various projects, often in connection with academic institutions and experimental contexts. Student design-build projects from DCS at Dalhousie University and the Rural studio at Auburn University and the University of Washington have used the Zollinger framing technique to study the merits of timber construction, historical building methods, and efficiency in pre-fabrication of modular building components. A highly developed instance of the lamella technique was used to create the beam geometry of the 2005 Serpentine Pavilion. Designed by Alvaro Siza, Eduardo Souto de Moura and Cecil Balmond, the canopy's form moved fluidly from wall to roof, and was composed of a mass-customized set of unique beams. Unlike historic lamella vaults, this structure was designed to act as hybrid between a compression shell and a conventional beam assembly, bearing loads via both bending and axial stress. The decision to use this construction method while abandoning aspects of its modularity and structural elegance highlights other benefits: manageable unit-size and connection simplicity.

Fig 3.8: A lightweight, modular archaeological site shelter (TESS Atelier)

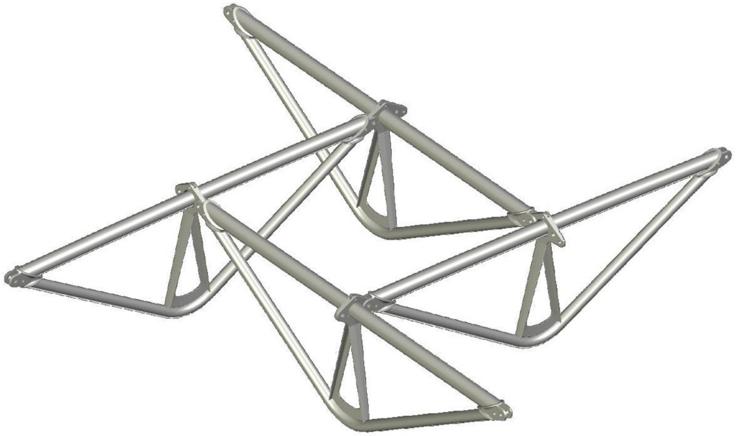


Fig 3.9: Assembly of reciprocal space frame module from ‘nexor’ truss units.

3.3 Modularity and Joint Conditions : Bibracte Archaeological Shelter

Reciprocal frames are rare in practice, in part due to their rigorous geometric constraints, and in part because they are generally less rigid than competing structural forms using the same amount of material. The benefits of reciprocal structures are most apparent in their adaptability to unusual site conditions and construction circumstances. An unusual shelter built to protect archaeological activities at Bibracte presents a unique example of this adaptability applied in contemporary methods and building materials.

The project was a collaboration between architect Paul Andreu, Bernard Vaudeville and Simon Aubrey of T/E/S/S Atelier Engineering, and Czech fabrication firm Sipral. The competition design brief called for a shelter that could be adapted to various archaeological sites, would not require foundations that might damage the integrity of the archaeological record, and could be erected by available labor in remote areas. The structure also has to withstand harsh weather conditions and heavy snow loads. The team chose to work with a reciprocal grid structure (or nexorade) for its topological modularity and extensibility, and for the simplicity of the on-site assembly process compared with conventional space frames.

The assembly logic of the system allows it to be built of small pieces, easily handled by two people. Each unit measures 3.75m in length and weighs only 43kg. Gradual camber in the overall surface of the shelter is created by a slight curvature in the top chord of units running perpendicular to the arc. This camber meant that the roof needed to be constructed of two distinct units rather than a single module. It is possible to generate simple curvature with a single modular unit, but this requires rotation of the pattern grid such that beams are oriented 45 degrees from the arc section of the vault. This pattern adjustment offers a benefit in unit production, but causes instability at the corners of the grid outline, where more significant

Fig 3.10: physical prototype assembly

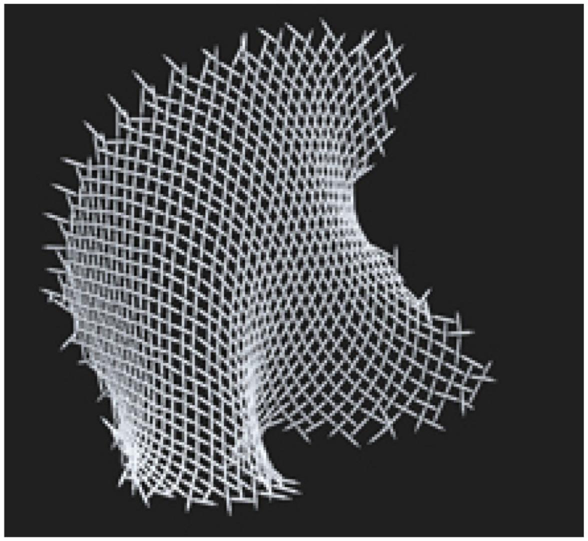


Fig 3.11: rendering of A.I. process output

edge beams may be required to maintain stability. The BIbracte shelter represents one of the most innovative implementations of the RF scheme, and one of the few built cases in which beams are used in bending action. In this respect, the unit geometry can be seen as a development on Siza and Balmond's pavilion structure.

3.4 Shape Classes within Constrained Eccentricity: Flocking Lamella

Among the more novel approaches to free-form timber construction is the application of agent-based generative form-finding to the traditional Zollinger lamella framing system. The basic 4-strut unit of a lamella assembly is treated as a kinetic frame with rotational freedom and translational freedom at the joint within a given set of domains. By defining tendencies for self-organization and iteratively correcting toward a state that satisfies the requirements of connection for all units, this system is able to produce a great variety of form within a topologically simple connection framework. The great strength of this technique is its applicability to a tightly constrained material palette while allowing some variation in the joint condition.

A drawback to this approach is the degree of fine-grain control over the overall form. Because the process is characteristically generative, or bottom-up, and due to the interwoven connection pattern of the reciprocal lamella grid, any change made to the structure will have consequent effects throughout the system, and may alter the overall form in dramatic and unpredictable ways. If this method is to be applied to a specific design situation, it must be incorporated early in the development of the project, as it may place driving constraints on other aspects of the building geometry. The prevalence of top-down rationalization methods in established building practice suggests that this type of uncertainty is difficult to manage. Nonetheless, this research represents a pivotal moment in the development of free-form timber construction and understanding of the inherent tendencies of reciprocal pattern assemblies.


Fig 3.12: CNC fabricated full-scale prototype by Tamke et al. (2010) show the promise of axially joined assemblies.

A visual appraisal of the forms hints at the kinetic tendencies of tightly constrained lamella systems. In every case, the geometric form is some approximation of a hyperbolic surface, presumably more or less true to the mathematical definition as the joinery conditions are constrained or relaxed. This observation suggests that a more straightforward kinetic simulation method may be able to predict the range of forms available in a fully or partially modular construction strategy. The hyperbolic paraboloid (or saddle) surface type has been well-documented for its applicability to efficient construction technology (Christiansen 1988.) and this work suggests that reciprocal lamella assemblies offer a new means of constructing this family of surface forms, perhaps with more control over orientation of the grid and possibly expanding the repertoire of modular framing to other hyperbolic surface geometries.

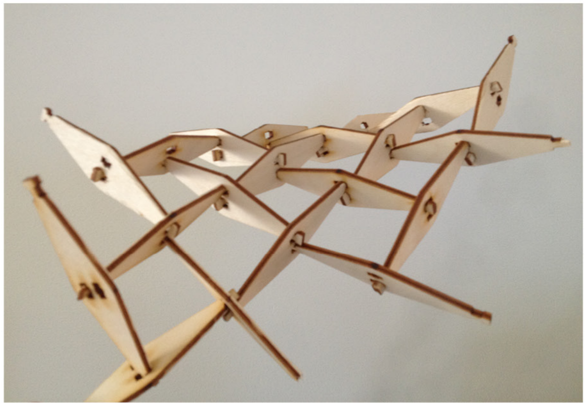


Fig 3.13: A modular kinetic test assembly displays similar approximations of a hyperbolic surface.

Kinetic simulation offers an opportunity for modularity that is not present in the CITA project. The joinery in the case study is completely customized to local joint geometry, using a mortise and tenon joint to achieve a rigid connection. While this reduces the need for metal fasteners, there are drawbacks to this approach. A large amount of material must be removed from each member at the point of highest bending resistance, and the fabrication process requires a sophisticated level of automation not available in many construction work-flows.

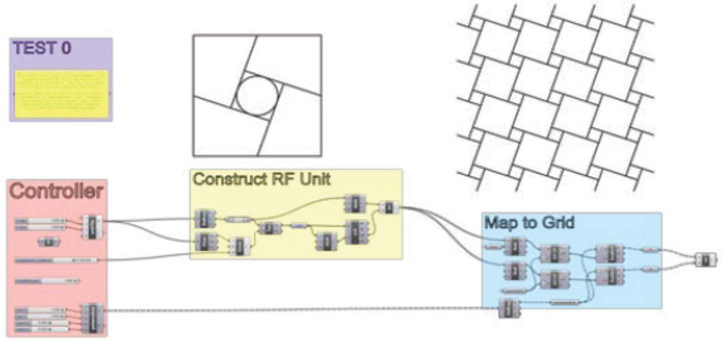


Fig 4.1: The base script produces a variable RF grid pattern.

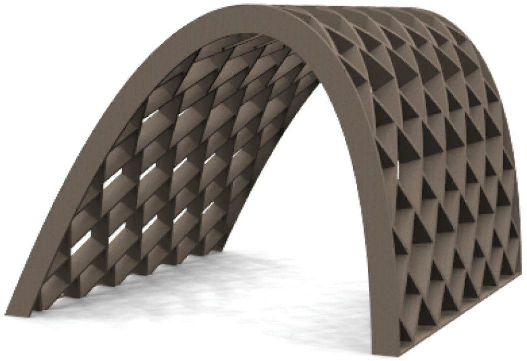


Fig 4.2: A variable catenary lamella vault is easily modeled by mapping to a surface.

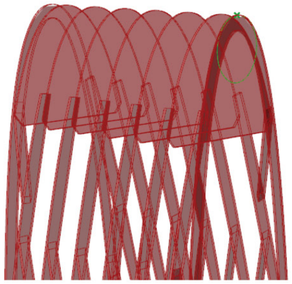


Fig 4.3: A failure mode of the beam generation process.

4.0 Form-finding and Rationalization Explorations

Throughout this project, the geometry of reciprocal was studied using various methods, each bringing different sets of assumptions and limitations to the basic concept. These approaches are characterized by a decision to fix a particular parameter as constant throughout the system or to define particular parameters as driving while allowing others to be driven. While no one of these provides a completely generalizable solution to rationalizing complex geometry, each exploration sheds further light on the opportunities and limitations inherent to the RF as a tectonic concept.

4.1 Pattern Mapping

Following the lead of current research, this investigation of lamella frames begins with a top-down rationalization strategy. It has been shown (Song et al., 2013) that planar tessellations can be used to generate RF geometry for complex spline-based surfaces. Similarly, the script developed for this project maps a planar reciprocal frame pattern to a given non-planar surface. The space of possible strategies and processes within pattern mapping is vast as one begins to add layers of optimization and unit-level geometric variation. The process used here uses a very basic u,v mapping strategy.

The first step in the process was the development of a pattern generating tool that could be dynamically adjusted while applied to a target surface geometry. 'Test 0' establishes a simple method for constructing and adjusting the basic pattern of the reciprocal frame. In the case of this study, the basic unit is a 4-member fan. Lines are defined by midpoints on a bounding rectangle and tangents on a central circle of variable radius. The base unit is propagated by mapping to a rectangular grid, which can be resized to change the proportions and density of patterning.

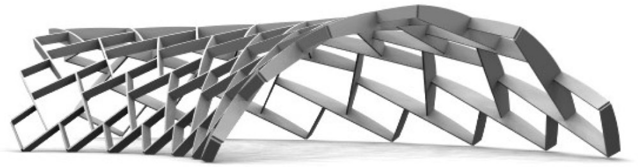


Fig 4.4: Frame based on a toroid surface.

Mapping this pattern as a structured set of points, the script develops geodesic line-work on a target surface by way of U,V parameters. This provides a lattice of curves coincident with the surface which are used to define the top profiles of lamella elements. This curvature serves an important purpose in a lamella vault. If the endpoints of each beam's axis lie on a curved surface, all other points on that axis must lie some distance away from the surface, yet the elements of a lamella vault never join end-to-end except at edges and openings. Curvature in the top profile of the lamella accounts for axial eccentricity between each member and those that attach to it mid-span, allowing for a cleanly resolved joint. This creates complications when mapping to surfaces with concave hull curvature as the compensating curvature on the top of the beam narrow's the member at the point where greatest bending resistance is needed.

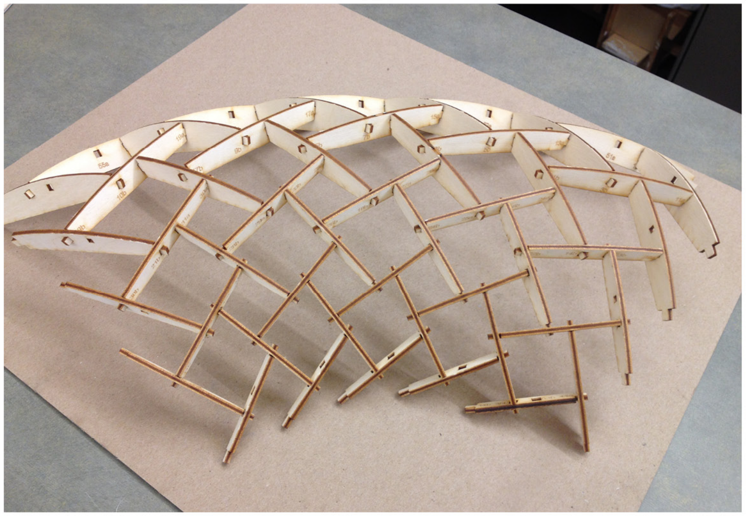


Fig 4.5: Scale model used to test fabrication strategy and structural characteristics.

The first test case for double curvature in this experiment is a toroid patch surface. It is a tame geometry for its category, and allows isolation other factors like compound hull direction. The torus belongs to a family of surfaces from which may be directly differentiated into planar quadrilateral meshes. These are surfaces of revolution, translation and other other affine transformations (Pottman et al. 2007). The shell frame shown above is oriented on the diagonal, as in a conventional lamella assembly. A radial grid is needed to take advantage of planar quad paneling, but his could be established either by rotating the pattern on the radius or by adding a grid of purlins. While the sheathing implications of this property are worth exploring, the parallel effect of PQ surface geometry is that grid cells are identical along each horizontal band of the mapped pattern. The units of the lamella assembly share this radial symmetry, and so the kit of parts needed to build such a structure is at least semi-modular. The fabrication geometry for the torus is manifest as several sets of identical parts, one set for each grid division along the profile arc. While the profile geometry of each part is fairly complex, this modularity greatly simplifies part tagging

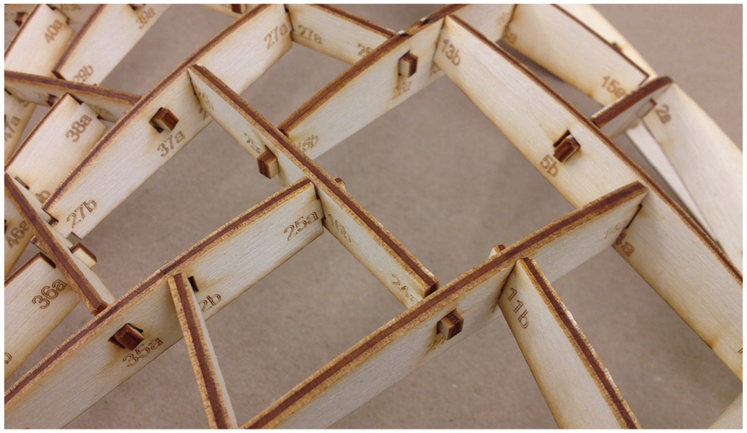
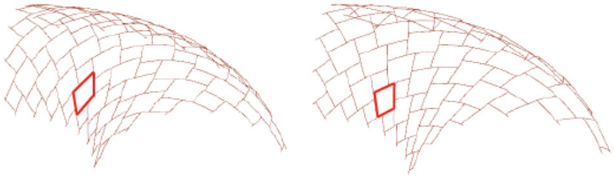


Fig 4.6: Joint tagging , associative by node



Mapped pattern and resulting RF wireframe

Pattern and wireframe after applying parabolic warp

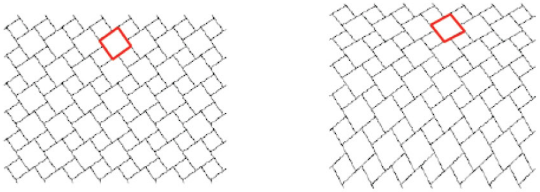


Fig 4.7: Grid cell aspect ratio can be optimized by adapting the input pattern before mapping.

and the communication of assembly process. Where a kit of unique parts is only feasibly produced using CNC tools, repetition of parts allows geometry to be jigged a set of templates for fabrication using less expensive, more portable machinery.

While reciprocal frames have complex unit relationships, their connections are relatively few compared to other strut-based space structures. This is a distinct advantage when building with wood, as more numerous joints lead to greater deformation over time. However, this simplicity is balanced by complexity in the design of the strut or beam itself. In ‘free-form’ lamella constructions, there is a likelihood that member size and joint conditions will become individually unique, creating an enormously complex kit of parts. Furthermore, the sizing of beams, being driven by joinery requirements, may not align with optimal structural performance. There is a need to parse the domain of ‘free-form’ geometries and the frame assemblies that they permit, either by identifying applicable optimization strategies, or by the domain required by a particular parameter of the idealized reciprocal frame unit. In this case, the engagement ratio and length are effectively fixed as uniform at the beginning of the script, and eccentricity is allowed to adjust as needed. This demonstrates 4 distinct ‘kit-types’, defined by input surface geometry as applied to a Zollinger-type lamella assembly.

1) Planar grids and cylindrical vaults with perpendicular joinery: may be composed of identical modular units.

2) Cylindrical vaults with other than perpendicular joinery: must be composed of at least 2 unit types, each the mirror of the other.

