Decoding Details

Integrating physics of assembly in discrete element structures

by

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Architect
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Submitted to the Department of Architecture
In Partial Fulfillment of the Requirements for the Degree of

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Abstract

Architecture is intrinsically the coordination of parts to form a whole, and the detail is the critical point where this coordination is resolved. Between technical and perceptual constraints, details are geometrical solutions and organizational devices that negotiate physics, construction, assembly, materials, fabrication, economy, and aesthetics, all at once.

Over centuries, detail formulas have been created, tested and revised by builders, architects, engineers and fabricators; collected in catalogs and magazines, they have been usually documented in two-dimensional sections that silence all intervening forces. While masters with knowledge in construction and materials are able to iterate through different possibilities creating novel details, usually less experienced designers can only reproduce standard solutions. In the era of digital design and fabrication, where material and building information can be parametrically linked and massively computed, can we challenge what we can build with a new way of looking at details?

This thesis introduces the concept of *synced detailing*, where conflicting constraints are resolved in the details. As a case study, stability and assemblability are studied on a structurally challenging discretized funicular funnel shell. The goal is to eliminate scaffolding during assembly using only joint details. Finite element (FE) analysis is performed at every step of the assembly sequence to show global and local instability. Local translation freedom (LTF) analysis shows the range of feasible assembly directions. Detailing knowledge is studied and encoded in shape rules to create a *detail grammar*. Real time visual feedback of the constraints informs the designer to apply these rules to create joints that satisfy across a range of priorities. This method is generalizable for other constraints, allowing architects to create novel solutions informed by quantifiable analysis and encoded knowledge.

Keywords: details, discrete element structures, assembly, funnel shell, digital fabrication

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1. Introduction

This thesis presents a new workflow for designing details digitally. How do the ways in which we describe something affect the possibilities of that thing? In the context of architecture, one of the motivations of this thesis is to understand how descriptions help us coordinate different design moves in pursuit of meaningful design possibilities. This chapter motivates and states this problem in detail, and introduces the main case study and organization of the thesis.

1.1 Role of detail in architecture

Architecture scale is inevitably achieved by the organization of diverse materials, technologies and goals. Vittorio Gregotti describes it as an assemblage of parts in different states of evolution (Gregotti, 1996). We could argue that architecture is intrinsically the coordination of parts to form a whole, and the detail is the critical point where this coordination is resolved (Figure 1).

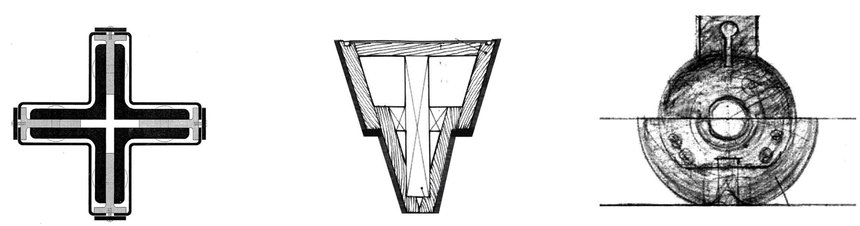


Figure 1. Three master detailers: Mies, Wright and Scarpa. (a) Ludwig Mies van der Rohe, Cross steel column detail, Barcelona International Exposition Pavilion, 1929, (b) Frank Lloyd Right, Rood Detail, Hanna House, 1936, and (c) Carlo Scarpa, Detail of candelabrum, Chapel of the Brion Cemetery, 1969-1978.

1.1.1 Detail as coordination of knowledge

Dennis Shelden defines detail as a point of collision of building information (Shelden, 2014), and we can also add that this necessarily comprises different kinds of knowledge: knowledge of construction, of structural performance, of materials and weathering, of sequence of assembly, economy, aesthetics, etc. Details necessarily resolve (for good or for bad) this coordination of different goals in one unique, single solution (Figure 2).

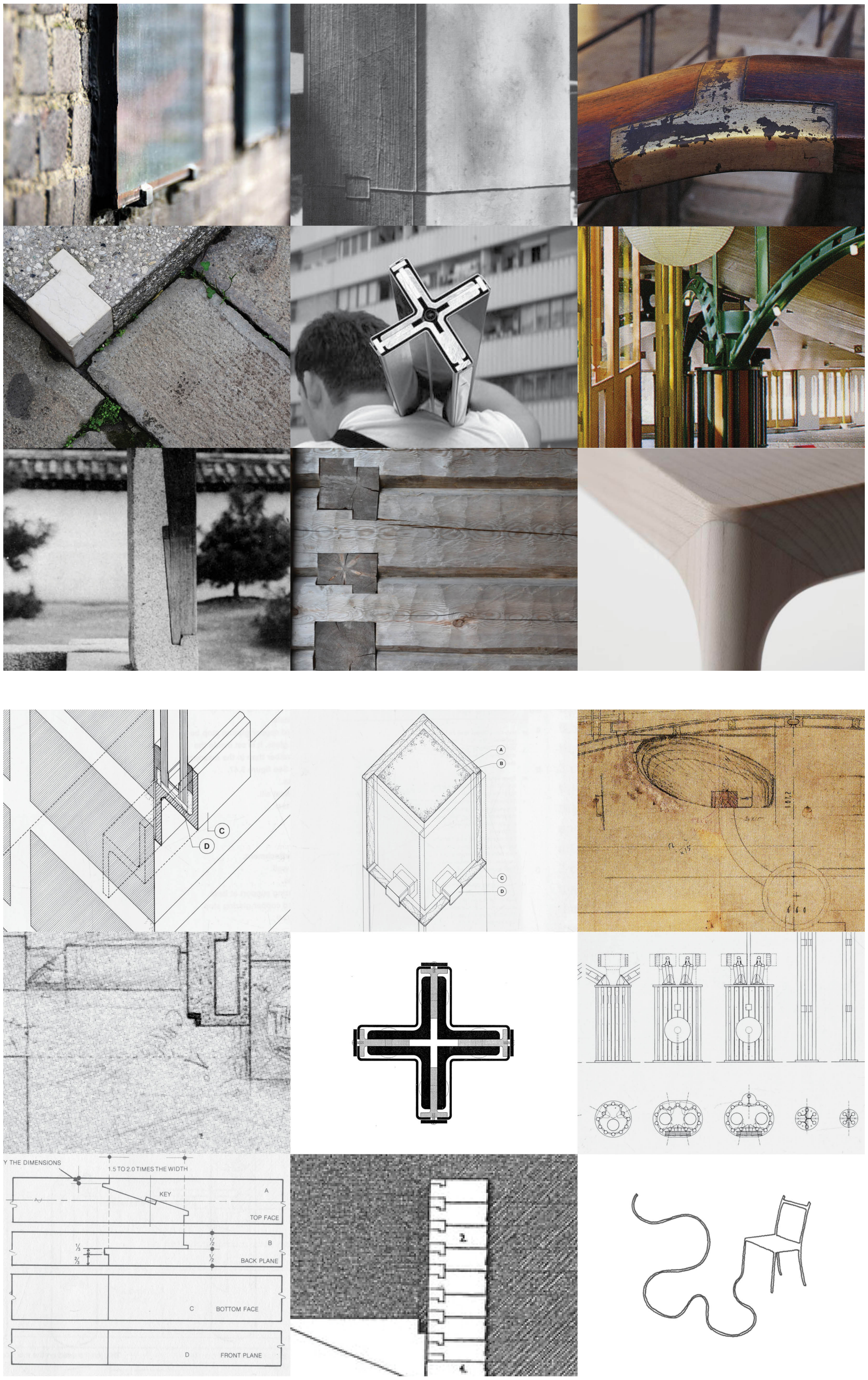


Figure 2. From left to right: S. Lewerentz, St. Peter, 1963-66; S. Lewerentz, St. Knut, 1943; C. Scarpa, Fondazione Querini Stampalia, 1963-66; C. Scarpa, Fondazione Querini Stampalia, 1963-66; M. van der Rohe, Barcelona Pavilion, 1929; A. van Eyck, ESTEC Complex, 1984-1989; NA, Japanese joinery; OOPEAA, Kärsämäki Church, 1999-2004; Nendo, Chord Chair, 2009.

In Kenneth Frampton words, details are a compound of knowledge and imagination (Cadwell, 2007). While masters with knowledge in construction and materials are able to iterate through different possibilities creating novel details (Figure 3), usually less experienced designers can only reproduce standard solutions.

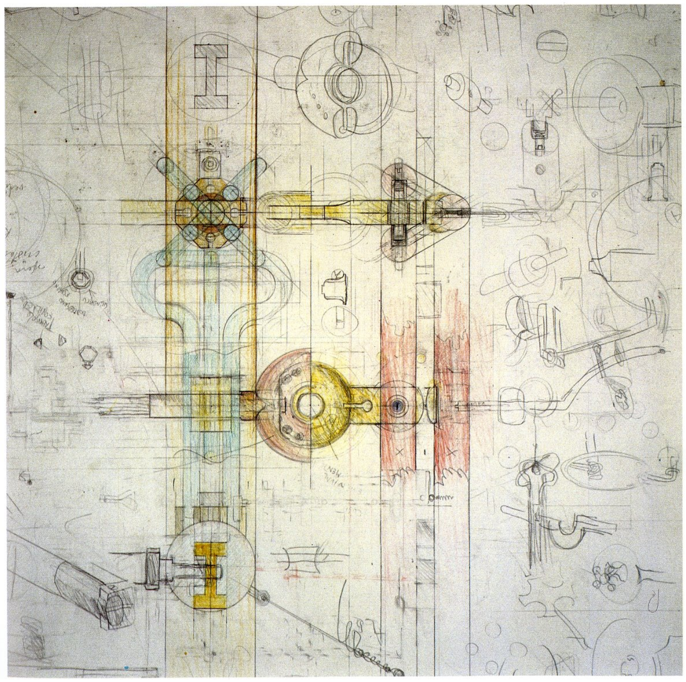


Figure 3. Detail as coordination of knowledge. Carlo Scarpa, Study for the detailing of the candelabrum in the chapel of the Brion Cemetery, Pencil and crayon on Bristol board, 1969-1978.