3) Toroid vaults and non-cylindrical, single-curved vaults: must be composed of at least 1 unit-type for each row of cells on the horizontal.

4) Irregular double-curved assemblies: requires n unique units for a kit of n parts, and may not be possible with this rationalization process. (Further testing is required.)

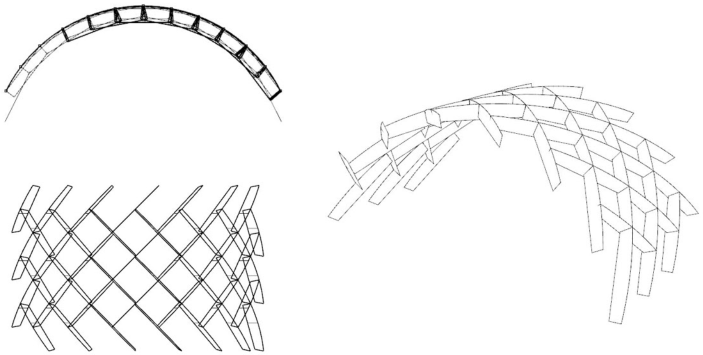


Fig 4.8: Construction of lamella vault geometry through direct manipulations.

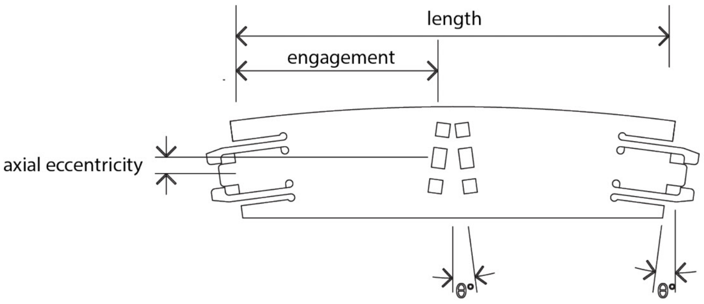


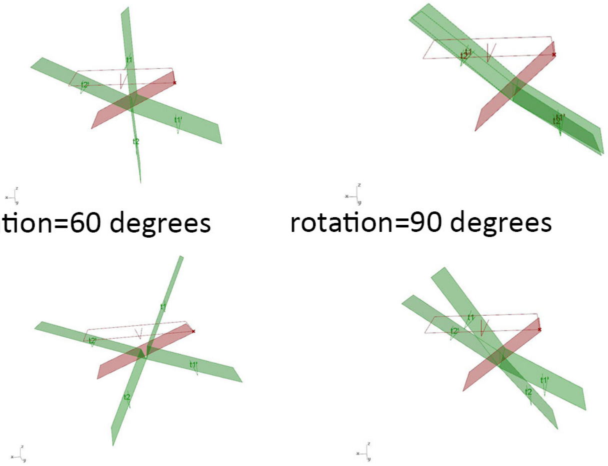
Fig 4.9: Relation of RF parameters to the shaped lamella unit.

These categories are based on a number of assumptions. One is that joinery is integral to the unit, and does not permit rotational freedom. Another is that the mapping between pattern and target surface is proportional and uses the default U,V coordinate systems of both surfaces. The simple optimization of cell aspect ratio in the case of the toroid vault shows that there is potential for more sophisticated optimization in this area. Further tests should look at using ‘unrolled’ surface grids or other parameters from the target surface as a means toward pattern optimization. Genetic algorithms offer further solutions in the form on dynamic relaxation scripts.

4.2 Rule-based Assembly

This study explores the reciprocal lamella frame as a self-propagating rule-based assembly. Previous attempts to understand this system have been characteristically ‘top-down’ in nature. This ‘bottom-up’ approach provides a very different framework for understanding the topological structure of the assembly. Where earlier experiments focused on imposing the aesthetic pattern of a reciprocal frame on an idealized target surface, this definition builds form by applying transformations to the base unit in a particular pattern. This study most closely emulates the traditional process used to rationalize lamella barrel vaults, wherein form is derved directly from unit geometry. The framework produced here offers opportunities to drive unit transformations by mathematical expressions and perhaps generate new form through a bottom-up logic.

Initially, the geometry of a cylindrical lamella vault was drafted directly, with manual input and transformation. This was achieved simply by dividing the arc of the roof in transverse section, generating a ‘keystone’ profile, and projecting the geometry to a plane oriented at the desired grid angle. at any non-perpendicular joining angle, two distinct units are necessary. The



rotation=60 degrees

rotation=90 degrees

rotation=45 degrees

rotation=80 degrees

Fig 4.10: elemental branching transformations of a Zollinger lamella vault at various angles of rotation

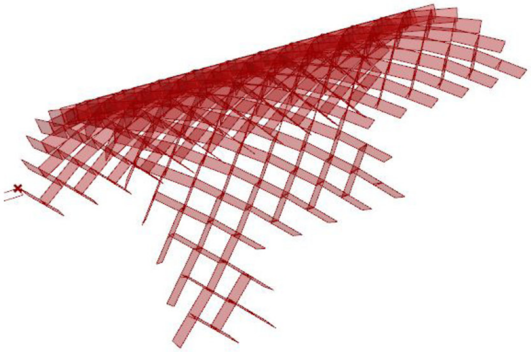
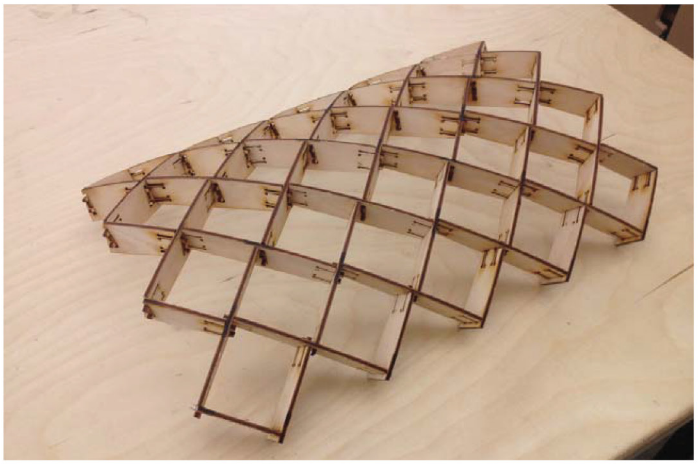


Fig 4.11: cylindrical vault generated by branching transformations

exercise provided understanding of the base unit parameters for a fully modular lamella system. Most importantly, the similarity of vertical end angle and joining angle was confirmed for this type of vault. In addition to the parameters identified by Baverel, this relationship between angles is something to be explored as the assembly moves away from member-uniformity. The parameters observed in the manual process were modeled as a parametrically flexible unit and assigned a series of transformations that relate directly to the local unit geometry. The four transformations modeled consisted of an oriented translation from end to mid-joint location and a rotation about the end of the new element. All four are mirrored iterations of a single transformation, and allow the vault structure to propagate in all directions. The parameters governing length and engagement are fixed as uniform in this example, but one can imagine that if these are allowed to be driven parameters, it should be possible to introduce variation at other nodes in the system.

A vault is generated by assembling ‘chains’ of transformations. From each chain, other chains may branch off, filling in the visual lattice of the lamella vault. Responsive propagation of data follows this branching structure, but there is no hierarchic communication across the branches of a system. This problem may be solved analytically, by establishing driving relationships between the parameters effecting transformation, or iteratively, by establishing a test for acceptable maximum error distance and adjusting parameters to converge on that value.

In this experiment, the latter strategy was employed. Using the Galapagos genetic solver utility, the script can be used to align a broken lamella assembly by adjusting length, vertical joint angle (fan incline) or axial eccentricity. The relation of these parameters is such that only one value must be adjusted to bring the geometry into equilibrium. Further tests will explore the effect of variation on this balance.



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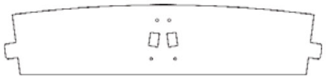

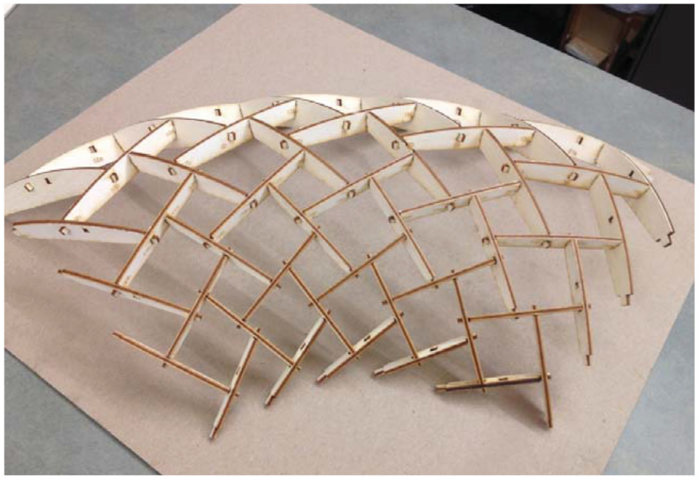

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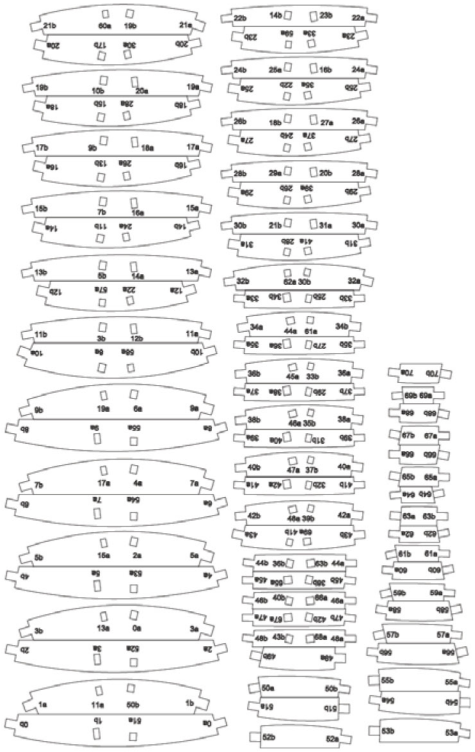


Fig 4.12: generating curvature by unit customization is efficient in cylindrical vaults, where a modular unit is possible, but becomes more complex in doubly curved forms.

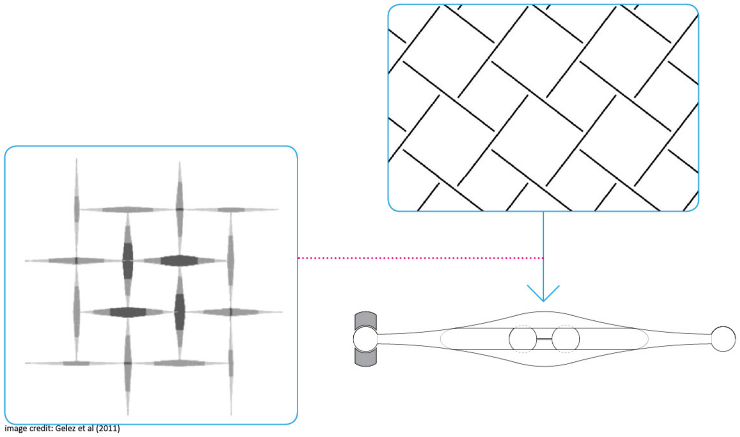


image credit: Gelez et al (2011)

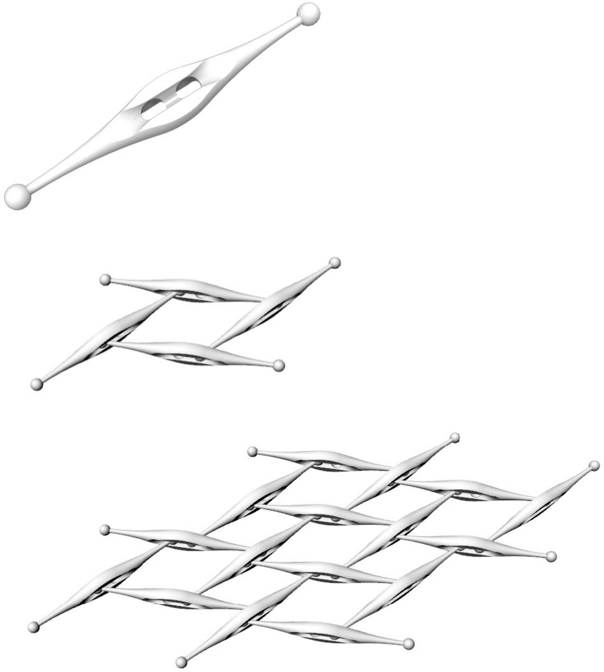


Fig 4.13: The base unit is designed to be built up into multi-fan structures.

4.3 Modular Kinetic Assemblies

Traditionally, lamella vaults of the type patented by Freidrich Zollinger are designed as hinged frames, gaining their rigidity from their reciprocal connection pattern and transfer of loads in nearly pure compression, rather than from moment resistance at the joint level. However, the axial eccentricity present in a traditional lamella assembly raises questions about lateral stability when the joint is modeled as a freely rotating pinned connection in 3 axes for non-cylindrical vault forms. There is an opportunity for the geometry to 'spill' in either of two directions as members rotate on axis. For ease of fabrication, simplification of structural questions, and material efficiency, it is desirable to find the range of forms that can exist when eccentricity is effectively set to 0. The modular system described here aims to represent the range and character of variation possible in the most basic manifestation of this assumption.

In a planar RF grid, the axial eccentricity at each joint is easily set to 0. However, a plane is not the only form available in a 0-eccentricity system. A similar condition is present in agent-based simulations performed by CITA (Tamke et al. 2010), and the forms generated are anything but planar. In this simulation, axial eccentricity and member length are limited by rules of relation between units. There seems to be a relationship between 0-eccentricity assemblies and doubly-ruled surfaces, namely the various forms of the hyperbolic paraboloid. Without considering the complexity of geometry at joint conditions, these systems promise the possibility of complete unit-modularity, or at a fall-back, uniformity of beam cross-section and variability in length as dictated by geometric demands. The independence of cross-section from length parameters also offers the possibility of variable cross-section optimization in frame geometries that place greater demand on particular members.

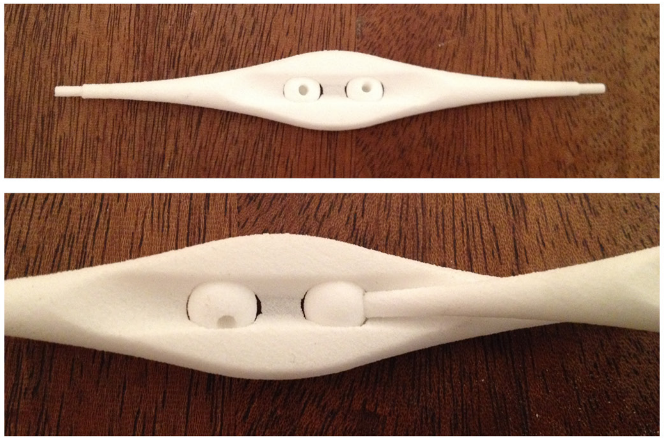


Fig 4.14: the module is prototyped at scale in laser-sintered nylon.

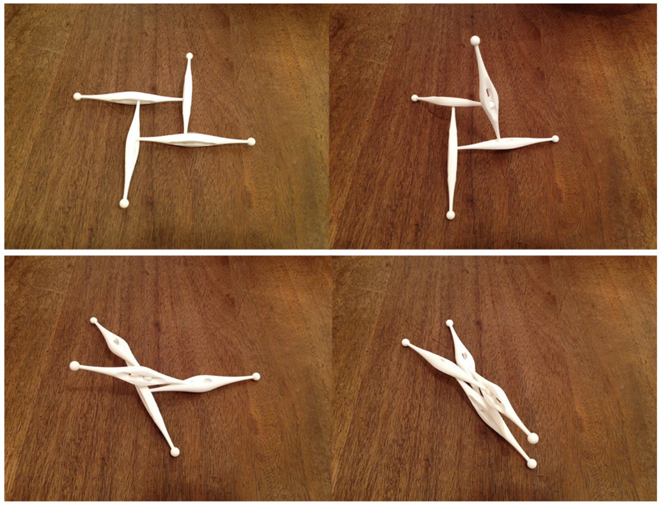


Fig 4.15: Folding of the engagement window in a single fan unit.

Methods

The system was represented as a manifestation of the kinetic behavior in a uniform planar RF grid. All parameters are fixed except for the connection angle at the joint, with the assumption that this will express the range of the variable in its purest form. The form of the grid is determined by the geometry of the the system base-unit, a simple strut with ball-and-socket joints concentric to the central axis and attaching at an engagement parameter of 40%. The unit is shaped for maximum freedom of rotation, which forces the minimum diameter at the ball-end to shrink dramatically. While this form is necessary for tectonic purposes, it also produces a form bearing strong resemblance to the bending moment visualization for a beam element in a planar RF grid structure. This elegant geometry is the tectonic by-product of physically manifesting an abstract system. The geometries produced by this assembly are intended to illustrate the range of forms available in RF lamella constructions using unshaped dimensional lumber and consistent unit length.

Execution

When prototyping the system, laser- sintered nylon was used as a test material. The reasons for this choice were availability (mostly), toughness of the material and the option to manufacture captive ball joints with acceptibly high tolerances at large quanity.

Instead of attempting to fit the ball into the socket after printing, it was decided that the ball should be printed in the socket and attached by a peg joint to the adjoining units. After testing tolerances, parts were modeled with an offset of .25mm between the ball from the socket so that the joint

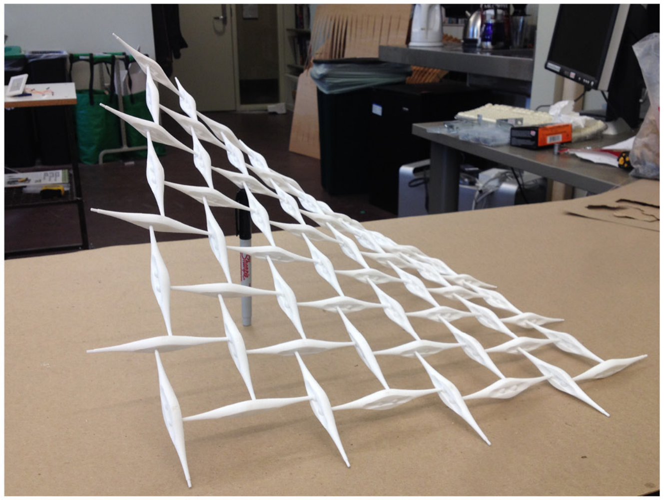


Fig 4.16:Hyperbolic paraboloid form.