1.1.2 A new way of looking at details: ubiquity

In contrast with the theme of this thesis, one can consider the problem of ubiquity in common modes of construction. For example, the rivet, a modern fastening strategy that allows for the construction of many large structures, nevertheless also communicates an excess of material and indifference of placement in terms of the properties of the two edges it joins (Figure 4).

This thesis is a critique of the way details have been considered and treated for the last century; a way in which one prescribed geometry is applied extensively to any assembly challenge disregarding manifest differences among parts.

Figure 4. Ubiquitous solutions to construction problems. Alfred T. Palmer, Riveting team working on the cockpit shell of a C-47 heavy transport at North American Aviation, 1942, Library of Congress.

As a counterexample, we have the sutures of the human skull, which are made of fibers that grow and develop during the first years of life. In the adult skull, the edge is locally designed to fit perfectly, allowing a very small amount of flexibility at the same time (Figure 5).

Figure 5. A counterexample: the sutures of the human skull. (a) The top of the skull, showing the sutures (In Albert F. Blaisedell, Our bodies and How We Live, Boston: Ginn &, 1904). (b) Parietal bone of the human skull, inner surface (In Diana C. Kimber, Anatomy and Physiology for Nurses, New York: The Macmillan Company, 1907).

1.1.3 Challenges and opportunities of digital detail descriptions

In the age of new fabrication and construction workflows, such as factory-to-file (Marble, 2012), how can we apply these digital strategies for the benefit of detail design? The solution to this new availability of information is not to automate a ubiquitous detail strategy but to isolate the ability for designers to engage with things that we don't typically design. Now in the age of digital design and fabrication, how can we use digital descriptions to explore details meaningfully? Can we ask the detail to solve more things, and to be more responsive, and more expressive, and less indifferent now that we have new available descriptions?

1.2 Detail in context: self-supporting structures as a case study

This thesis looks at the principles of physics and assembly in the context of discrete element structures. For this purpose, we will design and assemble a large scale precast self-supporting concrete structure, more specifically a funicular funnel shell, which works as a fruitful context to study details where physics and assembly constraints are explicitly challenging, and consequently where the detail can play an important role (Figure 6).

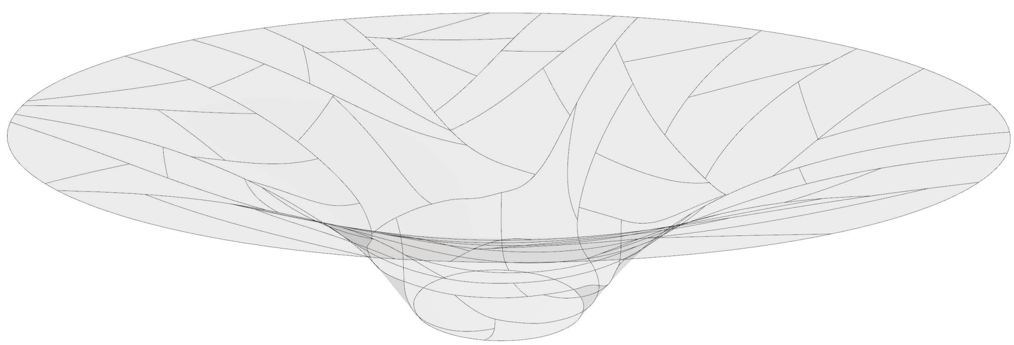


Figure 6.Discrete funicular funnel shell.

1.3 Organization of thesis

This thesis presents a new computational strategy for designing details informed by local and real-time analysis of structural and assembly results. In chapter 1, this thesis argues about the need of new detail strategies by presenting the limitations of current detail approaches. In chapter 2, this thesis presents a revised literature on detail definitions, strategies and main modes of access to detail knowledge. In chapter 3, we introduce the synced detail framework, which presents the steps of the new computational strategy for designing details. In chapter 4, the results of the application of the framework are exposed and discussed, opening a series of promising future work. Chapter 5 summarizes the contributions of the thesis, and discusses potential impact and a range of possible directions for future work.

2. Literature Review

2.1 Detail: a map of definitions

Details are hard to define since there are plenty of different strategies to approach them practically and conceptually (Ford, 2011). A map of definitions such as the one is deployed below, based on common architectural practice, though not intended to be comprehensive, will present the dominant of the existing interpretations of the concept of detail (the ubiquitous and the automated detail) and an alternative approach (the synced detail).

2.1.1 The ubiquitous detail

One dominant detail strategy is to extend a joining solution to all intervening parts. While this strategy is the only possible strategy for solving assemblies such as those on cars or planes that require water or airtight surfaces (Figure 3), architecture does not usually perform in the same way (Giedion, 1948). Specific locations face specific challenges, i.e. interior/exterior; roof/base; vertical/horizontal, intrinsic architectural problems that have been the basis for archetypal detail solutions (Semper, 1851). However, current contemporary algorithmic design and fabrication processes are shifting these prototypical conditions into continuously diverse conditions (Gramazio & Kohler, 2014).

There is a simplistic solution to this diverse behavior of the edge: the oversize. Supported by calculation limitations and standardization ideals, this strategy has modern and contemporary precedents (Figure 7).

Figure 7. ICD Institute for Computational Design: Achim Menges. ICD ITKE Pavilion 2015-2016.

Today we have overcome the calculation limitation and we are able to define the level of detail of any analysis we could wish to perform, but we still maintain some aesthetic ideals that do not correlate with our computation capacity.

2.1.2 The automated detail

One of the latest computational developments in detail strategies is the one introduced by Building Information Modeling (BIM), implemented as a digital communication tool in the early 2000s (Autodesk, 2002). Over the last decade, we have seen the growth of BIM making communication between designers, specialists and contractors more reliable and efficient. However, BIM has impregnated design offices as a dual tool: as a sharing platform and as a drafting tool, while it was conceived only as the former (Eastman, 2011). The automated detail strategy, such as the one generated by BIM software (i.e. Tekla Structures) as shown in Figure 8, respond to pre-defined detail rules as the ones we encounter in detail catalogs. The strategy finds its limitation in the nature of the input model, which predefines the array of all possible solutions. The automated detail is the result of an extrapolation of a communication tool into a design tool.

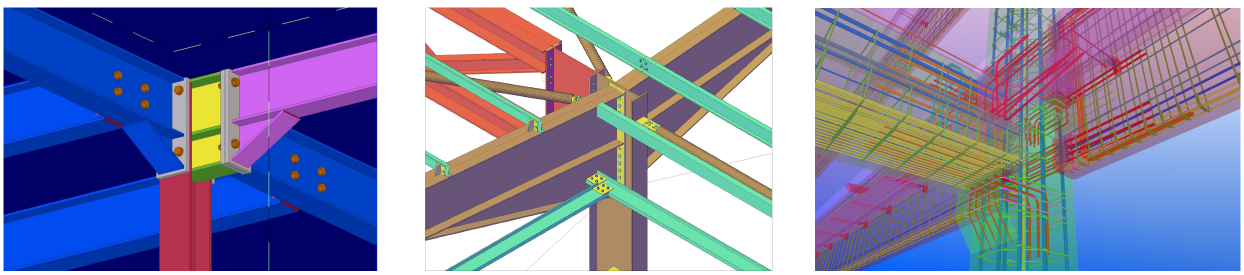


Figure 8. (a), (b) *Steel and (c) reinforced concrete details automatically produced with detailing software. O'Loughlin Project Engineers (a), Jensen Consulting (b), and Pittsburgh Flexicore Co. w/Tekla Structures.*

2.1.3 The synced detail

Beyond ubiquity and automation, this thesis introduces a new approach based on local and real-time understanding of constraints. Based on the now available integration of feedback loops in the design process, the synced detail framework proposes an alternative way of generating not-predetermined detail solutions that will be fully explained in Chapter 3.

2.2 Detail catalogs

A conventional form of access to detail strategies are detail catalogs, to which architects are exposed during training and common practice. These catalogs may be originated in aesthetic/stylistic ideas, in technical and material considerations, in fabrication problems, and in functional issues.

2.2.1 Style-based detail catalogs

Large firms usually tend to generate their own body of architectural details based on construction formulas that have been tested and that condense their tectonic ideals. L. Mies van der Rohe, Skidmore, Owings and Merrill (SOM), I. M. Pei (Ábalos & Herreros, 2005) are examples of large firms that have developed the curtain wall detail with small adjustments in each iteration to respond to air, water and structural requirements (Figure 9). This mode of building upon their own precedent solutions is very productive for the firm itself –there is no need to start from scratch each time, saving time, tests and having a design ready for the client on time– but the effect of this design method could be dangerous if the iteration is not taken actively, becoming a mere reproduction –which is actually what is happening in the majority of 'common practice' cases. The solutions developed are usually accessible to the firm's architects in the form of detail private libraries.

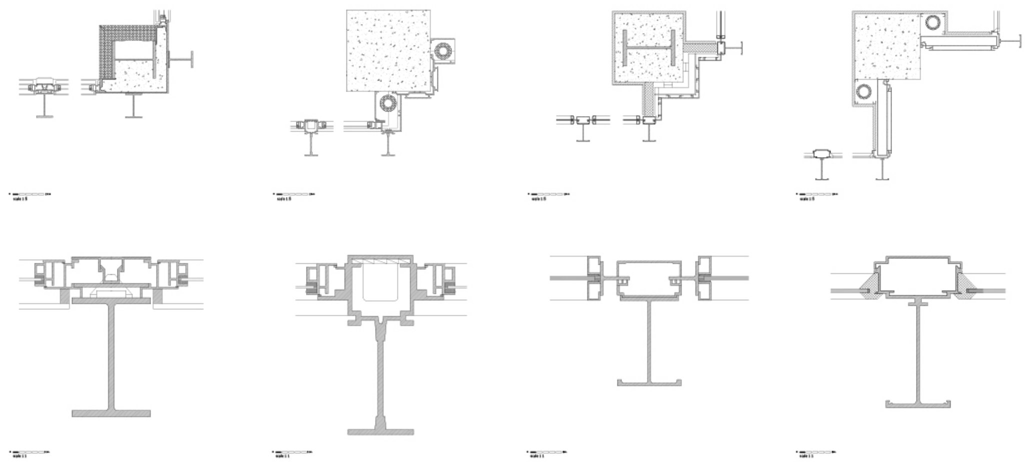


Figure 9. Ludwig Mies van der Rohe, corner and mullion solutions: 860-880 Lake Shore Drive Apartments (1949-1951); Commonwealth Promenade Apartments (1953-1956); Seagram Building (1954-1958) and Pavilion Apartments (1955-1963). detailsinsection.org.