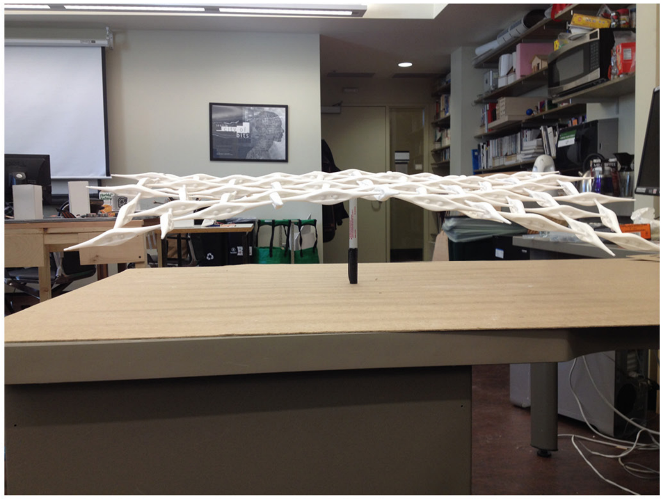


Fig 4.17: Compound hyperbolic form.

would be able to rotate freely. The freedom of rotation is much greater in the lateral plane than in the vertical as the socket surrounds on only two sides. There was concern that the lack of vertical freedom might constrain kinetic behavior as appeared to be the case in the original wooden test assembly, compromising the experiment in regard to observations on the effect of full rotational freedom.

Observations

Snapshots of the kinetic behavior displayed by the modular system are consistent with previous assumptions that hyperbolic surface form results when the length and engagement parameters of an RF system are fixed and eccentricity is 0. The hyperboloid forms shown here appear to be directly related to the folding behavior of the base unit. As each engagement window begins to fold into two hinged triangles, the outer nodes of the fan move. This motion opposes the folding action of the neighboring cell, forcing a semi-rigid spatial organization throughout the assembly.
Depending on the degree of curvature required, hyperbolic vaults promise to be one of the most economical forms available when designing lamella roof structures. These studies also provide insight into paths through which these assemblies distribute gravity and applied forces.
The examples below can be interpreted as gravity-based form finding studies within the context of a particular assembly and fabrication logic.

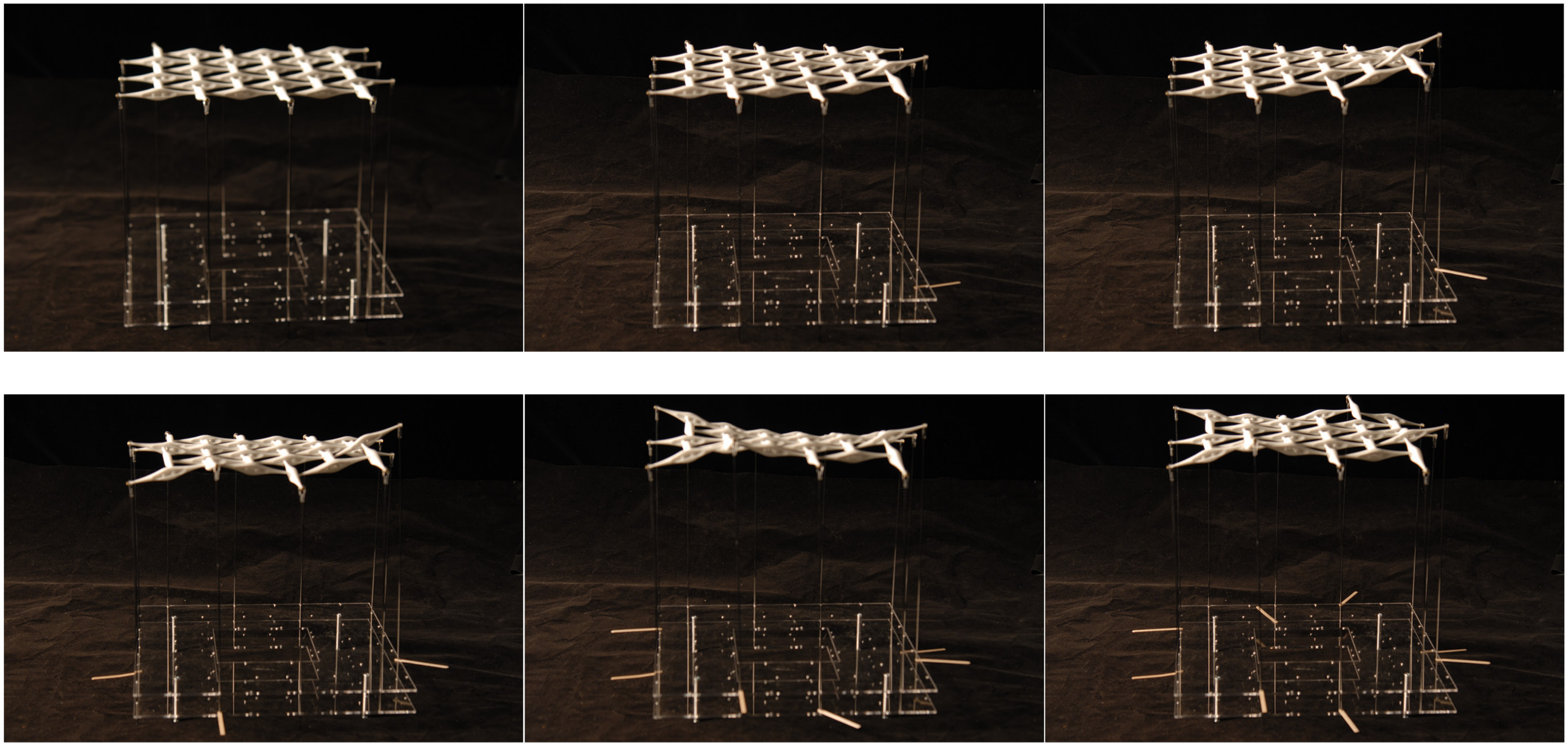


Fig. 4.18: A scaffold structure serves to illustrate the effect of changing edge conditions on the overall form of the reciprocal assembly. As suggested by previous research (Gelez et al. 2011), the system is not compromised or stressed by deformation at the boundary, provided there is freedom of translation in the lateral plane as supports move vertically.

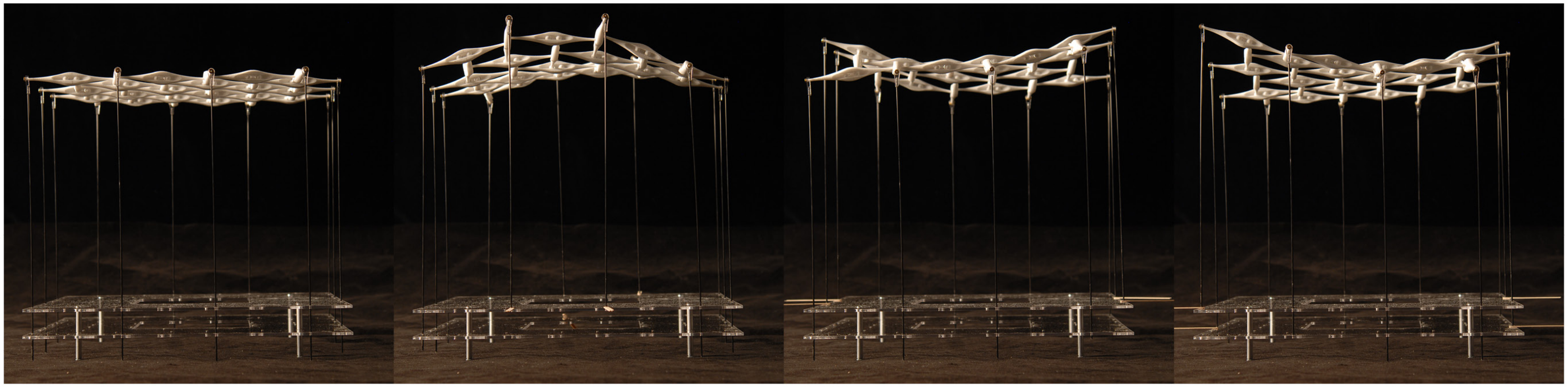


Fig. 4.19: A variety of stable forms are generated within a bounded modular assembly. These approximate the familiar forms of ruled hyperbolic surfaces used widely for architectural design. However, unlike precedents in this category of form, the modular RF grid derives these shapes from the inter-relation of unit geometries, meaning that structures may be erected with the use of minimal form-work and with smaller discreet building units than used in previous methods. The pre-fabrication of connection details integral to the building unit equates to efficiency on-site, as many of the tedious tasks of construction requiring additional false-work are already complete. This type of system is ideal in situations where site access is limited and skilled labor is unavailable.

4.4 Iterative Optimization

Modular RF systems with rotational freedom clearly provide a range of variation in form, depending primarily on the fixed location of edge nodes. While maintaining the requirement of axial connectivity, two levels of variability remain untapped in the modular system described above. These are variation in length and variation in pattern. In this case, length refers not only to the overall length of the mean unit, but to the distances between nodes along that unit and the ratios between these. In this area of variation, engagement ratio is controlled and distorted. However, due to the constancy of eccentricity at 0, unit cross-section may be considered independent of other parameters in the form-finding process and optimized to structural demand. As noted previously, this is valuable in assemblies that, due to geometry and orientation, rely on bending resistance for structural integrity, as some members are likely to be subject to greater forces than others.

Variability in pattern, as discussed in section 2.1, allows for flexibility in aesthetic effect, cladding options and possibly the adaptability of overall form to target surface geometry. Within this range of variability, patterns can be generated with regular or irregular topology, resulting in a wide array of aesthetic options. This is a decision that must be made early in the form-finding process as all optimization mechanisms are built on the topology of the base pattern. For the purpose of simplicity and to make a clear comparison between optimization cases, a single pattern topology has been chosen for the development of this process. The regular quadrilateral fan topology used here may later be replaced with other patterns and possibly relaxed to irregular topologies.

The optimization process developed in this project uses simplectic operators from Kangaroo Physics (a plug-in for GH) to manipulate geometry such that it is optimized for one purpose or another.

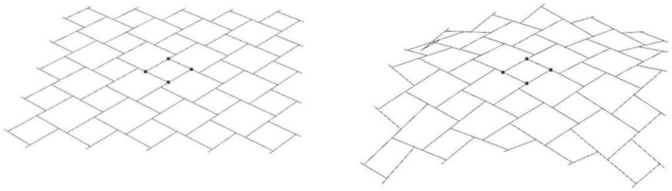
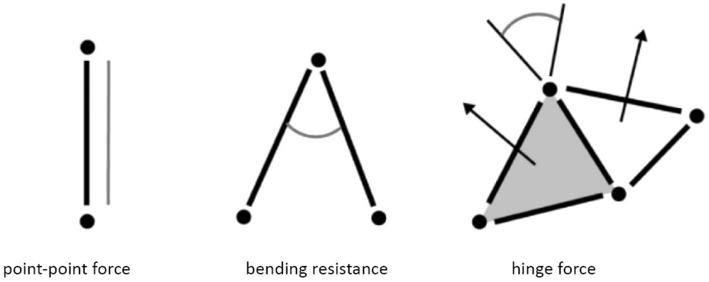


Fig. 4.20: Gravity simulation of the modular assembly produces accurate forms.



point-point force

bending resistance

hinge force

Fig. 4.21: Simplectic operations used in physics simulation

forces applied in form-finding

bending resistance

straightening : tendency of three points to become co-linear

(beams pattern is bent after mapping to the surface, so straightening is necessary)

point-point force

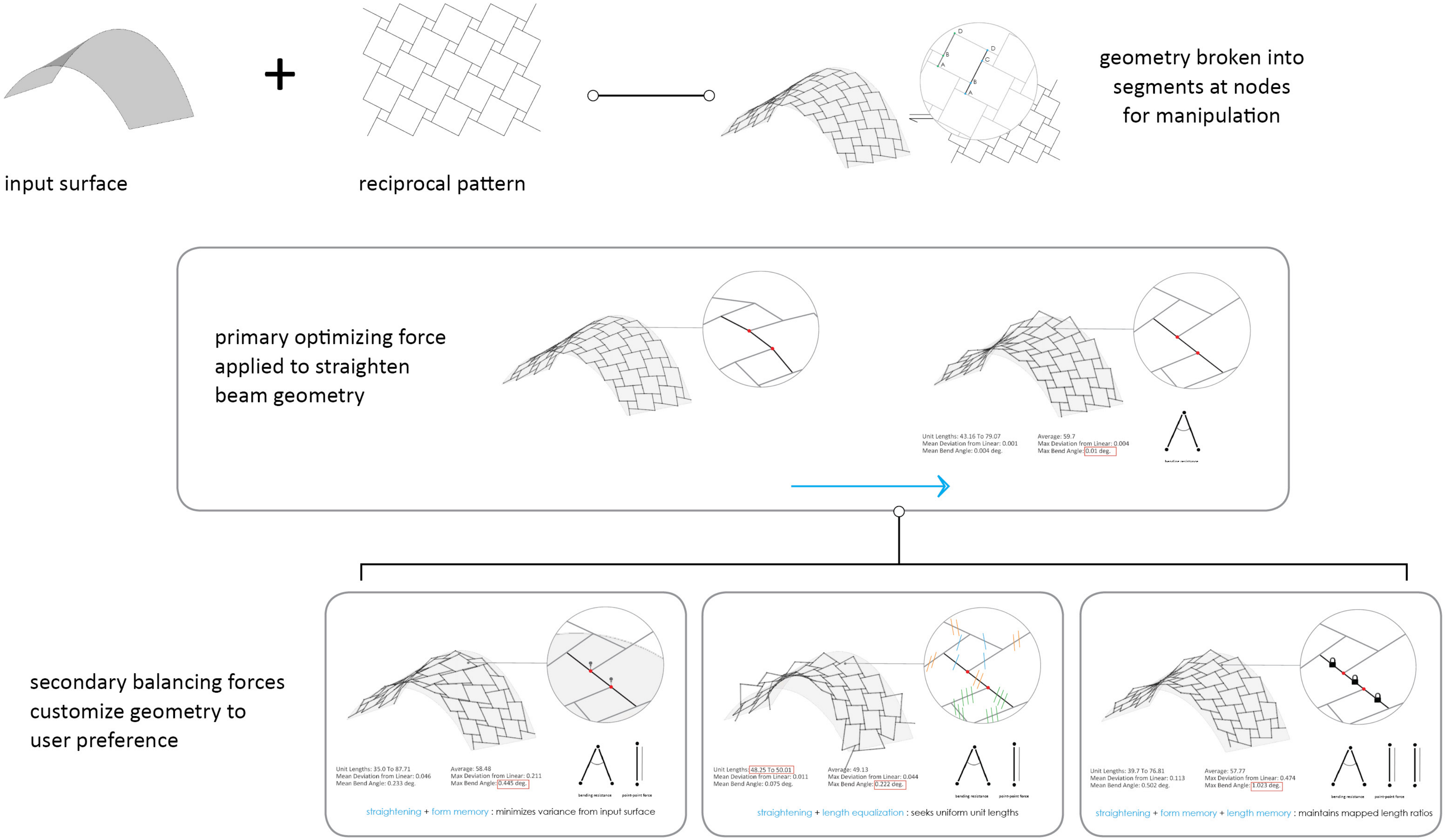
length equalization: tendency of lines to be equal (used in seeking modular forms)

length memory : pattern lines attempt to maintain original (mapped) length

form memory : pattern geometry seeks input form

anchoring : simulation of foundation points

image credit: AutoDesk Research



Unit Lengths: 43.16 To 79.07
Mean Deviation from Linear: 0.001
Mean Bend Angle: 0.004 deg.
Average: 59.7
Max Deviation from Linear: 0.004
Max Bend Angle: 0.01 deg.

Unit Lengths: 35.0 To 87.71
Mean Deviation from Linear: 0.046
Mean Bend Angle: 0.233 deg.
Average: 58.48
Max Deviation from Linear: 0.211
Max Bend Angle: 0.445 deg.

Unit Lengths: 48.25 To 50.01
Mean Deviation from Linear: 0.011
Mean Bend Angle: 0.075 deg.
Average: 49.13
Max Deviation from Linear: 0.044
Max Bend Angle: 0.222 deg.

Unit Lengths: 39.7 To 76.81
Mean Deviation from Linear: 0.113
Mean Bend Angle: 0.502 deg.
Average: 57.77
Max Deviation from Linear: 0.474
Max Bend Angle: 1.023 deg.

Fig. 4.22: Illustration of form-finding process and the hierarchy of application for optimizing forces.

Fig. 4.23: application to surfaces of different Gaussian curvature

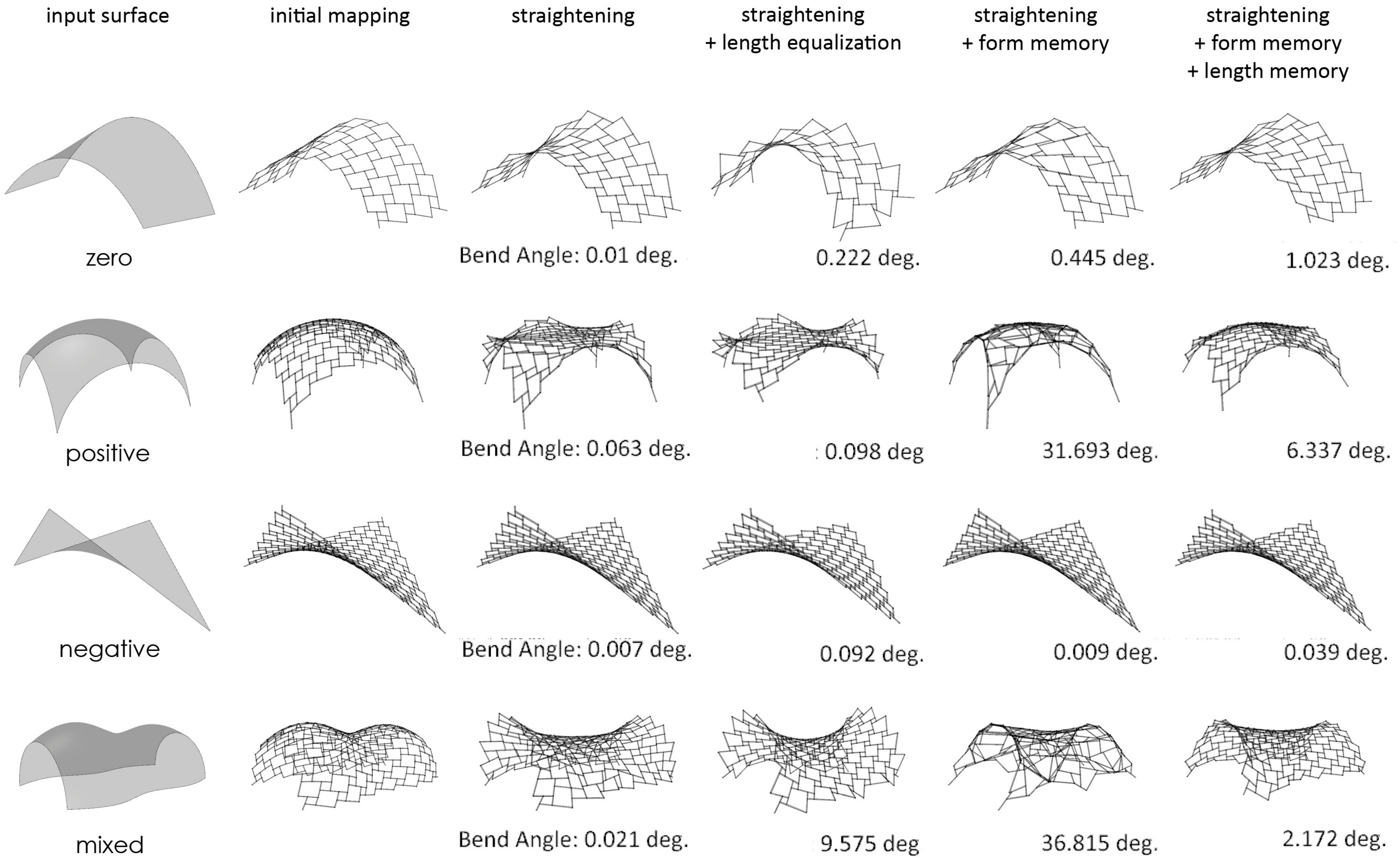
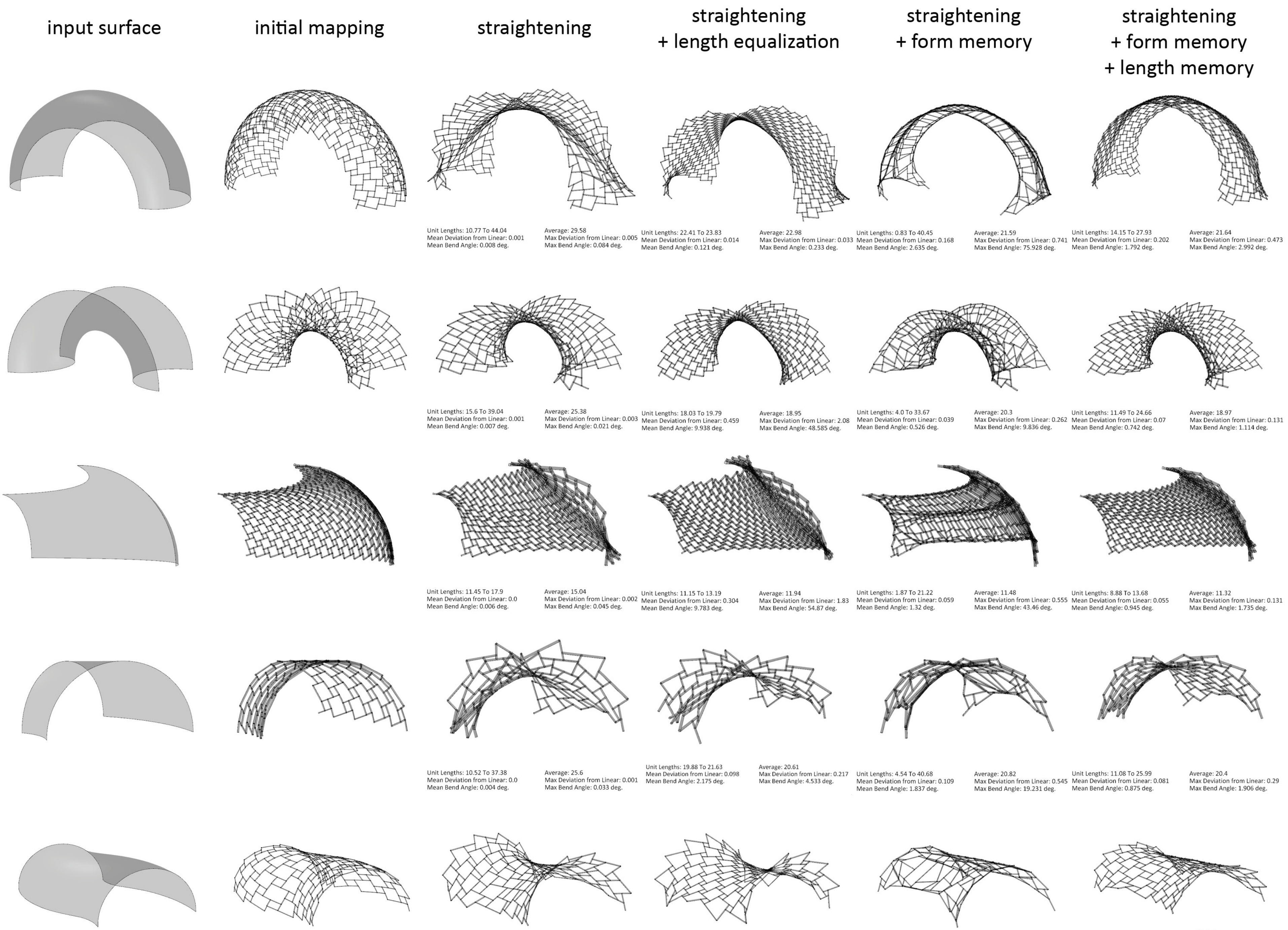


Fig. 4.24: application to different toroid surfaces



Unit Lengths: 10.77 To 44.04
Mean Deviation from Linear: 0.001
Mean Bend Angle: 0.008 deg.

Average: 29.58
Max Deviation from Linear: 0.005
Max Bend Angle: 0.084 deg.

Unit Lengths: 22.41 To 23.83
Mean Deviation from Linear: 0.014
Mean Bend Angle: 0.121 deg.

Average: 22.98
Max Deviation from Linear: 0.033
Max Bend Angle: 0.233 deg.

Unit Lengths: 0.83 To 40.45
Mean Deviation from Linear: 0.168
Mean Bend Angle: 2.635 deg.

Average: 21.59
Max Deviation from Linear: 0.741
Max Bend Angle: 75.928 deg.

Unit Lengths: 14.15 To 27.93
Mean Deviation from Linear: 0.202
Mean Bend Angle: 1.792 deg.

Average: 21.64
Max Deviation from Linear: 0.473
Max Bend Angle: 2.992 deg.

Unit Lengths: 15.6 To 39.04
Mean Deviation from Linear: 0.001
Mean Bend Angle: 0.007 deg.

Average: 25.38
Max Deviation from Linear: 0.003
Max Bend Angle: 0.021 deg.

Unit Lengths: 18.03 To 19.79
Mean Deviation from Linear: 0.459
Mean Bend Angle: 9.938 deg.

Average: 18.95
Max Deviation from Linear: 2.08
Max Bend Angle: 48.585 deg.

Unit Lengths: 4.0 To 33.67
Mean Deviation from Linear: 0.039
Mean Bend Angle: 0.526 deg.

Average: 20.3
Max Deviation from Linear: 0.262
Max Bend Angle: 9.836 deg.

Unit Lengths: 11.49 To 24.66
Mean Deviation from Linear: 0.07
Mean Bend Angle: 0.742 deg.

Average: 18.97
Max Deviation from Linear: 0.131
Max Bend Angle: 1.114 deg.

Unit Lengths: 11.45 To 17.9
Mean Deviation from Linear: 0.0
Mean Bend Angle: 0.006 deg.

Average: 15.04
Max Deviation from Linear: 0.002
Max Bend Angle: 0.045 deg.

Unit Lengths: 11.15 To 13.19
Mean Deviation from Linear: 0.304
Mean Bend Angle: 9.783 deg.

Average: 11.94
Max Deviation from Linear: 1.83
Max Bend Angle: 54.87 deg.

Unit Lengths: 1.87 To 21.22
Mean Deviation from Linear: 0.059
Mean Bend Angle: 1.32 deg.

Average: 11.48
Max Deviation from Linear: 0.555
Max Bend Angle: 43.46 deg.

Unit Lengths: 8.88 To 13.68
Mean Deviation from Linear: 0.055
Mean Bend Angle: 0.945 deg.

Average: 11.32
Max Deviation from Linear: 0.131
Max Bend Angle: 1.735 deg.

Unit Lengths: 10.52 To 37.38
Mean Deviation from Linear: 0.0
Mean Bend Angle: 0.004 deg.

Average: 25.6
Max Deviation from Linear: 0.001
Max Bend Angle: 0.033 deg.

Unit Lengths: 19.88 To 21.63
Mean Deviation from Linear: 0.098
Mean Bend Angle: 2.175 deg.

Average: 20.61
Max Deviation from Linear: 0.217
Max Bend Angle: 4.533 deg.

Unit Lengths: 4.54 To 40.68
Mean Deviation from Linear: 0.109
Mean Bend Angle: 1.837 deg.

Average: 20.82
Max Deviation from Linear: 0.545
Max Bend Angle: 19.231 deg.

Unit Lengths: 11.08 To 25.99
Mean Deviation from Linear: 0.081
Mean Bend Angle: 0.875 deg.

Average: 20.4
Max Deviation from Linear: 0.29
Max Bend Angle: 1.906 deg.

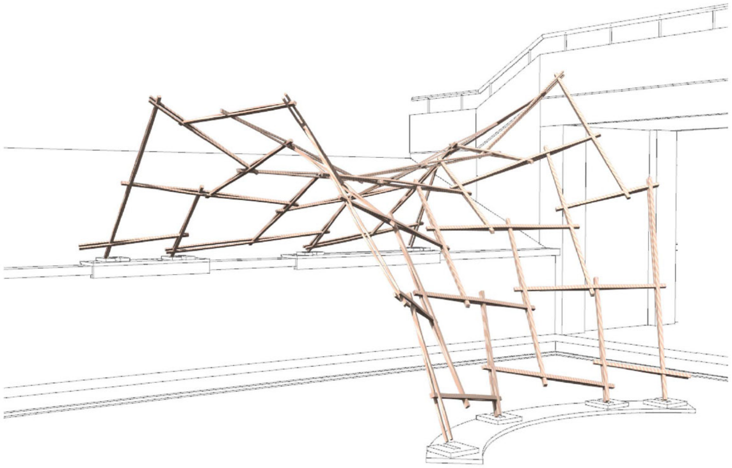


Fig. 5.1: Applying the form-finding process to an actual built artifact forces consideration of various tectonic and site-specific details not present in the previous development of this work flow.

5.0 Experimental Pavilion Design

In exploring processes of form-finding and in developing assembly strategies for non-standard geometric constructions, it becomes necessary at some point to prototype at full scale, to begin working outside the safe confines of model-making and digital simulation. The experimental pavilion has a long tradition in facilitating leaps of faith, allowing designers and builders to test in reality systems and assumptions developed in representative media. As a pedagogical model in architectural education, the construction of experimental pavilions has proved highly successful in providing exposure to the full cycle of a building project and in illuminating the material realities of designing in untrodden territory. (Thonnisen 2011, Walker & Self 2011.)

The test case for this investigation is intended to represent one possible approach to designing, rationalizing, documenting, and fabricating a reciprocal assembly based on the assumption of axial tangency. While representing only one possible configuration, the designed artifact and the record of its fabrication serve to demonstrate the advantages and disadvantages of this form finding approach as it relates to wood construction.

The geometry of the structure was generated using a workflow adapted from that developed in section 4.4, and evaluated for structural stability using Karamba FEA simulation, as well as gravity simulation in Kangaroo, where constrained rotational freedom at joints is more easily modeled. These tools provided some confidence in the performance of the prototype, but without rigorous destructive testing, it was difficult to predict how the structure would perform at the connection details. Knowing this limitation, the joinery and fabrication strategy developed in the following sections met the geometric demands of assembly (rotation angle between members and consistency of axial tangency) but the effect of deflection and material performance at the joints remained uncertain until final assembly.

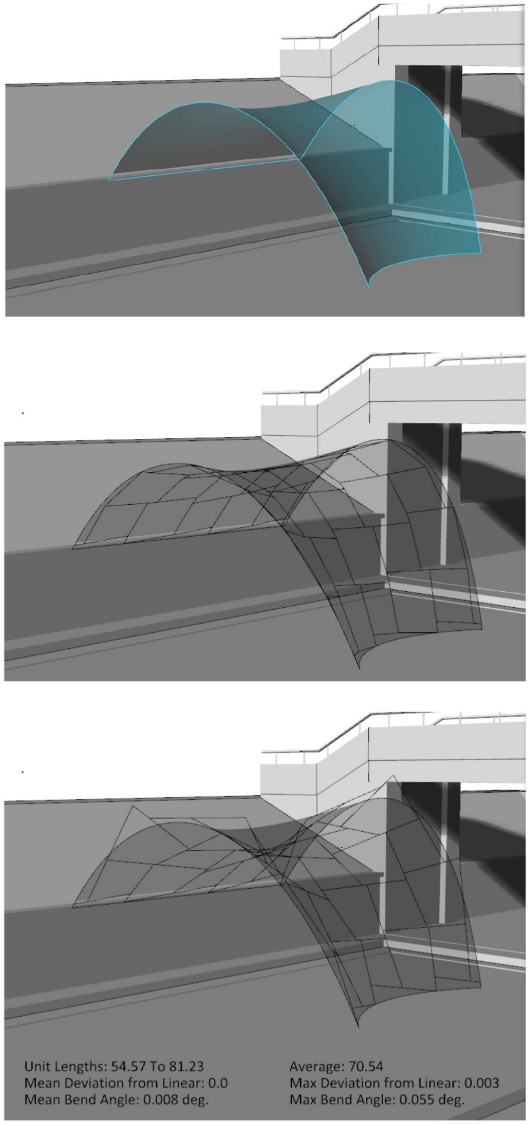


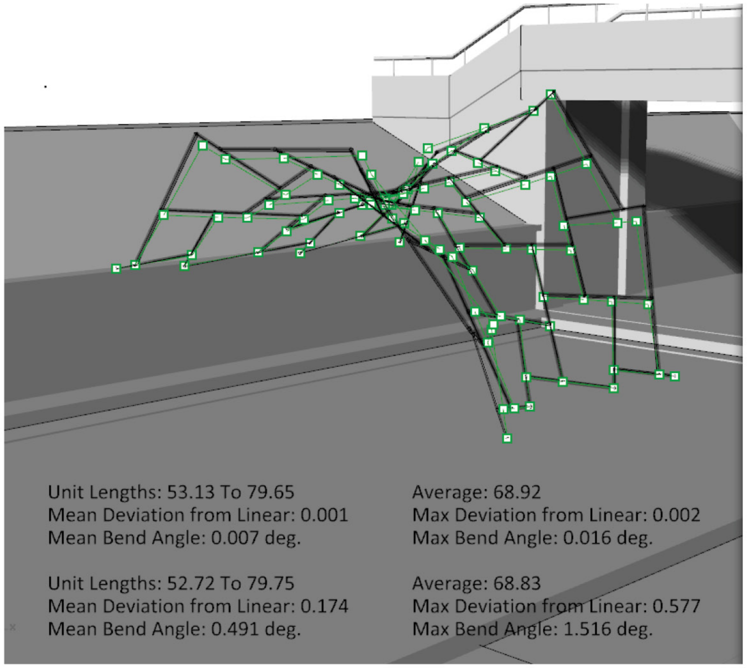
Fig. 5.2: The form-finding process established in section 4.4 is adapted and applied to a site-specific geometry.

5.1 Development of form

Given the highly responsive and driving relationships present in axially joined reciprocal beam assemblies, kinetic models show great promise as from-finding tools within a given set of constraints. The physical models discussed in section 4.3 easily allow the exploration of form within a set of fixed and identical length parameters, but do not easily permit the relaxation of distances between joints. This type of tool is useful when designing for an assembly of fully modular units, but limits the range of forms available if the design and construction strategy allow for variation in the length and attachment points of individual members. The construction and manipulation of physical models in the early stages of this process was vital to understanding the basic behavior of free-rotating reciprocal structures. Without this material experience, it would have been far more difficult to trust or evaluate the results of digital simulations.

The form of the test structure is determined by an input surface geometry, an input beam pattern and the application of artificial forces, as described in section 4.4. In addition to the forces used in preliminary simulations, the development of this structure also includes anchor points, which simulate foundations. The input surface is defined by 4 corner points, from which edges are developed as catenary curves. This setup allowed easy experimentation with the effect of subtle changes in the input on the final form and the stability of the structure. Curvature at the foundations proved to be very important in producing a self-stable edge, and in maintaining consistent negative Gaussian curvature across the entire surface.