2.2.2 Technique-based detail catalogs

Technique-based detail catalogs such as the *Precast concrete connection details: structural design manual* or *Japanese Joinery : A Handbook for Joiners and Carpenters* are very commonly used type of catalogs and a very good source for learning a specific technique (i.e. reinforced concrete or japanese joinery respectively). Usually based on traditional ways of working with a specific material, they normally lack an explanation of geometry that can teach designers how to modify the solutions presented in the volume. They work as compendiums of building knowledge developed over time. For certain techniques, numerical information is included to specify the minimum and maximum values of common parameters (i.e. minimum length of steel inserts for reinforced concrete). Still, these manuals usually lack the background explanation of the geometric principles and reasoning why a specific geometry is used, making it difficult to understand how to move beyond the solutions specified in the volume.

2.2.3 Fabrication-based detail catalogs

An interesting group is the catalog defined by the way details are executed: these include forms of production that are not a defined craft in itself (otherwise they would become a technique), such as the use of a particular tool across different types of materials or specific application – they could be used for any scale, application or purpose. Typical examples of this kind of catalogs are tool's manufacturers catalogs or detail compendiums (Figure 10).

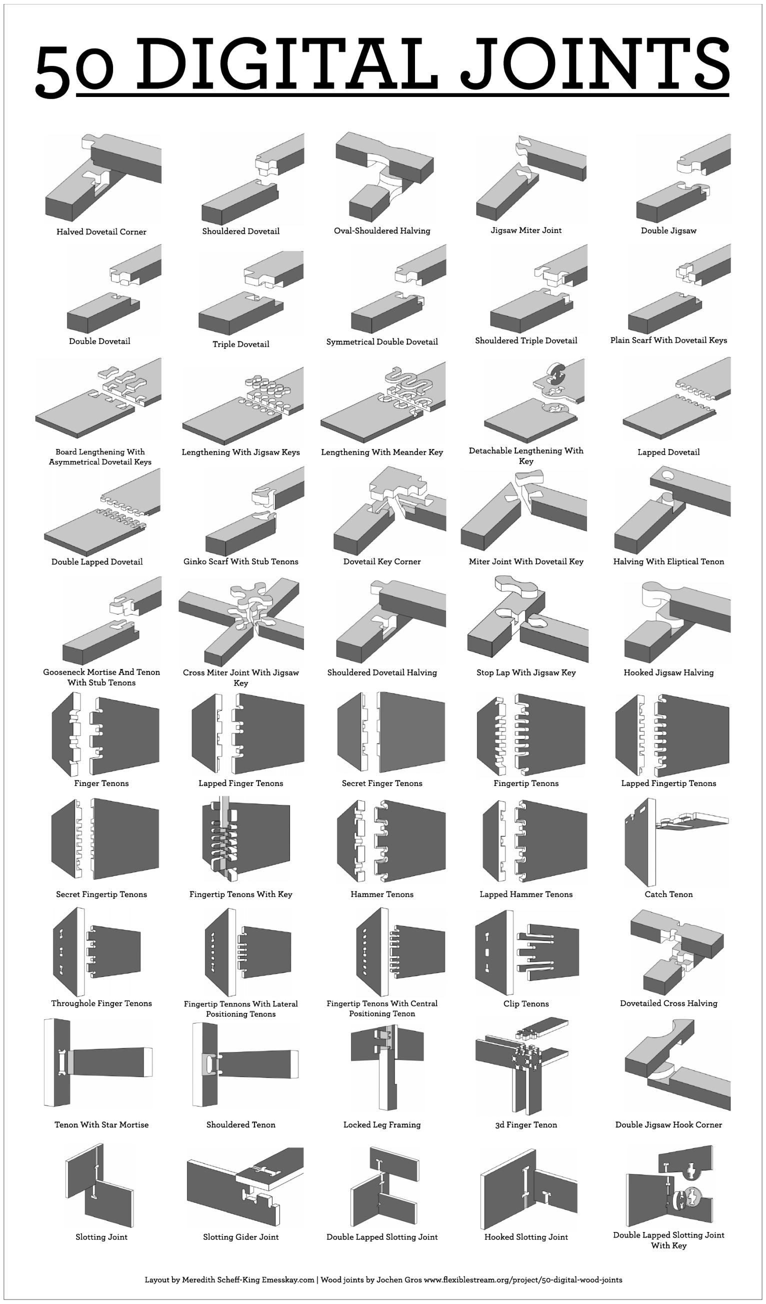


Figure 10. Jochen Gros, Meredith Scheff-King, 50 Digital Joints.

The introduction of industrial robots in architecture in the last decade has opened a new perspective on fabrication techniques. The results of the last ten years of research focused on the application of robots developing new digital fabrication techniques (Gramazio Kohler Research at ETH and the Institute for Computational Design at Stuttgart University) have shown the limitless possibilities of a generic and hackable tool, the robotic arm. While most of the research has focused on developing new material systems and assemblies by novel material deposition and design to construction strategies, less attention has been paid to the development of algorithmic coordination between design, material and machine information through innovative detail strategies (Figure 11).

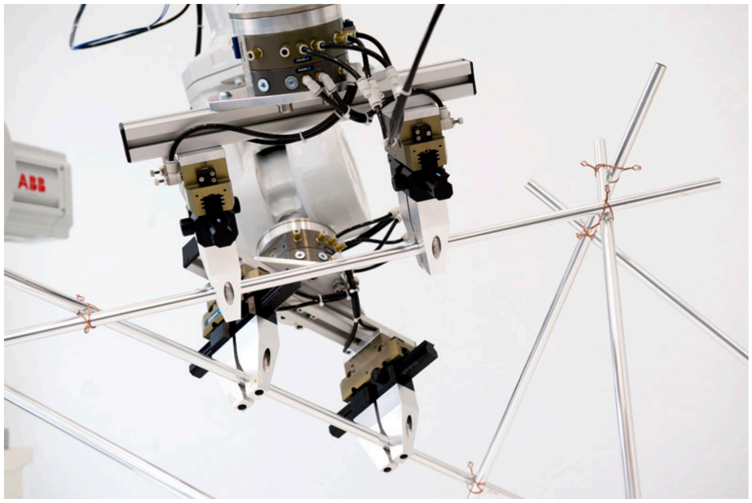


Figure 11. Gramazio Kohler Research, Design and assembly of lightweight metal structures, 2014-present.

2.2.4 Function-based detail catalogs

Functional or detail strategy-based catalogs are a useful type of catalog thanks to their adaptability to different fabrication, tool and material conditions. They present solutions described in terms of goals. They are a catalog of strategies rather than a catalog listing specific solutions. An example of this last approach is Allen's *Architectural Detailing* (Allen, 2007), which has been useful for the development of this thesis thanks to its clear definition of detail's patterns.

However, the way these catalogs are currently described is outdated, and their application to current algorithmic workflows is not clear (Marble, 2012). A more useful version of function-based catalogs would include an explanation of geometric strategies (and their supporting parametric definitions) rather than just an explanation of common patterns.

2.3 Detail descriptions

The way we describe something defines the space of possibilities of that thing. In other words, the way in which a problem is formulated defines the scope of possible solutions to that problem. Drawing an analogy between problem formulation and design description, we are interested in understanding which methods are the most optimal for describing and generating novel and accurate detail solutions.

2.3.1 Cross-section detail description

The most extended type of detail descriptions is the 2D cross-section drawing. Since the invention of descriptive geometry, technical drawings have been the main medium of communicating building information (Allen, 2000). Cross-sections, also called just sections, are most commonly generated in 2D medium such as paper or a 2D drafting software, although 3D software such as BIM includes specific detailing functions in 2D.

Cross-sections excel at communicating information such as relative distances and the position of parts (Figure 12). The intelligence of a detail cross-section is in its isolation of information. While an appropriate method for communicating information, cross-sections can be very restrictive for assembling different types of information, such as forces, kinematics, etc., and consequently limit the possibility to be an appropriate medium for comprehensive detail solutions.

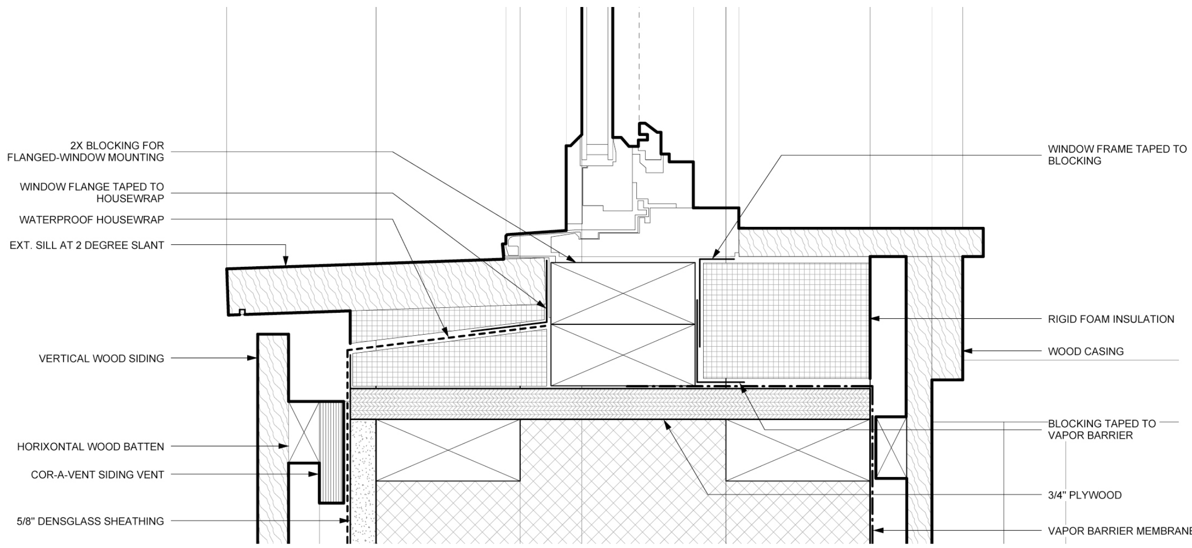


Figure 12. Building Type, Near Passive House: Typ. window head and sill detail [Section from Revit Model], 2012.