There is no question that the natural hyperbolic tendencies of an axially joined reciprocal system are limiting if one wishes to faithfully approximate a surface of positive Gaussian curvature. This approach is limited in formal variation to the same degree that we see in overlaid assemblies As vaulted forms, these tend to reach high at the edges in order to accommodate overhead heights at the middle of the pattern. In order to achieve this head



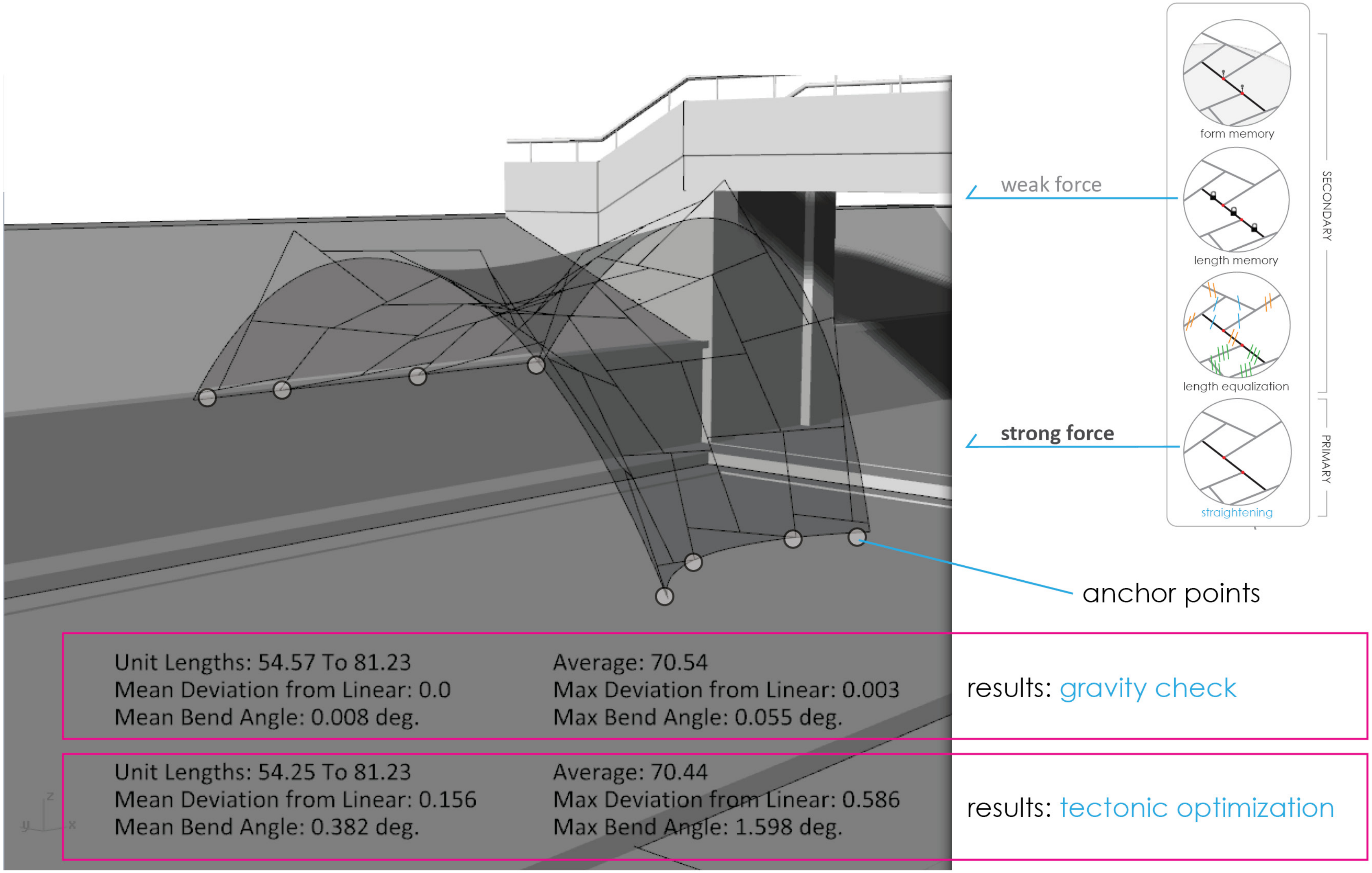
```
Unit Lengths: 53.13 To 79.65             Average: 68.92
Mean Deviation from Linear: 0.001        Max Deviation from Linear: 0.002
Mean Bend Angle: 0.007 deg.              Max Bend Angle: 0.016 deg.

Unit Lengths: 52.72 To 79.75             Average: 68.83
Mean Deviation from Linear: 0.174        Max Deviation from Linear: 0.577
Mean Bend Angle: 0.491 deg.              Max Bend Angle: 1.516 deg.
```

Fig. 5.3: Application of a gravity force at preliminary analysis illustrates the nature of rigid motions in the frame when used as a bridging structure.

height while remaining in the range of curvature, the foundations of the form are lifted onto the concrete retaining wall on the north edge of the site. This asymmetric configuration also allow for observations of beam behavior at different orientations.

Stability is initially checked in a successive simulation by applying a gravity force to the nodes of the frame while maintaining forces that enforce the tectonic rules of the system. As unbounded reciprocal structures have the potential for rigid-body motions (Brocato 2011), it was important to simulate the effect of gravity without resistance to rotational freedom at the joints of the structure. The structural uncertainties inherent in this assembly are a direct result of its role in this situation as a bridging canopy. Fixing the edge nodes to bounding walls would eliminate the possibility of rigid motion. While a bridging form may not be as stable as a bounded one, this construction will allow for observation of the severity and character of these failure modes by folding

A further development of this work flow might offer the option to optimize the stability of a given form by manipulating input parameters. This may be achieved through adjustment of the input pattern, foundation points, or artificial forces during geometric optimization. However, this requires that decisions made at these points in the process be treated as malleable aspects of the design. Stability is perhaps the most important factor in the success of the system, but it is not the only factor. The layering of this process seems to demand a certain flexibility of vision on the part of the designer, but in submitting to the constraints of an efficient tectonic system, gains are made available in fabrication, transportation and assembly costs.



Unit Lengths: 54.57 To 81.23 Average: 70.54
Mean Deviation from Linear: 0.0 Max Deviation from Linear: 0.003
Mean Bend Angle: 0.008 deg. Max Bend Angle: 0.055 deg.

Unit Lengths: 54.25 To 81.23 Average: 70.44
Mean Deviation from Linear: 0.156 Max Deviation from Linear: 0.586
Mean Bend Angle: 0.382 deg. Max Bend Angle: 1.598 deg.

Fig.5.4: The process used in developing the form of the pavilion is identical to that described in section 4.4 with the added inclusion of anchor points, which constrain the frame to contact with the site, and a stability check to identify the propensity for collapse by rigid body motions. The maintenance of length values and low bend angles from tectonic optimization through the gravity check shows that beams are not stretching unrealistically on axis or folding at engagement points. This initial check allows the user to observe the behavior of the geometry with unconstrained rotational freedom at the joints.

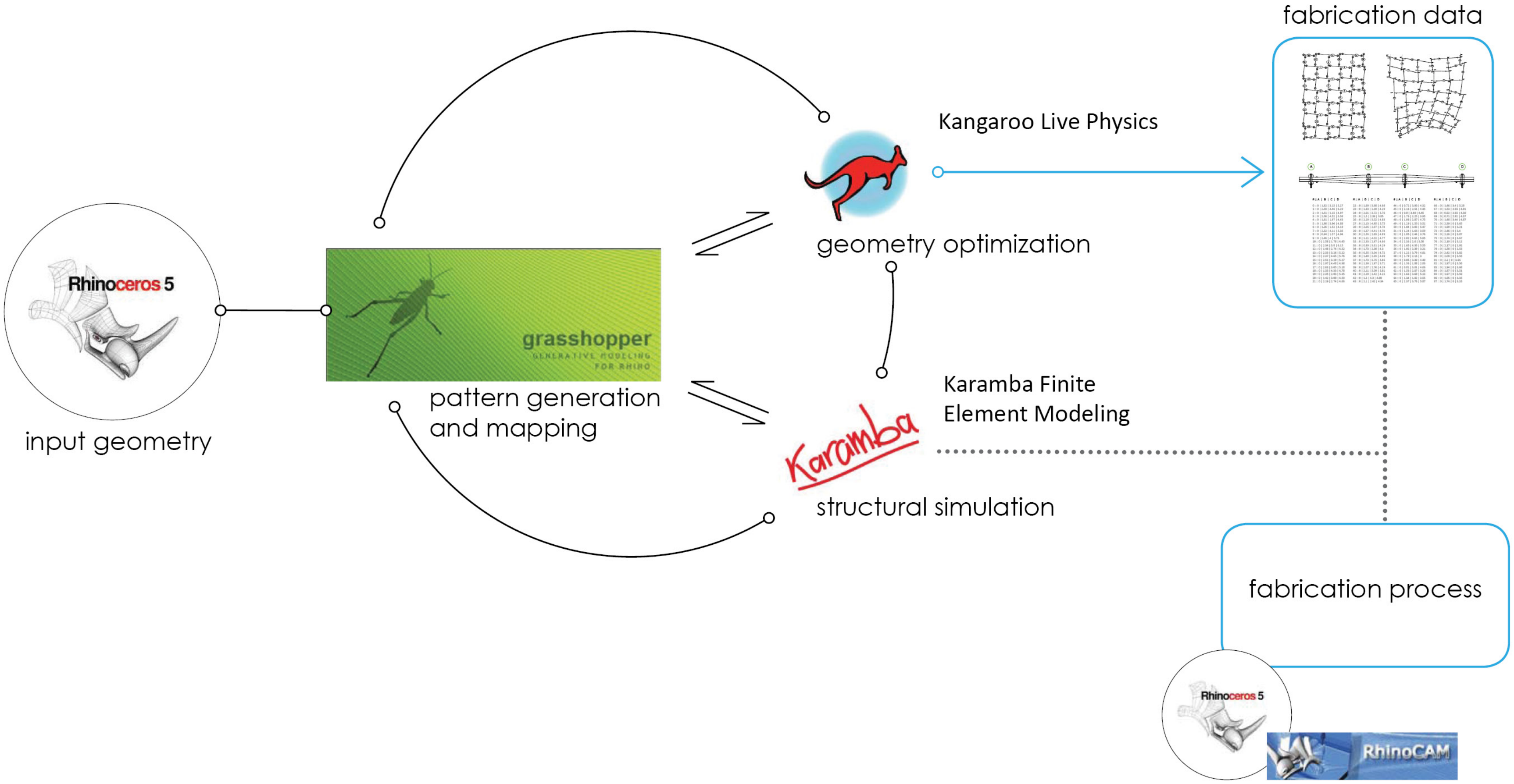


Fig.5.5: Visualization of the parametric workflow and connection to construction process.

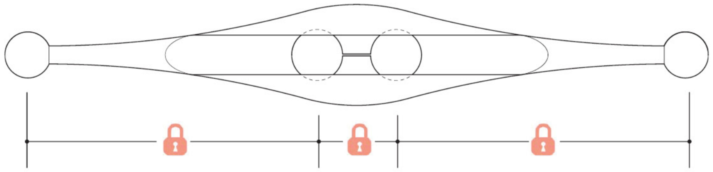
5.2 Joinery design and prototyping

Scalability of the modular unit

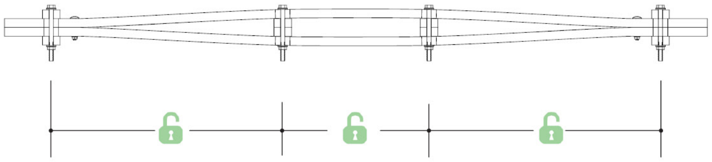
Fig. 5.6: Scaling of the modular unit is achieved by dividing the piece on axis.

In a reciprocal frame assembly, the locations of joints correspond to the points of greatest bending moment in each member. This presents challenges of rationalization when designing for pre-dimensioned linear materials. The shaping of the modular ball-jointed unit accounts for these forces by increasing the overall depth and cross-section at the socket joint, where internal moment forces are greatest. However, when considering this shaped geometry as a solution for timber construction, efficiency in the fabrication process becomes a major concern. Subtractive manufacture of such a complex geometry is time-consuming, and produces a great deal of waste. While sculpted wood provides an appealing aesthetic, it is preferable to find a rationalization solution that works in simply dimensioned material if any variation in length parameter is desired. In regard to the process used, this type of modular system is much more scalable using formative manufacturing techniques such as bending, casting, and die-forming.

Such formative processes have been employed in fabricating solid timber reciprocal frame units at the scale of a building roof. A recent project built by students at the Architectural Association used steam-bent beech wood to construct highly customized units. This process has the potential to broaden the range of buildable forms within the RF tectonic language, but due to the labor and process involved, the efficiency of this method is only slightly better than a subtractive process and the freedom at the joint condition is significantly less variable. As a scalable unit, this moment-optimized geometry has been most elegantly attained by triangulating bending forces in a type of truss unit (Gelez et al 2011[2]) from formed and welded standard sections with standard or custom-cast joint fittings. These units, when assembled into a structure, form a '1.5 layer' space frame, meaning that while the frame has two layers of triangulated nodes, they are connected to each other at only one layer. Other formative fabrications



complex geometry >> modular unit



simplified linear geometry >> variable lengths with modular joints

Fig.5.7: Adapting to customizable tectonics.

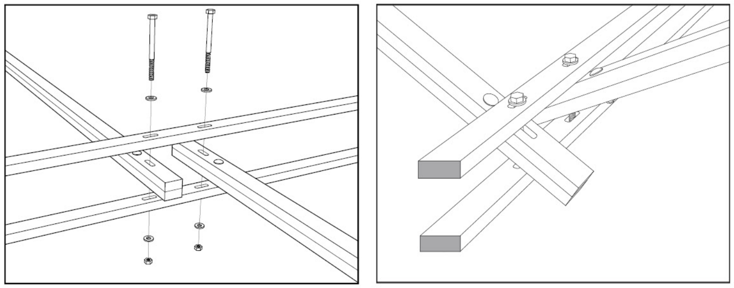


Fig.5.8: Assembly process for interleaved slot joint.

methods might include cast metal shell modules or solid glass-reinforced plastics/ceramics (concrete). In a casting process, uniform units are likely to be the only economically viable option, while solutions using linear stock in a built-up fabricated unit are more likely to offer efficient means of variation in unit parameters.

Adaptation to Linear Material Processing

This study has found that it is possible to generate a range of variation in form simply by manipulating the length parameters of an axially joined reciprocal assembly. A primary motivation for developing form within the constraint of 0-eccentricity is the possibility of variable member sizing while maintaining modular joinery. To accomplish this, it is necessary to separate the joint from the body of the part in the fabrication process or to design an integral joint that is more-or-less ambivalent to member cross-section.

A final development in joinery design is inspired by the node connections of a conventional timber grid shell, in which bypass members are slotted to allow for movement during assembly. In designing the modular joint for this assembly, it was necessary to preserve freedom of rotation while maintaining an efficient fabrication process. The chosen solution is a doubly-cambered beam that weaves through adjoining beams, held in place by a double-slotted bolt connection. By slotting in two axes and cambering beams around the joint, it was possible to produce an interleaved connection that allows members to meet on axis and rotate within the range necessary to achieve the idealized geometry of the test structure. While bolts are intended to act mostly as pins, it is possible to control rotational freedom in two axes by tightening the fasteners.

American ash wood was chosen when prototyping for its low cost and high resistance to splitting (shear parallel to the grain.) Extreme angle conditions for all three axes of rotation were extracted from the model and used to define benchmarks for joint testing. These conditions were tested

Fig. 5.9: A prototype joint, designed to test the limits of the material as required by the assembly system.

on a part in the assembly with the least distance between middle and end connections in order to observe the effect of increased camber at the limit required. This test is intended to effectively surpass the stress resulting from rotation for any joint in the assembly. The prototype achieves this easily with no sign of failure.

The dimensions chosen when milling linear profiles for the assembly were determined in large part by the thickness of the stock available. Rough stock with a thickness of 0.75" was used for all of the members in the assembly, and these were milled to a width of 1.5" to create a square cross-section when stacked as a cambered unit. The square compound profile is desirable as a baseline for observing the effect of cambering on the rigidity of the structure. This profile is also better able to accommodate axial rotation (torque) at the joint in this particular design. Further development of this project would ideally produce a joint design that is more ambivalent to material cross-section but still allows the use of linear material with minimal labor required in fabrication and assembly.

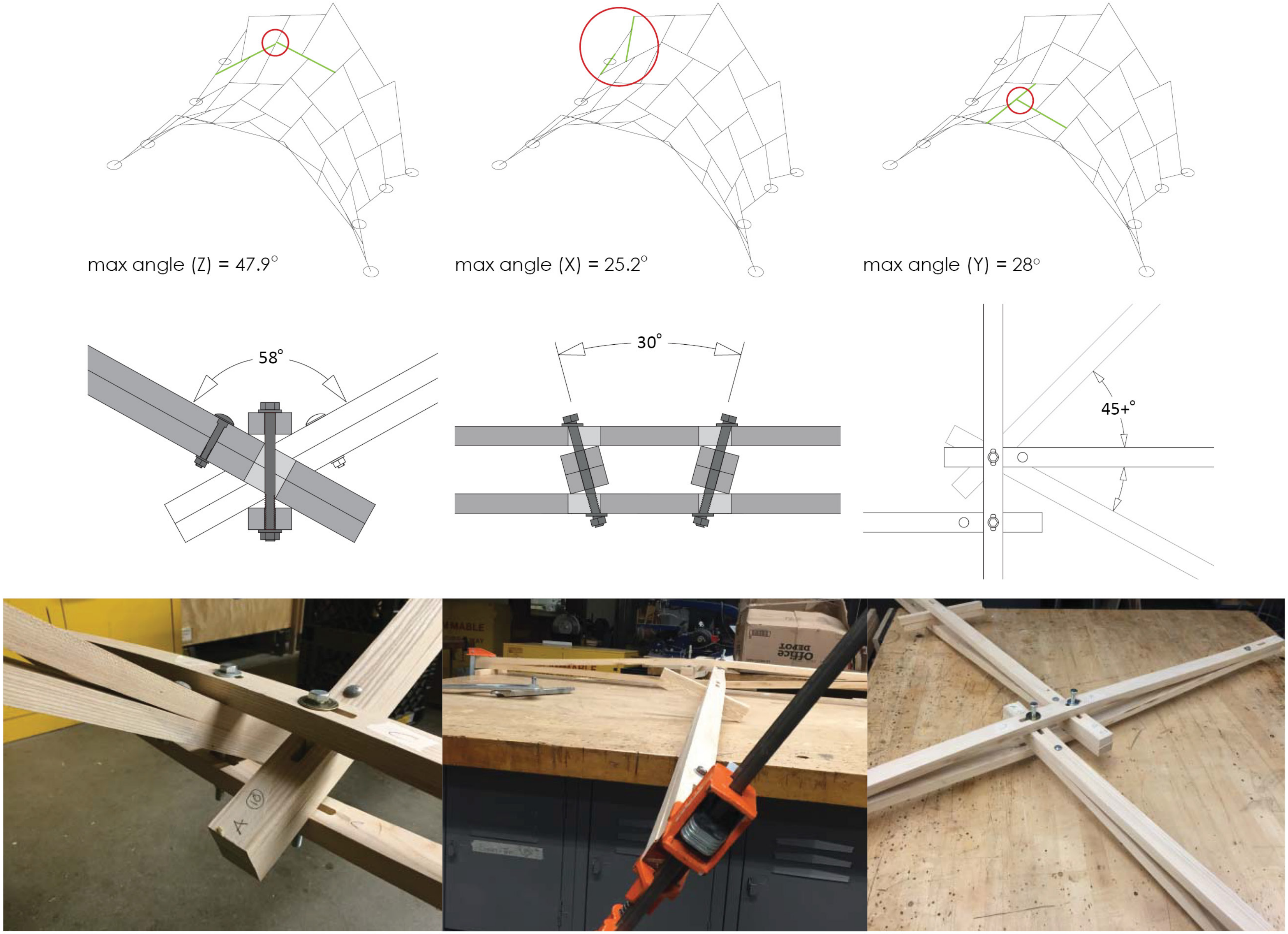


Fig. 5.10: Requirements for joint performance are extracted from the model. Rotational freedoms provided by the slot length perform as designed, and the material appears capable of handling the necessary torque and flex without any sign of failure.

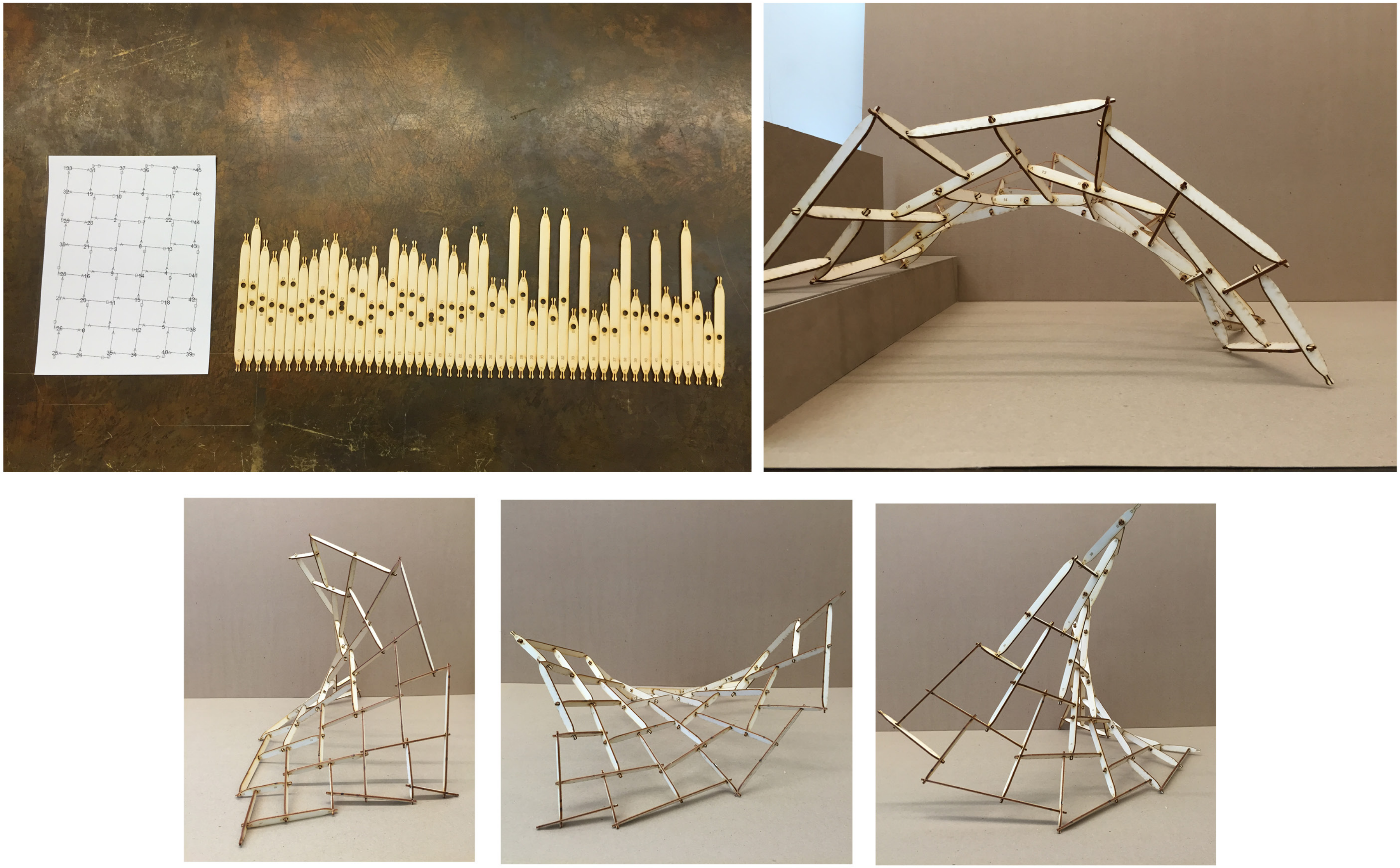


Fig. 5.11: A 1-to-12 scale model was constructed to experiment with assembly sequence and test the concept of an arbitrary joint with variable unit lengths. A snap joint is used to simulate the freedoms of the interleaved slot joint intended for use in the full-scale structure. Assembly went smoothly using the regular topology diagram as a guide, and the play in the joint had very little effect on the form of the completed structure. This scale study also provided an opportunity to observe rigid motions that might occur at full scale. The full rotational freedom provided by the pin joint allows the assembly to twist and contort, finding least resistance in a saddle form. This contortion is unlikely to be a problem with fixed footing connectinos, but presents the possibility of uplift caused by internal forces.

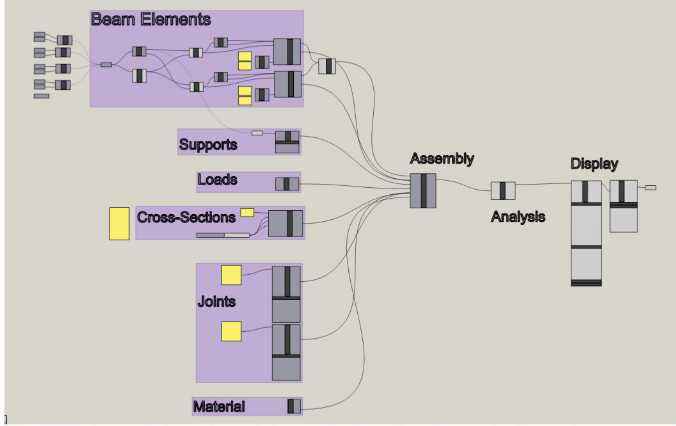


Fig. 5.12: An early iteration of the analysis script shows the flow of information needed to simulate the performance of a single fan unit.

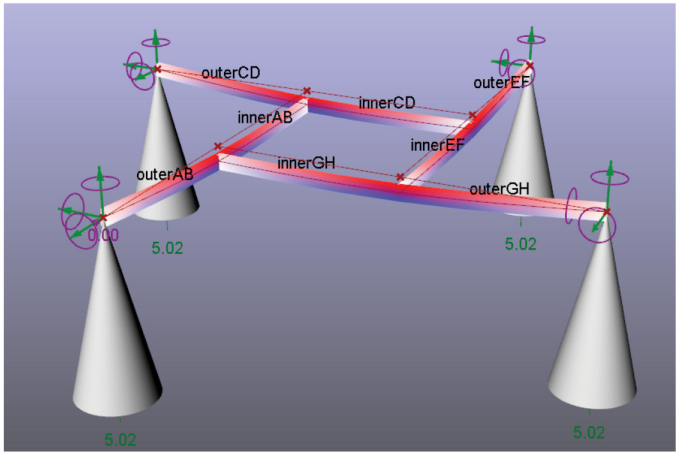


Fig. 5.13: FEA model of a single fan: 4 beams described as 8 perform realistically due to the assignment of joint freedoms.

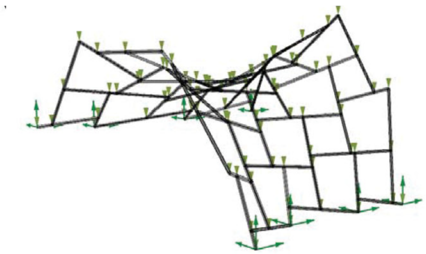
5.3 Structural Analysis

Following a check against rigid motions using Kangaroo, and having decided on material and cross-section dimensions, structural evaluation was carried out in using Karamba, a finite element modeling platform designed to work within Grasshopper. Properties are assigned to simulate actual material behavior and four load cases are observed. First, the self-weight of the structure is applied to see if it will stand. Two lateral loads and an uplift case are simulated as well. This evaluation is primarily a safety measure to make sure that the structure will not collapse due to material failure and to give a prediction of its behavior during and after assembly.

In defining a FEA model, it is necessary that all elements terminate at shared nodes if they are to affect one another in simulation. That is, the end of one beam may not fall on the midspan of another beam element and still transfer forces to its neighbor. It is necessary to divide beams into segments at all joints and then define the false joints as equivalent to continuous material. This process takes advantage of the topology already set up for mapping and optimization, and separates the definition of joints in a similar way. Beams are treated as either 2 (edges) or 3 (field) discrete elements with an association to one another. Midspan joints on a beam are treated as fully fixed joints, and end joints are treated as fixed in translation but free in all 3 axes of rotation. Rotational resistance is set unrealistically low in order to simulate a joint with simpler rotational freedom than the one used.

The joint designed for this prototype is effective in testing the feasibility of this type of structure and in evaluating the assembly process, but represents an intermediate step in the design process. An ideal joint for this type of construction system would be mass-produced, capable of accommodating varied material cross-sections, and rotationally free without exerting moment forces. It is likely that the bypass joint adds stiffness to the structure that allows it to perform considerably better than the simulations would suggest. However, in the interest of scalability, it is more useful to simulate a joint with greater freedom.

The metrics used in evaluating the performance of this structure are relatively simple. First, deformation is observed under the current load case. This is measured in inches, and gives a prediction of how far the structure is likely to move under that load. The second metric observed is utilization of elements. This is calculated by evaluating the maximum internal stress of an element and dividing that value by the yield stress for the material identified. In Karamba, utilization takes bending stress and buckling into account, giving a general value for the degree to which the resisting capacity of the element is being used (Preisinger 2014.) This metric is expressed as a percentage. Using these evaluations, uplift and self-weight cases both provided satisfactory results, enough so that the structure appeared safe to build. Not surprisingly, the structure does not perform particularly well against lateral loads. The cells of the grid must act as moment-resisting frames in lateral shear, and the material is not heavy enough to resist much load in this direction.



beam elements: line segments in structured lists

supports: intersections with site

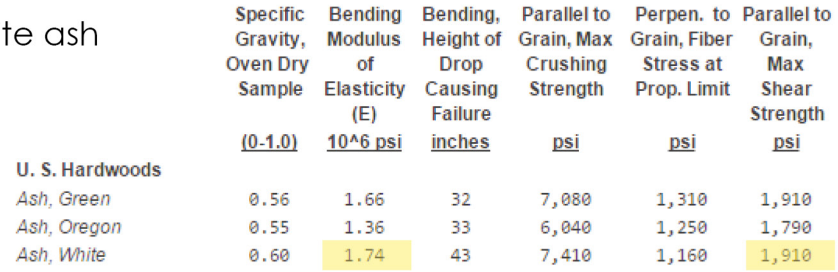
joints: rotational resistance

x = 10lb-ft/radian
z = 10lb-ft/radian
y = 1lb-ft/radian

*unrealistically low

cross-sections: 1.5" square

material: American white ash



	Specific Gravity, Oven Dry Sample (0-1.0)	Bending Modulus of Elasticity (E) 10^6 psi	Bending, Height of Drop Causing Failure inches	Parallel to Grain, Max Crushing Strength psi	Perpen. to Grain, Fiber Stress at Prop. Limit psi	Parallel to Grain, Max Shear Strength psi
U. S. Hardwoods						
Ash, Green	0.56	1.66	32	7,080	1,310	1,910
Ash, Oregon	0.55	1.36	33	6,040	1,250	1,790
Ash, White	0.60	1.74	43	7,410	1,160	1,910

Fig. 5.14: definition of FEA model

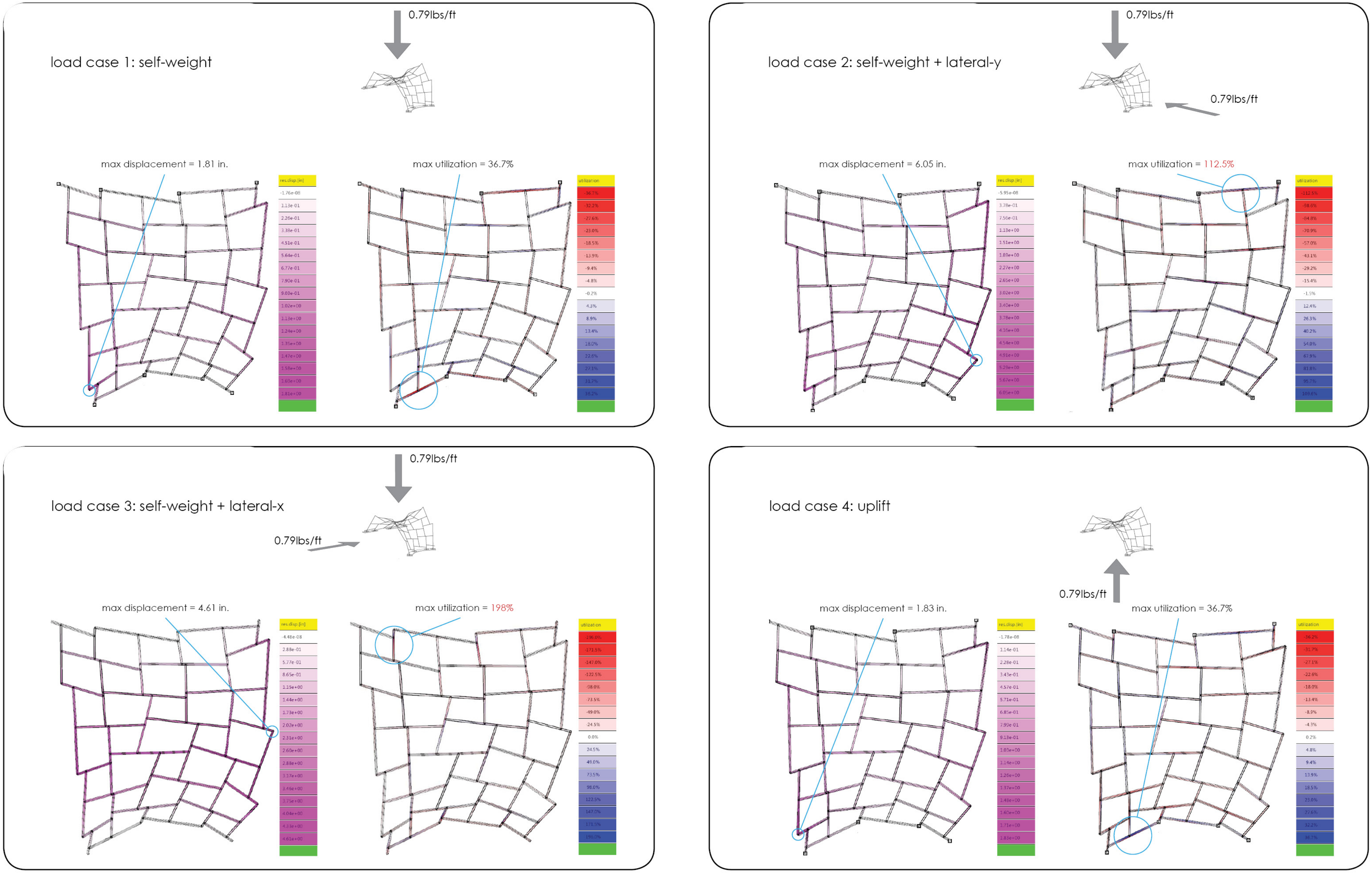
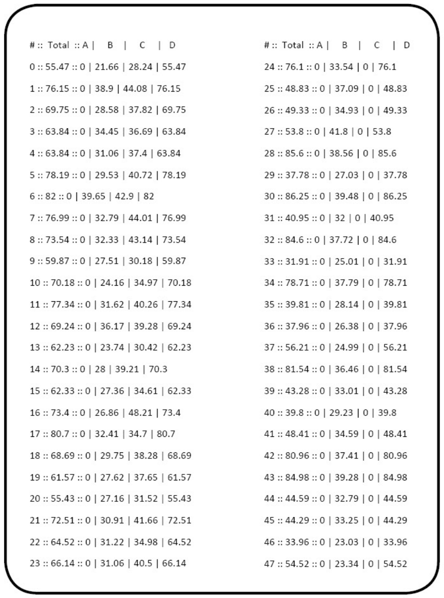


Fig. 5.15: Performance analysis using Karamba FEA predicts that the structure will support its own weight and that movement will be minimal under this load condition. Lateral loads present a challenge to the geometry, as it is essentially required to act as a moment frame in this case. This illuminates a challenge of designing free-edge reciprocal structures and suggests that bracing may be necessary in quadrilateral RF grids for some situations. (Other patterning options maybe better able to cope with lateral forces without additional bracing.) These simulations are based on a conservative model, and it is expected that the structure will be more robust than predicted.