2.3.2 Rule-based detail description

Explicitly representing ideas that are usually treated intuitively is the basis of every computational strategy (Woodbury, 2010). In the context of detail descriptions, we are interested in finding accurate and flexible description methods that can serve to explore the space of detail possibilities according to determined problems.

Rule-based approaches or grammars are systems that can be used to generate form across typological solutions (Mueller, 2014). As first introduced by Stiny and Gips in 1972 in a design context, the ability of shape grammars is the unlimited and unpredicted number of solutions that can result from the combination of simple geometrical rules. For our purposes, rule-based approaches are useful in two ways: (a) they are compoundable –they can be freely combined to produce infinite number of solutions- and (b) they are extendable –the system can be expanded at any step of the process-, making them a perfect system for design.

2.4 Precedents: shells and self-supporting structures

Previous developments of shell structures in the 50's and 60's with figures like Candela, would rely on surface continuity to achieve performative complex structures (Figure 13a). The downside of assuring performance through a continuous cast is that for best results the structure needs to be poured all at once. This means that we need a large area of continuous scaffolding (which in turn translates into great amount of labor, material and time).

Currently, there is a large amount of studies looking at compression only structures (Ochsendorf, Block, Rippmann, Van Mele, Whiting, et. al). In these cases, the overall structure is discretized in elements – but the equilibrium is not achieved until the final state, which leads to also plan for supporting techniques during assembly (Deuss et al., 2014). Consequently, the question of how discretized structures can be built is still open (Figure 13b).

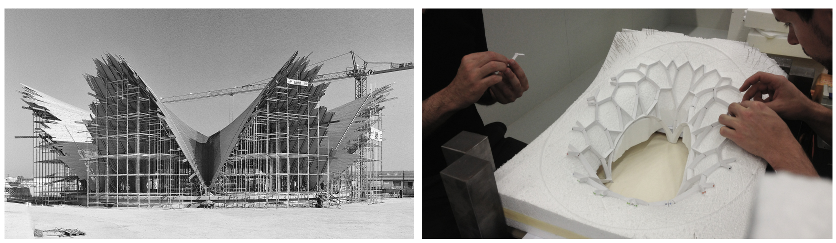


Figure 13. (a) Felix Candela (design), PERI (scaffolding), Restaurant Florante Submarino, Parque Oceonográfico in Valencia, 2002, (b) Structural scale model of a discrete funnel-shaped rib vault during assembly, Rippmann & Block, 2013.

3. Methodology: how to sync details

As described in the literature review, designers usually lack the vast and diverse knowledge in physics, construction, materials, fabrication, etc., that are necessary to develop responsive detail solutions to non-standard geometric conditions. This chapter proposes a new approach to generating details based on in-sync analysis of local conditions. While the method is generalizable to other constraints, this research focuses on the stability and assembly constraints.

3.1 Framework overview

The synced detailing framework includes 5 steps illustrated in Figure 14 and developed below in points (3.2) global form and discretization, (3.3) stability analysis, (3.4) detail design, (3.5) assembly check, and (3.6) materialization.

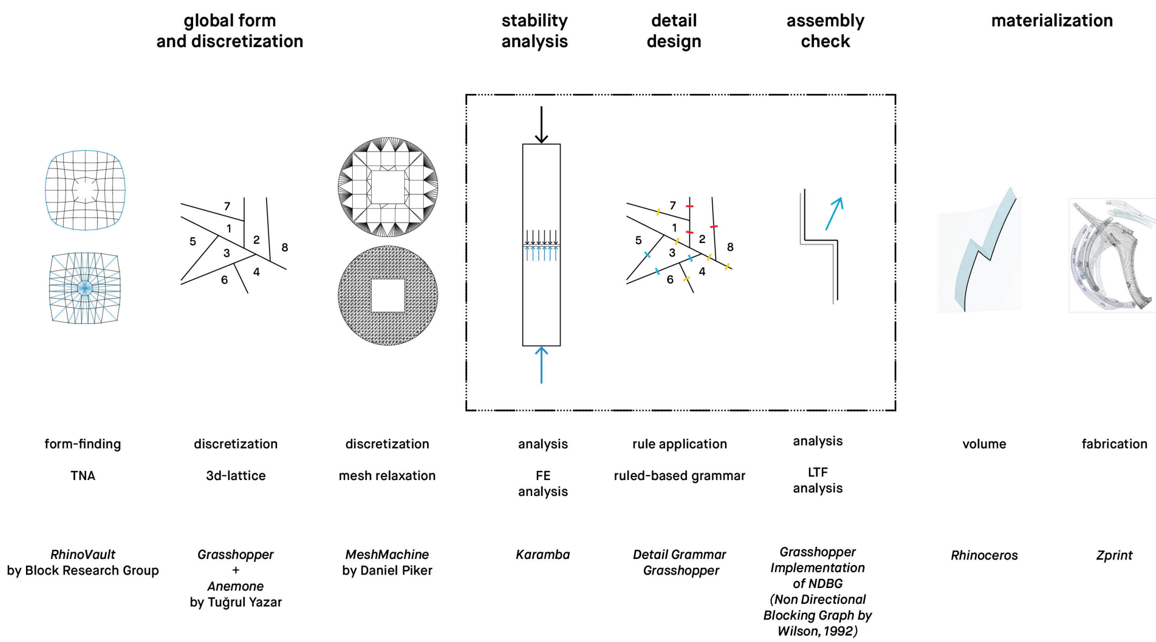


Figure 14. Framework: (3.2) global form and discretization, (3.3) stability analysis, (3.4) detail design, (3.5) assembly check, and (3.6) materialization.

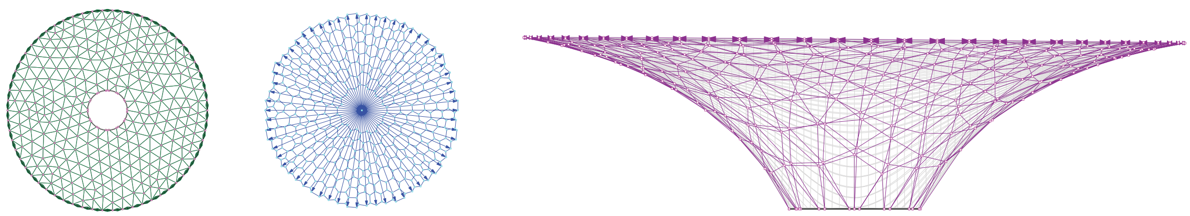
3.2 Global form and discretization

Although the contributions of this thesis are not focused on geometry generation at a global scale, the question of how the global geometry of a structure is generated and what relation does it establish with the local or detail geometry is a relevant one. In this thesis, the method assumes an overall geometry in which the global stability is guaranteed (3.2.1) and a non-rational discretization that creates variable edge geometries (3.2.2) to serve as test case.

3.2.1 Global stability

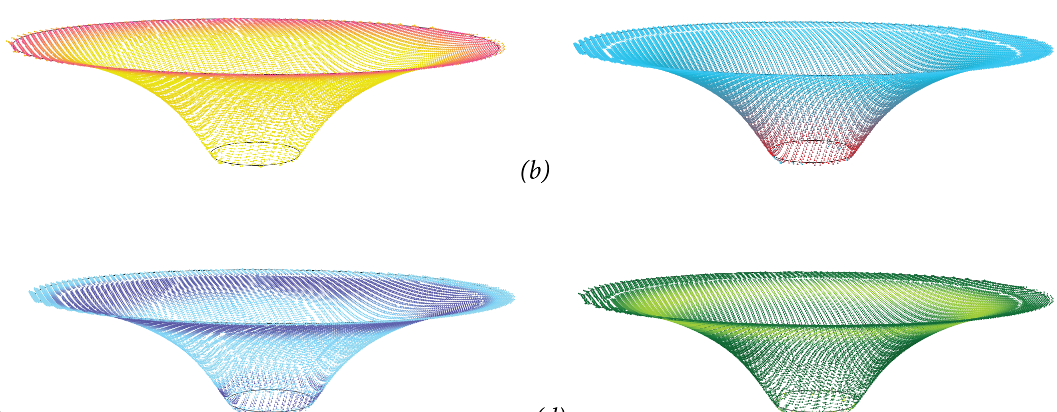
As stated in the previous section (3.1), the synced detailing framework supports any type of geometry. To illustrate how the framework works, a discretized funicular funnel shell will be used. Figure 15 shows the funnel shell case study achieved via a funicular form-finding interactive tool based on thrust network analysis (TNA), RhinoVAULT (Rippmann & Block, 2012).

Funnel shells are compression-only structures combined with tension rings on their open edges. The efficiency of these structures relies on their load-bearing, or axial force, capacity (Rippmann & Block, 2013) that is an alternative efficient strategy to carrying load through the bending capacity of the material. The study case is a 20 in. diameter and 5 in. height structure, supported by a 4 in. diameter base and continuously tied with a tension ring at the open higher edge.



(a) (b) (c)

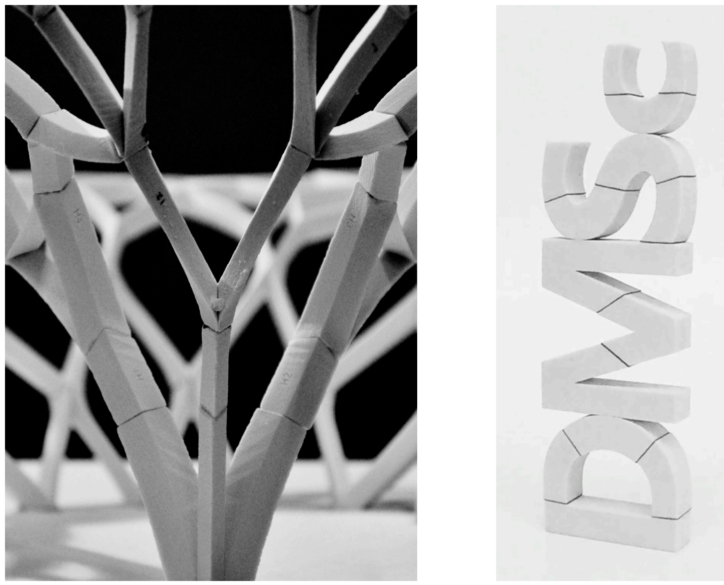
Figure 15. Funnel shell included in this research as a case study. (a) form diagram, (b) forces diagram, (c) 3D result and interpolated surface between points.