#	Total	A	B	C	D
0	55.47	0	21.66	28.24	55.47
1	76.15	0	38.9	44.08	76.15
2	69.75	0	28.58	37.82	69.75
3	63.84	0	34.45	36.69	63.84
4	63.84	0	31.06	37.4	63.84
5	78.19	0	29.53	40.72	78.19
6	82	0	39.65	42.9	82
7	76.99	0	32.79	44.01	76.99
8	73.54	0	32.33	43.14	73.54
9	59.87	0	27.51	30.18	59.87
10	70.18	0	24.16	34.97	70.18
11	77.34	0	31.62	40.26	77.34
12	69.24	0	36.17	39.28	69.24
13	62.23	0	23.74	30.42	62.23
14	70.3	0	28	39.21	70.3
15	62.33	0	27.36	34.61	62.33
16	73.4	0	26.86	48.21	73.4
17	80.7	0	32.41	34.7	80.7
18	68.69	0	29.75	38.28	68.69
19	61.57	0	27.62	37.65	61.57
20	55.43	0	27.16	31.52	55.43
21	72.51	0	30.91	41.66	72.51
22	64.52	0	31.22	34.98	64.52
23	66.14	0	31.06	40.5	66.14
24	76.1	0	33.54	0	76.1
25	48.83	0	37.09	0	48.83
26	49.33	0	34.93	0	49.33
27	53.8	0	41.8	0	53.8
28	85.6	0	38.56	0	85.6
29	37.78	0	27.03	0	37.78
30	86.25	0	39.48	0	86.25
31	40.95	0	32	0	40.95
32	84.6	0	37.72	0	84.6
33	31.91	0	25.01	0	31.91
34	78.71	0	37.79	0	78.71
35	39.81	0	28.14	0	39.81
36	37.96	0	26.38	0	37.96
37	56.21	0	24.99	0	56.21
38	81.54	0	36.46	0	81.54
39	43.28	0	33.01	0	43.28
40	39.8	0	29.23	0	39.8
41	48.41	0	34.59	0	48.41
42	80.96	0	37.41	0	80.96
43	84.98	0	39.28	0	84.98
44	44.59	0	32.79	0	44.59
45	44.29	0	33.25	0	44.29
46	33.96	0	23.03	0	33.96
47	54.52	0	23.34	0	54.52

Fig 5.16: Table of length parameters for fabrication

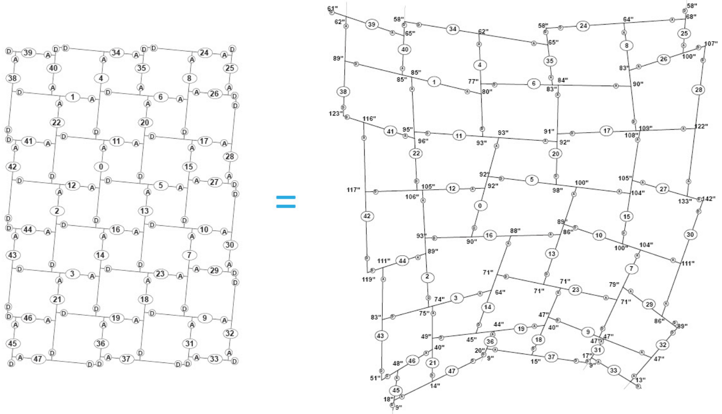


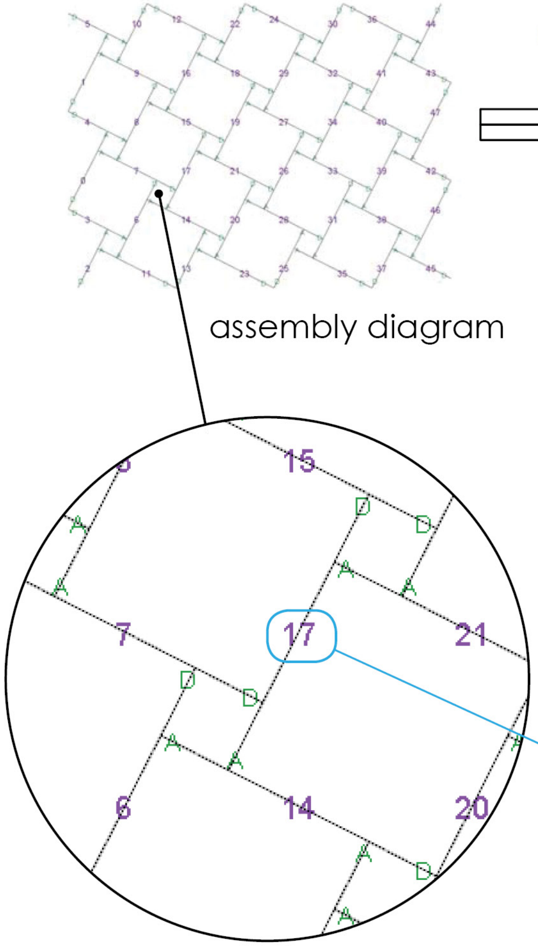
Fig 5.17: Maintenance of topology from input pattern to final form

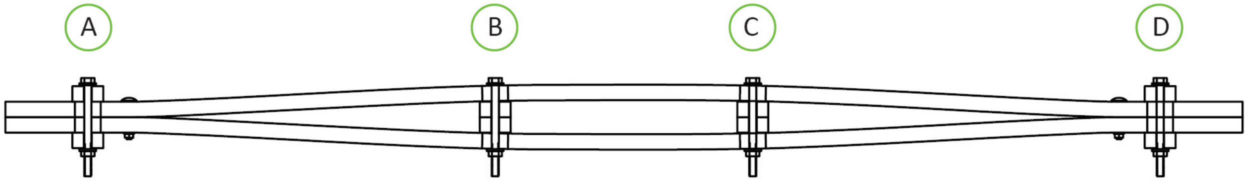
5.4 Construction Data

The fabrication and assembly of the frame system are facilitated by simple documentation and a uniform topology structure at both unit and assembly levels. Because the beams are constructed of linear material, the only data required in fabricating these elements can be formatted in a table of simple length parameters. The order of parameters in this list structure corresponds to the location of a starting node, two middle nodes, and an end node, under the naming convention [A,B,C,D]. Where edge members have only one middle node, the missing parameter 'C' is replaced with a '0' placeholder. This list of specific data corresponds to an assembly diagram, which describes the orientation of members and the relationships of nodes to one another.

The maintenance of a regular topology in this work flow allows edge conditions to be more easily controlled and permits the use of a single assembly diagram in describing any number of morphological variations on the same pattern. This consistency of pattern and data is useful in documenting complex forms that do not easily transfer to 2D construction plans. Node tags, using the naming convention described above, show the index of each beam and describe the orientation of that beam in the assembly. These also show the correlation of the two beams that meet at each node. The final piece of information marked on the assembly diagram is the height of each node from a datum level. This is intended to facilitate accurate scaffolding during assembly and evaluation of the geometric fidelity of the system for the purposes of this study.

The separation of fabrication and assembly data from one another is valuable in maintaining simplicity at each stage of a geometrically complex project. The intended ambivalence of this tectonic system to beam cross section further compartmentalizes the information needed to complete the construction. A joint design must be compatible with the material and cross-section, but the information describing overall geometry is separate from all of these parameters.





```
# :: A | B | C | D

0 :: 0 | 1.92 | 3.15 | 5.27
1 :: 0 | 2.59 | 4.46 | 6.29
2 :: 0 | 1.51 | 2.15 | 4.97
3 :: 0 | 2.56 | 4.52 | 5.58
4 :: 0 | 1.61 | 1.97 | 4.43
5 :: 0 | 1.98 | 3.96 | 4.88
6 :: 0 | 1.26 | 1.52 | 4.18
7 :: 0 | 2.32 | 4.11 | 5.35
8 :: 0 | 0.94 | 1.57 | 4.04
9 :: 0 | 2.46 | 4 | 5.76
10 :: 0 | 1.58 | 1.78 | 4.45
11 :: 0 | 2.34 | 3.8 | 6.15
12 :: 0 | 1.48 | 2.74 | 4.32
13 :: 0 | 2.33 | 3.26 | 5.22
14 :: 0 | 2.37 | 4.65 | 5.76
15 :: 0 | 2.51 | 3.28 | 5.27
16 :: 0 | 1.97 | 4.48 | 4.98
17 :: 0 | 2.63 | 3.05 | 5.18
18 :: 0 | 1.33 | 4.33 | 4.78
19 :: 0 | 2.35 | 2.83 | 5.35
20 :: 0 | 1.42 | 3.88 | 4.59
21 :: 0 | 2.19 | 2.74 | 4.66

# :: A | B | C | D

22 :: 0 | 1.69 | 3.68 | 4.98
23 :: 0 | 1.83 | 2.18 | 4.29
24 :: 0 | 2.01 | 3.72 | 5.76
25 :: 0 | 1.5 | 2.39 | 3.85
26 :: 0 | 2.29 | 3.02 | 4.83
27 :: 0 | 2.13 | 4.95 | 5.75
28 :: 0 | 2.06 | 2.97 | 4.74
29 :: 0 | 1.37 | 4.41 | 4.74
30 :: 0 | 2.56 | 2.83 | 4.89
31 :: 0 | 1.11 | 4.02 | 4.77
32 :: 0 | 2.33 | 2.97 | 4.96
33 :: 0 | 0.89 | 3.61 | 4.29
34 :: 0 | 1.73 | 2.38 | 4.3
35 :: 0 | 0.55 | 3.04 | 4.72
36 :: 0 | 1.48 | 2.35 | 4.09
37 :: 0 | 1.73 | 3.75 | 5.66
38 :: 0 | 1.39 | 1.97 | 3.71
39 :: 0 | 2.07 | 2.76 | 4.29
40 :: 0 | 2.11 | 5.09 | 5.81
41 :: 0 | 2.18 | 2.42 | 4.25
42 :: 0 | 1.3 | 4.3 | 4.88
43 :: 0 | 2.1 | 2.42 | 4.34

# :: A | B | C | D

44 :: 0 | 0.72 | 3.93 | 4.32
45 :: 0 | 2.16 | 2.51 | 4.45
46 :: 0 | 0.8 | 3.48 | 4.45
47 :: 0 | 1.73 | 2.25 | 3.95
48 :: 0 | 1.08 | 2.87 | 4.75
49 :: 0 | 1.29 | 1.55 | 3.51
50 :: 0 | 1.84 | 3.83 | 5.47
51 :: 0 | 1.24 | 1.66 | 3.59
52 :: 0 | 1.85 | 2.44 | 3.76
53 :: 0 | 2.02 | 4.65 | 5.85
54 :: 0 | 2.33 | 2.6 | 3.58
55 :: 0 | 1.65 | 4.35 | 5.55
56 :: 0 | 1.92 | 2.39 | 3.21
57 :: 0 | 1.22 | 3.79 | 4.81
58 :: 0 | 1.78 | 2.16 | 3
59 :: 0 | 0.85 | 3.39 | 4.49
60 :: 0 | 1.53 | 1.88 | 2.83
61 :: 0 | 0.81 | 3.01 | 4.66
62 :: 0 | 1.53 | 2.07 | 3.26
63 :: 0 | 1.63 | 3.68 | 5.13
64 :: 0 | 1.34 | 1.92 | 3.55
65 :: 0 | 2.37 | 3.76 | 5.87

# :: A | B | C | D

66 :: 0 | 1.46 | 3.4 | 5.28
67 :: 0 | 1.53 | 2.93 | 4.91
68 :: 0 | 0.92 | 2.65 | 4.38
69 :: 0 | 0.71 | 2.82 | 4.37
70 :: 0 | 1.48 | 3.44 | 4.87
71 :: 0 | 2.39 | 0 | 3.65
72 :: 0 | 1.99 | 0 | 3.21
73 :: 0 | 2.46 | 0 | 3.4
74 :: 0 | 2.26 | 0 | 3.87
75 :: 0 | 2.74 | 0 | 3.67
76 :: 0 | 2.19 | 0 | 3.12
77 :: 0 | 2.17 | 0 | 2.92
78 :: 0 | 1.58 | 0 | 2.53
79 :: 0 | 2.42 | 0 | 3.82
80 :: 0 | 2.09 | 0 | 3.55
81 :: 0 | 2.2 | 0 | 3.66
82 :: 0 | 1.97 | 0 | 3.56
83 :: 0 | 1.94 | 0 | 3.68
84 :: 0 | 1.97 | 0 | 3.51
85 :: 0 | 1.97 | 0 | 3.59
86 :: 0 | 1.85 | 0 | 3.35
87 :: 0 | 1.74 | 0 | 3.26
```

length values for fabrication

Fig. 5.18: Fabrication and assembly 'DNA' are represented in a table of length parameters and a correlated assembly diagram, essentially an annotated copy of the input pattern used in form-finding. This information is ambivalent to the method of joinery, material used and the cross sections of members. The value in this organization of data is that these variables can be optimized after the form has been developed.

Fig. 5.19: Pre-fabrication is carried out using simple documentation. The form of the installation is coded in this length data, but not apparent until assembly.

5.5 Fabrication

Fabrication begins with preparation of beam material from rough stock and location of joints by measuring to length parameters listed on a data table. Once joints are located and the material is organized into matched sets, slots are milled at the specified locations using a small CNC router running a single simple machine code file. The milled material is clamped against a fence on the machine bed, and the joint to be cut is located by an indexing mark on the fence. The cut operation mills a slot of the specified length and also drills a hole for the bolt used to assemble matching pieces into a beam.

This operation could easily be performed in the field or in a more basic facility using simple jigs and hand-operated routers. The machine used for this project is small enough that it could be brought to a site with standard small construction tools. The advantage of using a CNC tool is the minimization of setup time between cuts. On average, each of 48 beams required 9 minutes at this stage of fabrication, including time to set up and move the material from the jig. In total, the entire fabrication process required an investment of approximately 50 human-hours including time spent milling rough stock to the correct cross-section dimensions, measuring and marking values taken from the data table, grading material, cutting joints, and assembling pieces into beam elements. The process is relatively efficient when performed using this method, but would easily scale to automated linear timber processing technologies (e.g. Hundegger CNC.)

When establishing total lengths in the cut table, an extension of 4” was added to the beam lengths from the model. This was done to keep the slots far enough from the beam ends that the material would resist splitting at the joints under axial torque. Where the structure would attach to the site, extension was determined on a case-by-case basis by taking distances from the model, and the ends were fitted with a foundation connection. (See Fig. 5.22.)

Fig. 5.20: Beams arranged in order of assembly

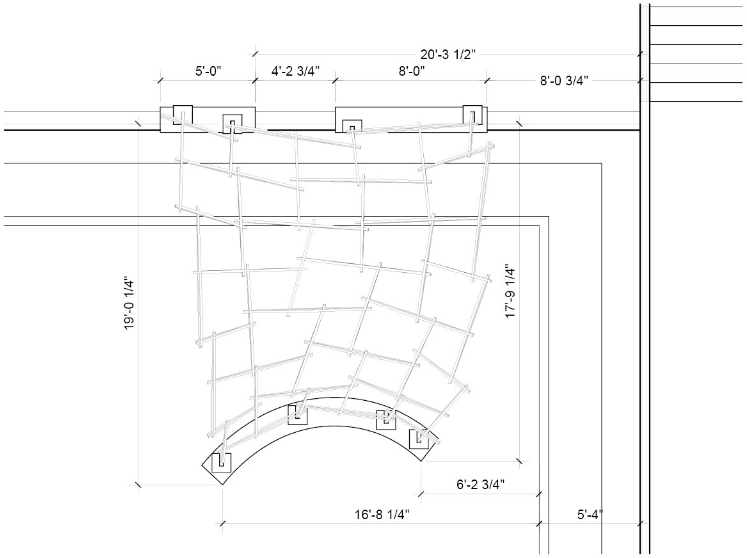


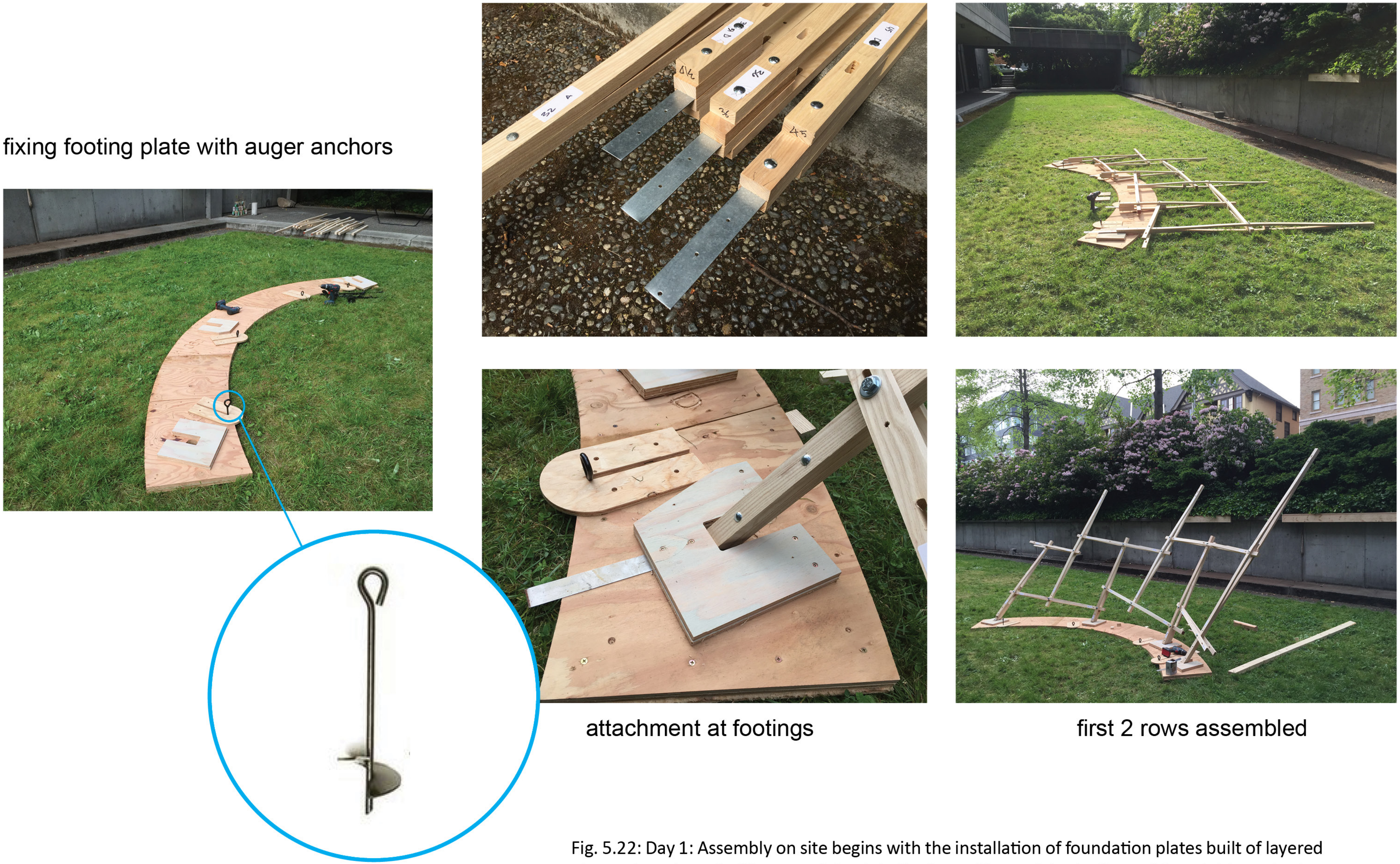
Fig. 5.21: Footing Plan

5.6 Assembly on Site

The experimental structure was assembled over the course of two consecutive days in May of 2015, but required only 4 hours of active assembly time. On the evening of the first day, foundation plates were installed according to a simple site plan (fig. 5.21) and the first two rows of beams were attached to the lower plate. The main assembly effort was carried out the following day by a team of five students. Parts were brought to the site pre-fabricated and arranged in order of assembly. Because the beams are required to flex around the interleaved joint, temporary blocks are used as temporary spacers to maintain camber prior to and during assembly. During assembly, the camber was opened with a spreader mechanism, allowing the connections to be made safely and with minimal effort.

Assembly order was determined by row, working from the south footing on the lawn to the north footing, which was fastened to the cap of the retaining wall. Connection of each joint required the attention of 2 people, one to support the piece being attached and one to position the joint and insert the fastener. As successive rows were raised incrementally into position, the internal forces of the structure became noticeable. Compression in the outer north-south members caused some difficulty in making connections, requiring an additional helper to bring beams into position for fastening. While some worked on ladders to make these connections, others passed beams and fasteners from the ground to facilitate the process.

Scaffolding was minimal, but important in assembling the installation. Simple 2x4 lumber was used, and this was clamped to the nodes wherever needed using height values on the assembly diagram to locate the structure on the support. At most, 4 supports were in place at any time, and these were used only to keep the structure up, the final form being generated entirely by the interaction of length parameters in the assembly and the location of anchor points at the footings.



fixing footing plate with auger anchors

attachment at footings

first 2 rows assembled

Fig. 5.22: Day 1: Assembly on site begins with the installation of foundation plates built of layered plywood, anchored with auger stakes into the lawn. These plates both provide a stable anchoring surface and locate the edge points of the frame relative to one another, expediting the installation process. Edge points that connect to the foundations are fastened using simple buttressing blocks and steel straps to withstand both lateral compression and uplift.

3 rows / 3 supports

4 rows / 3 supports

5 rows / 4 supports

6 rows / 4 supports

bridging to wall plates

attaching final row

Fig. 5.23: Day 2: The structure is assembled in rows, working from one footing to the other. The first two rows are able to cantilever off the foundation plate, but successive rows require support during assembly. Simple scaffolding posts serve to support the structure as it takes shape, but do not affect the final form. At maximum, 4 posts are needed to support the frame during assembly. The placement of supports is determined by node height values marked on an assembly diagram.

Fig. 5.24: Assembly team, left to right: Siddharth Jadhav, Calder Danz, Alden Mackey, Winston Davis, Michael Riha, Lokeshsingh Masania (photo credit: Dawn Cleveland)

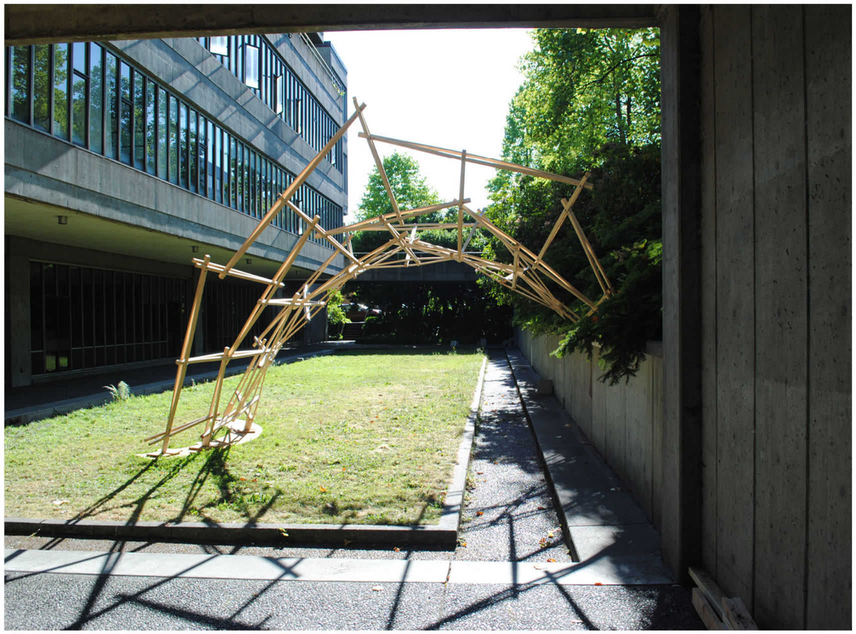


Fig. 5.25: The finished installation is stable and true to the geometry of the model within expected tolerances. As predicted, flex is significant under lateral loading, but the material resists without any indication of failure by splitting. The interleaving of joints provides rotational resistance not modeled in the FEA process. This contributes to the resistance of rigid motions at the outer edges of the frame.

Fig. 5.26: Disassembly provided further insight into the structural requirements of the assembly. Releasing the south footing plate from the lawn, the structure did not appear to be placing significant compression or uplift on the footing. The plate could be moved, but the structure resisted this action. After releasing the north plates from the wall, the entire structure was lifted from its footings and placed on the lawn. As the scale model had done, the frame maintained its form to a great degree. Rotational resistance provided by the interleaved joints prevented the grid from twisting significantly as the model had done. When the outer edge members were removed, the grid was able to lie almost completely flat. This suggests that compression in the border of the frame was largely responsible for its form.

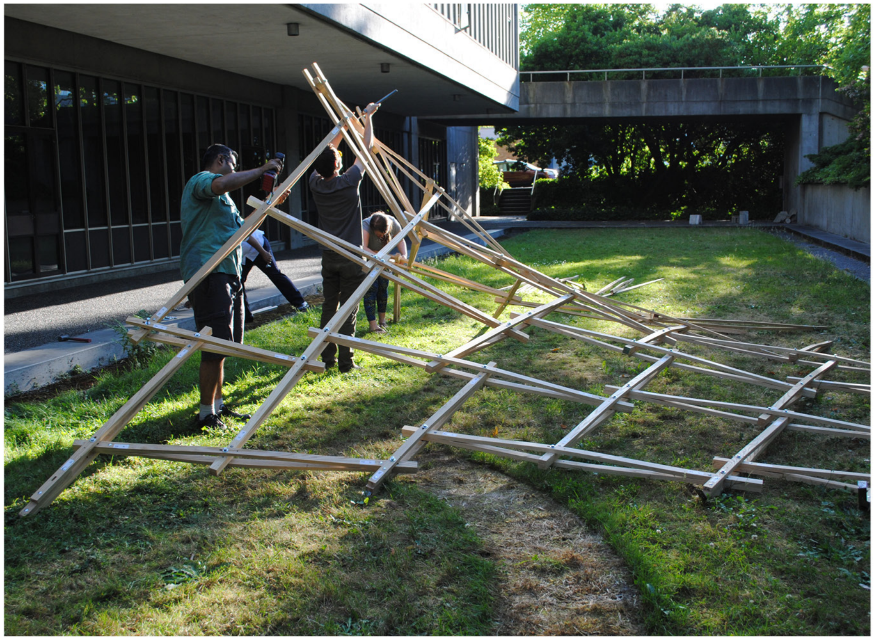


Fig. 5.27: The pavilion's hyperbolic geometry is generated by the interaction of unique beam lengths, and requires no false-work to create curved edges.

Fig. 5.28: A conventional framing plan for a hyperbolic paraboloid roof follows common rules of beam hierarchy.

5.7 Evaluation

The pavilion installation was valuable in many ways. It demonstrated that this process of form-finding can produce stable frame geometry, and that the pre-fabrication and assembly approach provides an efficient construction workflow for this type of geometry. Building at full-scale allows observation of phenomena that are not apparent at model scale or in the digital environment.

The hyperbolic form generated by the script for this installation is a doubly ruled surface. This shape class has been used repeatedly in architectural design for its tectonic rationality and visual interest. Typical hyperbolic paraboloid vaults are built by orienting a rectangular grid of beam members along the edges of a non-planar quadrilateral boundary such that the successive rotation of beams approximates the HP form. This technique can be used to create tension structures, one-way beam assemblies and form-work for concrete shells (Christiansen 1988.) The novel difference between previous methods used to rationalize the HP and the application of reciprocal beam geometry to the shape class is the efficiency of material and labor gained through tectonics. In many ways, these are the same benefits seen in the application of the RF to other building geometries. Traditional methods of HP roof construction have required lengths of material capable of spanning the entire width of the boundary on their particular axis. The hyperbolic form of this RF assembly is generated without a complete boundary and with beam elements much shorter than the span of the structure. Furthermore, the boundary of the form is curved and asymmetric, but does not require the fabrication of custom curved edge beams.

Geometric Fidelity

After installation was completed, the structure was allowed to settle for two days. Following this period, the accuracy of the geometry was checked

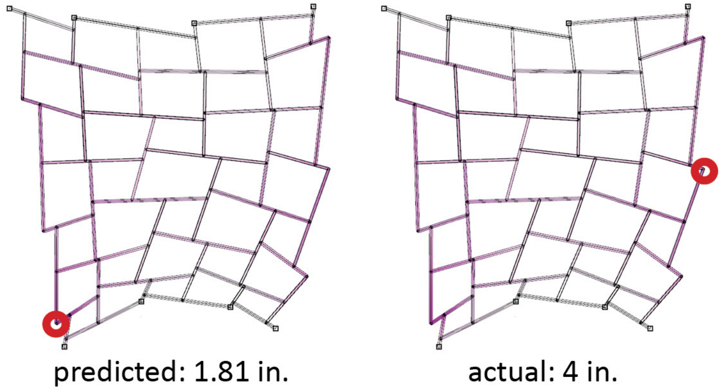


Fig. 5.29: Measurements of the finished installation show that actual deformation of the frame geometry is somewhat different than expected. This is attributed to unmodeled rotational resistance in the joinery design and greater resistance to beam deformation than modeled in simulations.

Fig. 5.30: Pattern and topology variation may add lateral stability.

against the model by measuring heights from the ground and comparing these values to the digital model. The method of comparison did not provide a complete picture, being limited to measurements in only one axis, but from this data, inferences can be made about the nuanced discrepancies between FEA results and the physical installation. Most nodes were within an inch of target height, and settled less than simulations had predicted under self-weight. The notable exceptions occurred at the free edges of the assembly, where heights diverged from the model by as much as 4 inches. This is attributed to complex force transfer in the joint design. Because the interleaved joints effectively act as rotational springs, lateral rigid frame motions were likely exaggerated in nodes placed early in the assembly sequence and the balance of that motion transferred vertically in the upper edge nodes. Results of this comparison support an argument for more robust bracing and constraint at the edge conditions.

Structural Performance

Without resorting to destructive testing, it was possible to observe that the structure bore its own weight as well or better than predicted in simulation. This was not surprising, as the simulation was set up to represent an isotropic material, defined conservatively using the yield statistics for the material's weakest axis. Lateral loading was applied, and though the frame was seen to flex considerably, material failure was not observed in the locations indicated by FEA simulations. The camber produced by interleaving joints is likely to have added some stiffness to the structure by effectively increasing beam depth in one axis at the point of greatest stress, but this geometric nuance has not been analyzed in depth. Destructive testing of future design details will offer better insights into the effects of beam shaping and joint design. Further explorations of this geometry may look at the application of tension bracing to stabilize the frame in the direction perpendicular to the span (east-west.) Other pattern topologies may offer increased lateral rigidity as well.

6.0 Summary and Future Work

The goal of this thesis has been to explore opportunities for tectonic simplicity in complex architectural geometries using the concept of reciprocal connectivity. Through analysis of built precedents and previous research, the condition of axial connectivity was chosen as a constraint case worth exploring in more depth, as this represents an opportunity for variation in other performance-dependent parameters which are otherwise controlled in assemblies with traditional joint tectonics. The product of this work is, in large part, a validation of existing structural research and a documented exploration of a very specific case in reciprocal frame design.

In both modular and variable-length configurations, the axially joined reciprocal frame is constrained to approximating surfaces of negative Gaussian curvature. In this respect, the geometry is similar to an inelastic fabric. This pre-defined shape class is limiting in the design of true free-forms. However, this correlation offers an alternative process of tectonic rationalization for hyperbolic surface geometries that presents certain advantages over conventional methods. Frames constructed in this manner can span large boundaries with relatively short beam material. Connections can be designed simply and are relatively few compared to other space frames. In contrast to HP vaults constructed using the properties of a ruled surface, reciprocal assemblies can produce hyperbolic forms that lack consistent rule lines.

Applicability

The simplicity of data needed to construct these forms is another advantage over conventional approaches. With simple hierarchic documentation, parts can be produced using widely available fabrication tools and assembled efficiently by a team of people unfamiliar with the particular construction logic. This, combined with the manageable size of structural elements and relatively low requirement for scaffolding, makes this niche structural form an intriguing case for disaster relief solutions and other situations requiring rapid construction of enclosures with limited materials.

Future Work

Necessary work on the RF concept has been identified in previous research, and includes investigation of cladding systems, joinery design, and scalability. In the course of this research, joint design has been considered in some detail, but many questions remain. Particularly valuable to the validity of axially joined RF structures is the ability to vary member cross-section in accordance with structural needs. Joinery that better accommodates this requirement will make this structural form infinitely more valuable, as this relates to scalability more generally as well. The use of truss geometry, cast metal fittings and other existing technologies may allow RF structures to be applies to a wider variety of applications. The synthesis of conventional overlaid RF joints with the interleaved joinery concept developed here may offer a wider range of available shape classes while maintaining tectonic simplicity.

Cladding these systems has previously been achieved primarily by use of membrane materials such as fiber-reinforced PVC sheet. The lack of planar openings in the grid poses problems when considering a paneling option. The development of panel tectonics that solve this problem will add immensely to the applicability of the reciprocal frame as an approach to complex architectural geometry. The physical models explored in this study point to the possible use of RF geometry as a means of creating actuated kinetic architectural elements. Subsequent research should consider actuation and cladding as coordinated systems, possibly with the end effect of enhancing ventilation, natural lighting or other aspects of passive building performance.

In sum, the reciprocal frame remains an interesting but esoteric structural option in architectural geometry. The benefits promised range from aesthetic interest to resource adaptability, but these are balanced by a host of complexities that constrain the application of the concept to a particular combination of unusual circumstances. The characteristically bottom-up nature of these frame systems demands early consideration in any design effort. With greater understanding of the methods by which these structures can be developed, it is hoped that the RF will become a more accessible element in the designer's palette. The form-finding methods described in this thesis aim to illuminate practical applications of this concept to complex geometry while remaining true to the tectonic simplicity of its origins.

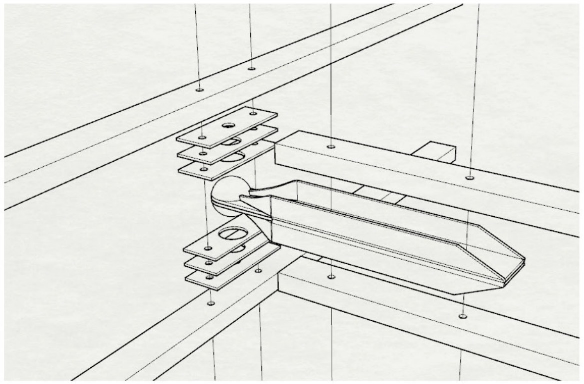


Fig. 6.1: More sophisticated modular joinery adds complexity to the system, but may allow for variation in member cross-sections.

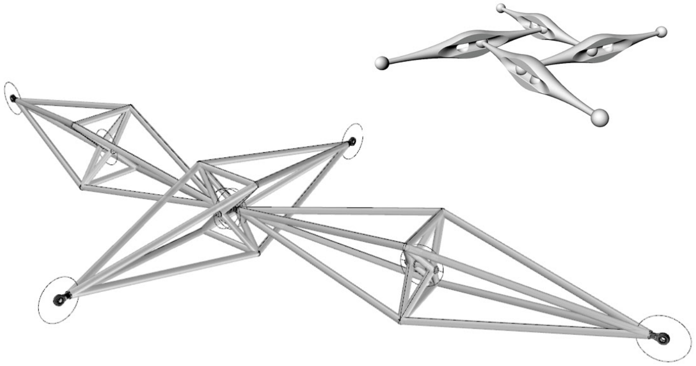


Fig. 6.2: Scalability requires exploration of unit geometry as a structure within the larger frame assembly.

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