(a) (b) (c) (d)

Figure 16. Funnel shell internal forces. (a) normal forces in first principal direction, (b) normal forces in second principal direction, (c) moment forces in first principal direction, and (d) moment forces in second principal direction.

Current methods based on statics and TNA assure overall stability, while intermediate equilibrium stages during assembly are not taken into consideration (Frick, Van Mele & Block, 2015). In existing case studies, discrete funicular funnel shells 'details' are plain parallel interfaces that maximize compression forces (Figure 17).



(a) *(b)*

Figure 17. Existing case studies which do not take into consideration intermediate equilibrium stages. (a) Structural scale model of a discrete funnel-shaped rib vault (Rippmann & Block, 2013) and (b) discrete element assembly in equilibrium as a result of arching, friction, and balancing, and without mechanical connections or glue (Frick, Van Mele & Block, 2015).

In addition to not including intermediate equilibrium stages, funnel shells are currently still built relying on the use of scaffolding (Rippmann & Block, 2013). Hence, the problem of how to build these structures with a consistent construction method is still open.

3.2.2 Non-rational discretization

As presented in the previous chapter, the construction of a funicular funnel shell presents a challenge at every stage of the construction sequence. Because the form finding method takes into account only global behavior, the way in which the structure is discretized has no effect on the overall stability once the structure is completely assembled. The undivided funnel shell can theoretically be discretized in any way as long as the overall form is reached at the end of the assembly sequence. While there exists current research focusing on how the discretization can play a role in assuring global stability (Frick, Van Mele & Block, 2015), these studies do not solve intermediate equilibrium stages.

In this research a random discretization method is used to generate diverse division conditions such as horizontal, vertical and any range of angle directions to force the synced detailing method to solve variable interface solutions (Figure 18). The implemented algorithm was developed by Tuğrul Yazar, and is originally inspired in the ice-ray grammar (Stiny, 1977).

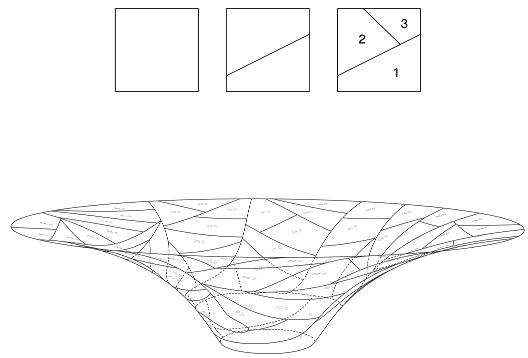


Figure 18. Ice-ray discretization of funnel shell.

3.3 Stability analysis

As explained in previous sections, the synced detail method can be applied to any type of constraint that can be accurately computed. One of the focuses of this research is the structural stability constraint. Structural stability of a structure under actuating forces is its capacity to reach a mechanical equilibrium state. The stability analysis comprises 3 consecutive steps illustrated in Figure 19: (3.3.1) assembly sequence, (3.3.2) local stability analysis, and (3.3.3) global intermediate stability analysis.

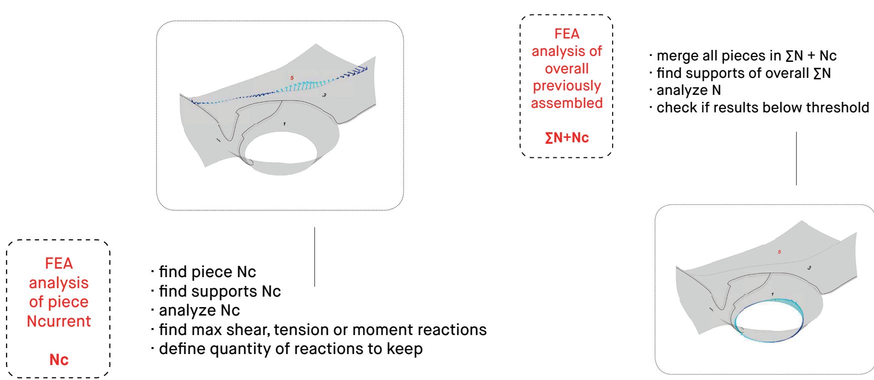


Figure 19. The steps comprised in the stability analysis.

3.3.1 Assembly sequence

Because the overall stability and discretization methods do not depend on intermediate stages, there is no pre-defined required sequence of assembly to guarantee a global satisfactory behavior. Thus, designers can re-define the assembly sequence at each stage of the design process (Figure 20). At this step, the designer defines which piece will be assembled and analyzed. In our case study the initial piece is the base piece.

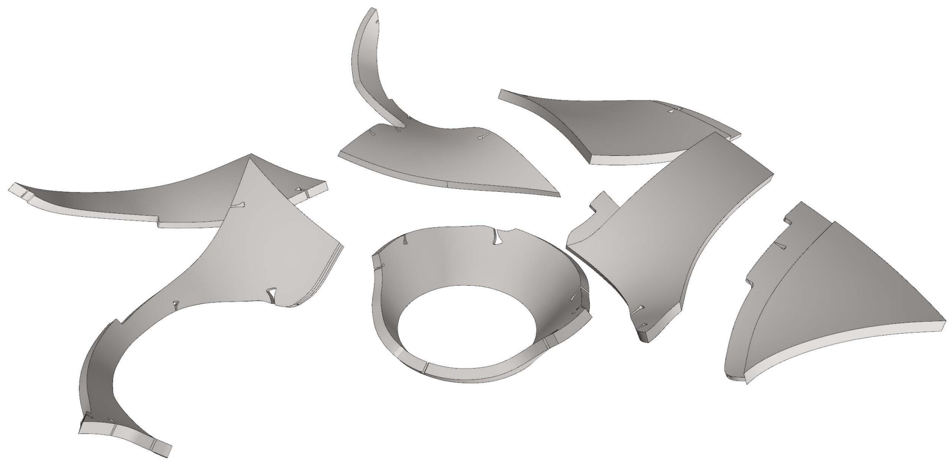


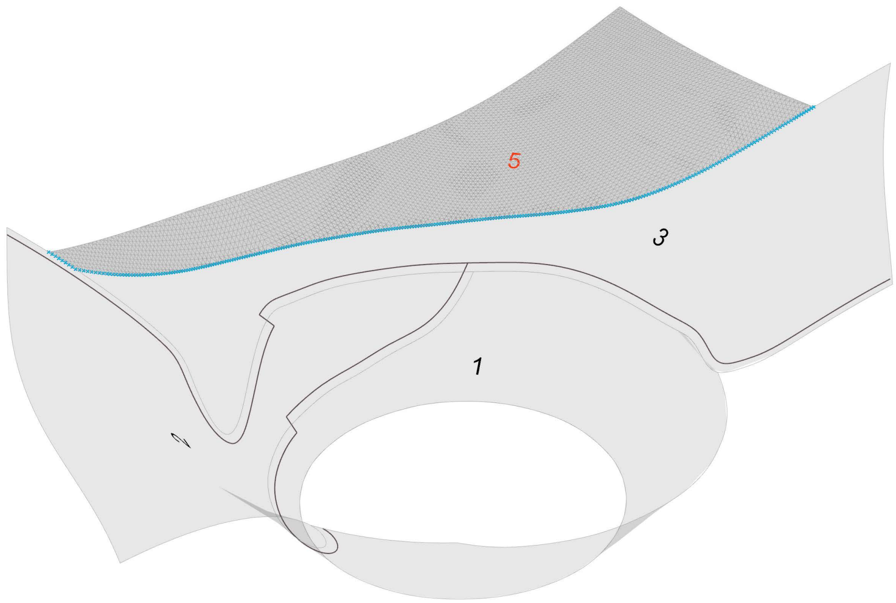
Figure 20. Designers can re-define the assembly sequence at each stage of the design process.

3.3.2 Local stability analysis

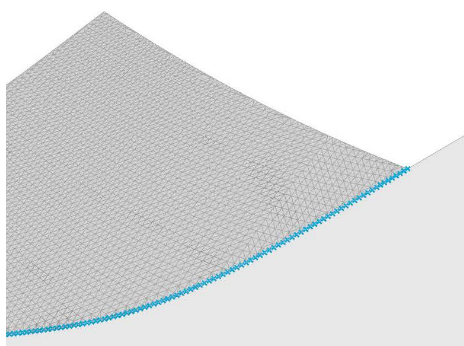
The stability analysis is performed in Karamba v.1.1, a finite element analysis (FEA) plugin for Grasshopper (Preisinger, 2013). The model set-up consists in the assembly of meshes, loads, supports, material and cross section information. This analysis only considers gravity load but it can be performed for any load condition. We are simulating results for concrete whose material properties such as Young's and shear modulus, density and yield strength need to be specified for the analysis to be precise. The assembled finite element model gives two main results that we can use: internal forces and reactions forces and moments at supports. We decide to use the latter.

3.3.2.1 Discretization for analysis

The first step in the analysis is describing the surface of the current piece as smaller discrete elements to perform an accurate FEA. For this purpose we use *MeshMachine*, a (re)meshing component of the Kangaroo Physics v. 2.02 plugin for Grasshopper. *MeshMachine* includes parameters such as target length of triangles, curvature adaptability, etc. Once the remeshing is complete, we select the boundary and naked vertices of the mesh that will be used as supports in the analysis (Figure 21).



(a)



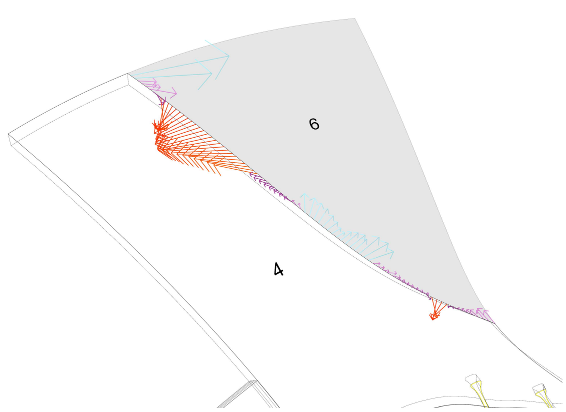
(b)

Figure 21. Meshing and selection of boundary vertices as supports of Piece 5.

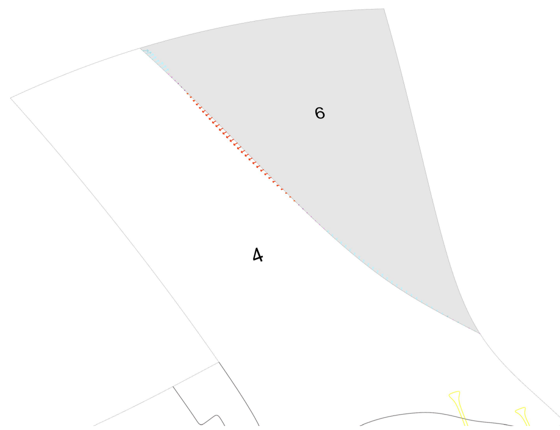
3.3.2.2 Supports

We need to define the support conditions enabling translations (*tx, ty, tz*) or rotations (*rx, ry, rz*) at points of support and identify the coordinate system of each support.

The analysis is first performed in the most simple support condition, inside the plane (*tx, ty*) (Figure 22a). In view of the results we may change the support conditions to work outside of the plane (*tz*) or incorporate rotations (*rx, ry, rz*) (Figure 22b) in order to decrease the values of reaction forces.



(a)



(b)

Figure 22. Comparison of results under different support conditions of piece 06, (a) in-plane translation supports only (tx, ty), and (b) all translations and all rotations (tx, ty, tz, rx, ry, rz).

Because our edge geometry is complex and is not simple to describe it in the global coordinate system, it is important to associate each point of support with its respective locally oriented plane (with its x and y components inscribed inside the geometry of the piece). Consequently, the results of the analysis will correspond to the support locally oriented coordinate system, important consideration for an accurate visualization of results (3.3.2.4).

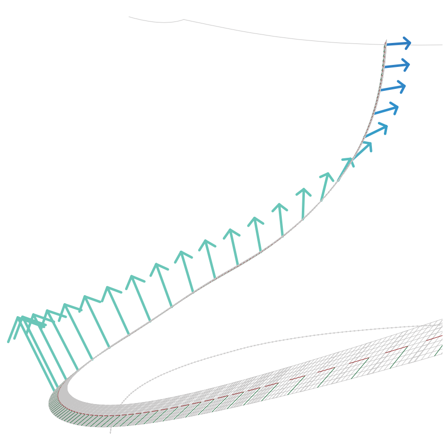
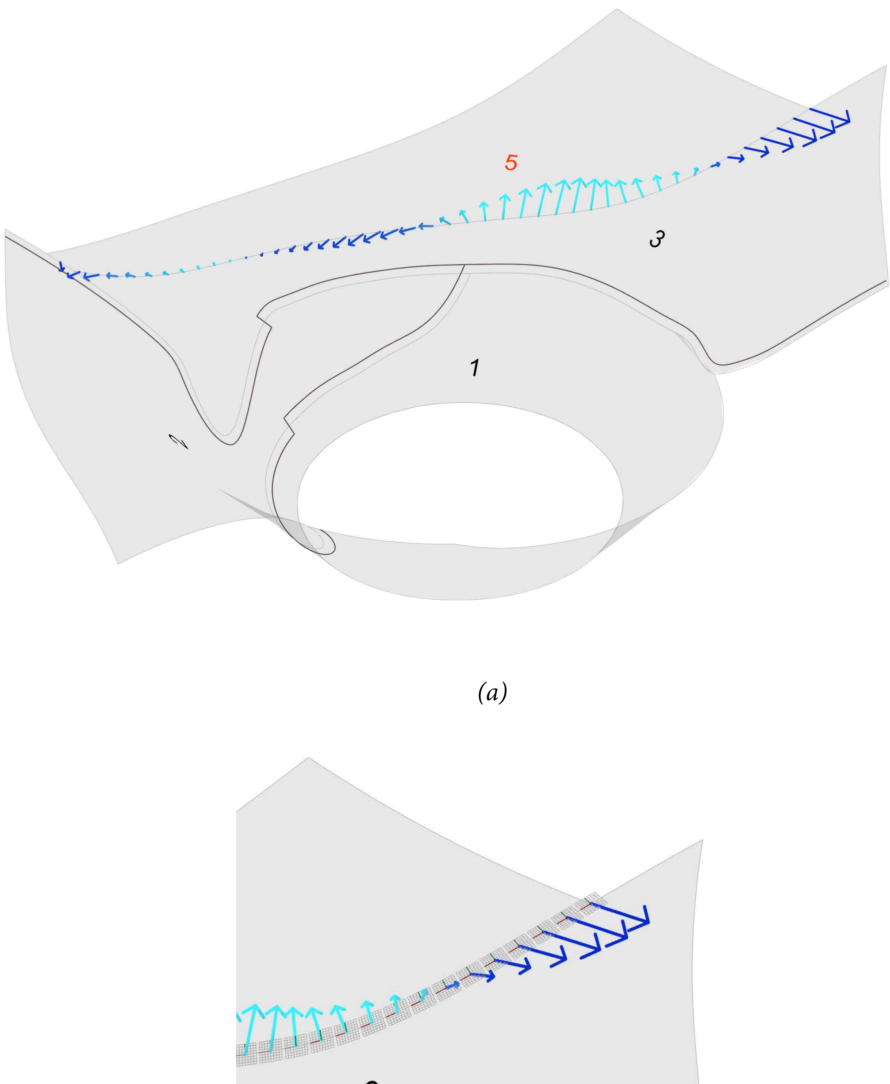


Figure 23. Orientation of points of support: locally oriented planes (correct).

3.3.2.3 Reaction forces and moments at supports (Results)

Supports cause reaction forces. Reactions forces and moments are the loads that represent the effect of supports on a rigid body preventing motions (Emri & Voloshin, 2016). The novel contribution of this thesis is that thanks to the synced and feedback analysis we can understand stability looking at the reaction forces across the edges of parts at each stage of its assembly sequence (Figure 24).



(a)

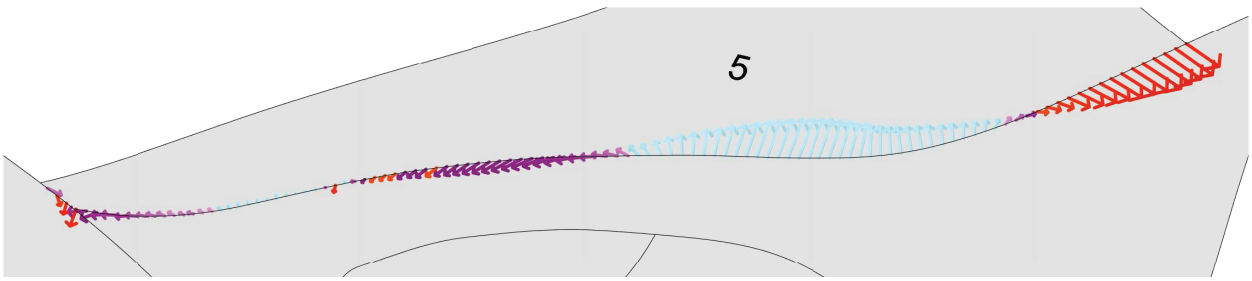
(b)

Figure 24.(a) Reaction forces at supports of piece 05, (b) detail of locally oriented planes at supports.

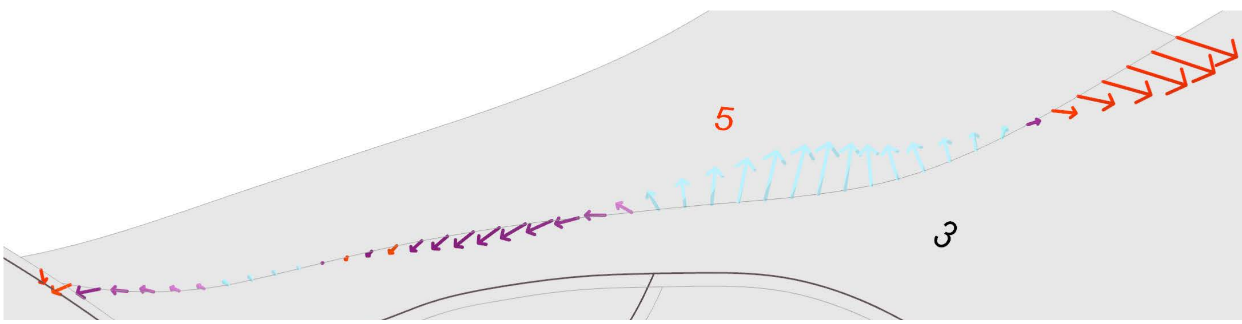
3.3.2.4 Visualization of reaction forces and moments

The essential step that allows an in-sync understanding of stability forces is the legible visualization of results. As one of the outputs of the FEA, reactions are represented as 3D vectors and, as previously mentioned, they need to be visualized in the locally oriented plane of each support. A second contribution of this thesis is how to visualize these results. We use a series of strategies: (a) average, (b) classification and (c) color.

(a) Average: a fine grain discretization for analysis (3.3.2.1) assures accurate results. However, fine grain results are easily blended and hard to read as seen in Figure 25a. To solve this problem we make an average of reaction forces and moments at a constant length of the curve edge (Figure 25b).



(a)



(b)

Figure 25. (a) Blended results without averaging and (b) post averaging.

(b) Classification: results are classified according to different goals. In this case we classify reaction forces according to its angle deviation from the *y* component of each locally oriented support, which results in an easily readable stable/non stable scheme. For a more precise understanding of stability and structural functions along the edge, we also classify results with a finer grain according to the angle deviation (α) from the *x* component of each locally oriented support according to the following subgroups: $60° \leq \alpha < 120°$ are categorized as compression forces; $120° \leq \alpha < 210°$ or $300° \leq \alpha < 60°$ are as shear forces; and $210° \leq \alpha < 300°$ as tension forces (Figure 26).

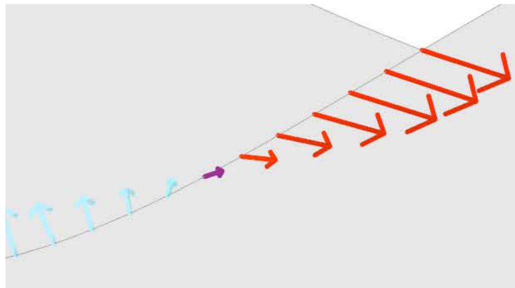


Figure 26. Classified reaction forces at supports of piece 05.

(c) Color: to make the results readable, we assign a different color to each of the classified subgroups. In our analysis: light blue (compression); purple (shear); and red (tension).

3.3.3 Global intermediate stability analysis

At each addition of new pieces, we cannot assume that the previous state of equilibrium is still valid. Ultimately, we will check every previous joint because they are all affected each time we add a joint. Although it is conceptually included in the synced detail framework, in this thesis we do not check previous assembly states. As a proxy, the stability of the global intermediate or the sum of all previously assembled pieces at the base is checked at every stage. The steps of this analysis are the same as described in 3.3.2 (discretization, supports, reaction forces and visualization) (Figure 27).

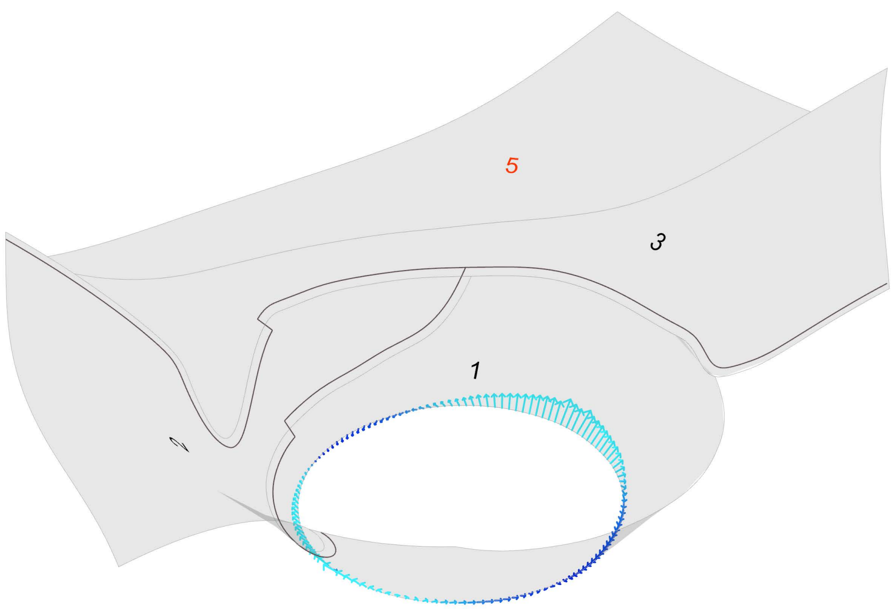


Figure 27. Reaction forces at base after assembly of piece 05.

3.4 Detail design

As presented in Chapter 1, details can be defined as organizational devices whose role is to coordinate different, usually conflicting, constraints. This thesis proposes to use this conflict as an opportunity for design.

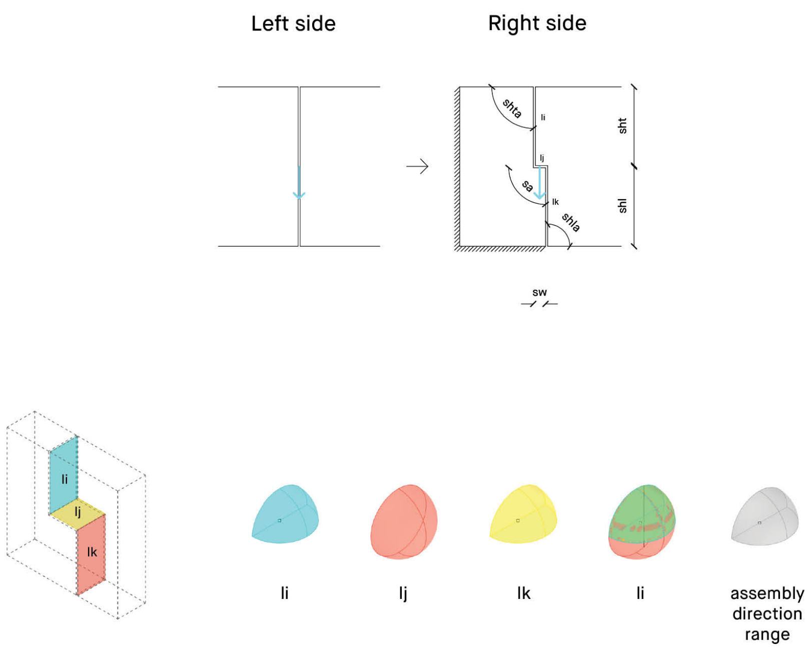
In our case study, the conflict to be resolved is the instability of a piece. While we could use the ubiquitous detail strategy to erase the presence of conflict once and for all, we introduce an alternative, the synced detail strategy, which takes into account the nature, location and scale of conflict constraints to be solved. The next step in the method is to find a generative tool for designing details that can be adaptable enough to any nature, location and scale. For this purpose, we propose to use a detail grammar.

3.4.1 Detail grammar

Shape grammars are a type of rule-based system composed by sets of rules that perform computations with shapes to produce designs (Stiny & Gips, 1972). The rules can also be interpreted as design moves or design strategies. If the rules are oriented towards specific goals, they fall into the category of functional grammars. Based on iterative application of rules, grammars are very rich production methods that can generate an infinitely wide range of designs (Mueller, 2014).

The detail grammar presented in this research is composed by geometric strategies that are usually applied in detail design, across any material or fabrication logic (Figure 29-30). The rules are materially independent, there are geometric rules or we can also call them design moves that have specific functionalities and goals. Because there are geometric rules, they can be combined freely to generate infinite detail solutions.

To ease the application of rules, a description of its type, function, parameters, assembly type, and left and right states is created (Figure 28).



Rule
Step (01)

Type
Bearing Detail

Functions
3 D.O.F.
Constraints movement in
3 DOF (tx, ty, ry)

Parameters
8
sa: step angle
sw: step width
sht: step height top
shl: step heighwt low
shta: step height top angle
shla: step height low angle

Assembly Type
1-phase
determined by relationship between
angles (sa-shta-shla)

Figure 28. Step rule description.

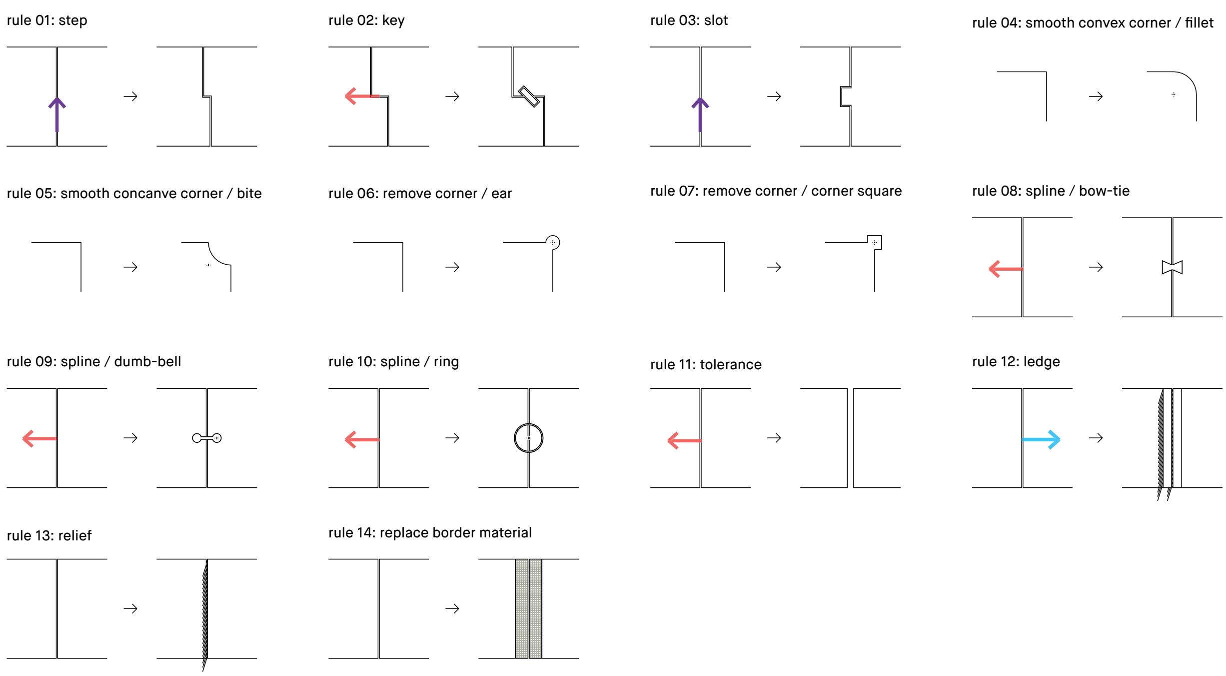
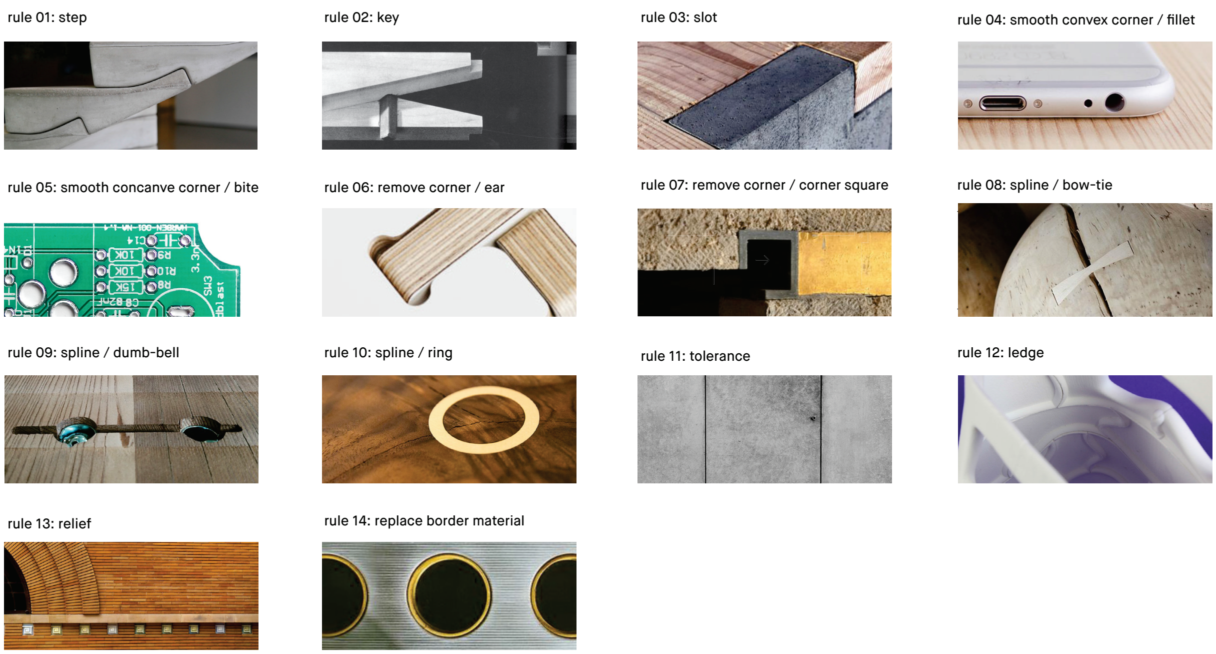


Figure 29. Detail grammar rule set.



Brandon Clifford + Wes McGee, *Helix,* 2013
Synth Rotek, *Cosmic ECHO Squared,* 2015
Lookwright Furniture, *Tite-joint fastener,* 2015
Frank Lloyd Wright, *V. C. Morris Gift Shop,* 1948

Kiyosi Seike, *Isuka-tsugi,* c.1977
Fraaiheid, +/- *Table,* 2013
Jeff Martin, *Bronze ring spline,* 2015
Jean Prouvé, *Prouvé House*, c.1940

Addicted-To-Retail, *Deus ex Machina,* 2013
Carlo Scarpa, *Gavina Showroom,* 1963;
Peter Zumthor, *Kunsthaus Bregenz,* 1997

Apple Inc., *Iphone 6,* 2015
Joshua Vogels, *Vase with butterfly (bow-tie) joint,* 2013
Larry Sass, Paloma Gonzalez Rojas, *Module Finding for Large Printed Objects,* 2015

Figure 30. Detail grammar rule set application across different materials and techniques.

3.4.2 Grammar application

Designers can apply rules manually or automatically to generate detail designs. In this case, we have applied the rules manually to test different detail possibilities. The grammar application comprises two steps: (a) rule matching and (b) rule application.

(a) We start inspecting and identifying unresolved conflicts in the previous analysis step. In our case, the results of our stability analysis show that where there is a tension or shear reaction force, we need to apply a stabilizing force. We perform the matching assembling the FEA results one by one (first shear, then tension) with the left side of our detail rules. Depending on how nourished is our grammar, the number of rules it contains to solve a specific constraint. In our grammar, we can choose between two different rules to solve the shear constraint: rule 01 (step) or rule 03 (slot) (Figure 31).

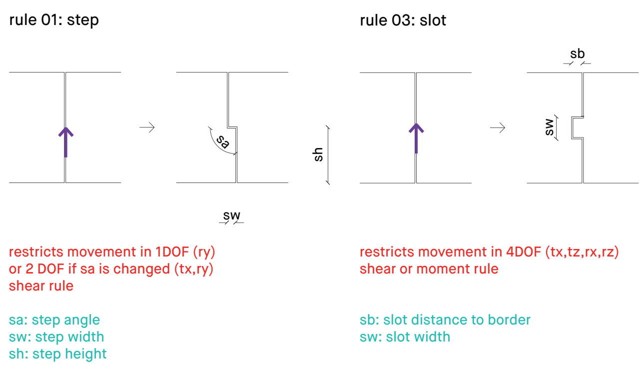
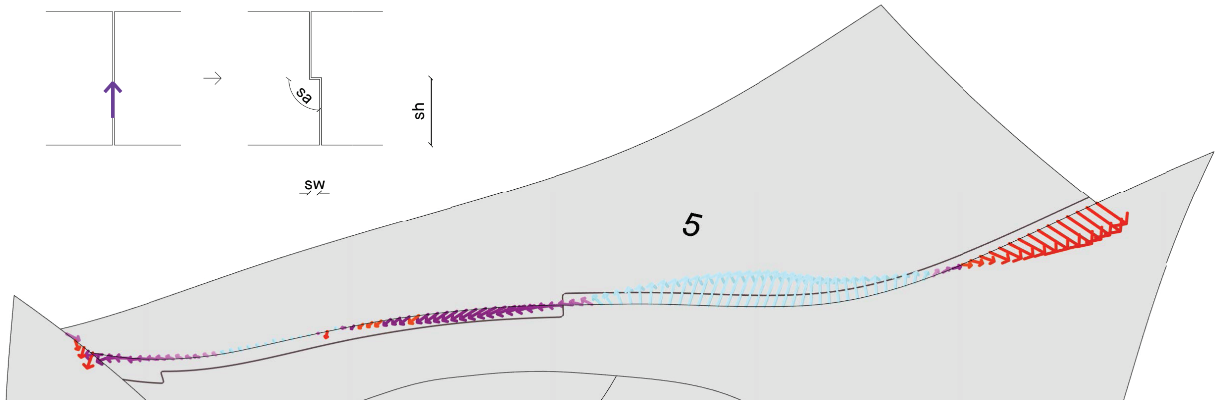
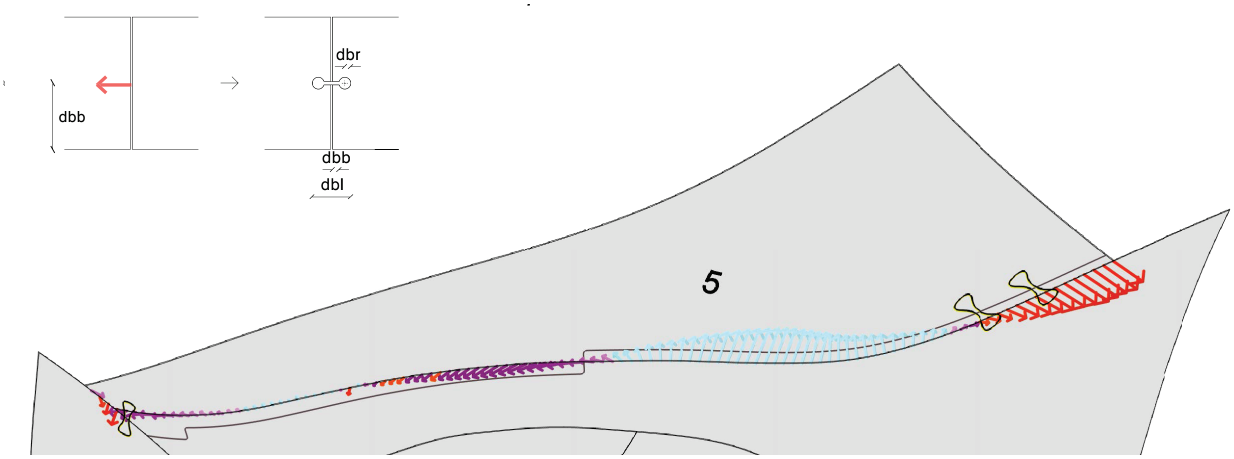


Figure 31. Rule matching (shear).

(b) Once we have picked the rule we want to apply, we need to take into consideration the rule's parameters. In this study, we apply parameters proportionally to the value of the force we require to stabilize the structure. However, a more in depth strength calculation can also be performed at this stage, making the detail solution more accurate (Figure 32).



(a)



(b)

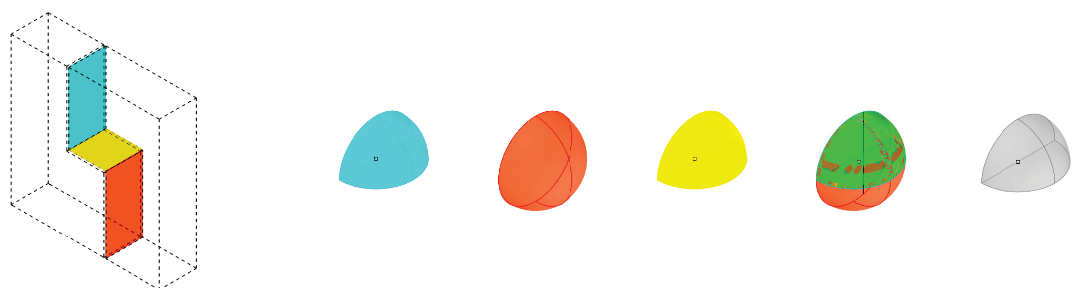
Figure 32. Rule application,(a) step, and(b) dumb-bell.

We apply each rule iteratively, building upon previously defined solutions. In our case study, the sequence of constraints to resolve are as follows: shear > curvature > tension > tolerance. Because the rule application is a geometrically visible alteration, we can immediately see the results during the entire rule application process. If we find new constraints during the process, we can add more rules. This real-time application of a compoundable and extendable grammar is what gives the synced detailing method the potentiality of a design tool.

3.5 Assembly Check

An assembly analysis as studied in the field of assembly planning includes both a combinatorial aspect –being computing the most optimal feasible assembly sequence– and a geometrical aspect –understanding the separability and blocking relationships between parts at each stage of the assembly (Jimenez, 2013). This thesis focuses on the geometrical aspect.

In the previous step (3.4) we applied the rules locally, which can ultimately bring new conflicting results. For example, a piece that is no longer assemblable due to the application of a rule that constraints its assembly range to zero. In order to analyze and avoid these types of results, we implement an assemblability check after the computation is done (only in the cases we apply the rules that have planar assembly types, rule 01 or rule 03). For this purpose, we implement a Non-Directional Free Graph (NDFG) to analyze the geometry of the edges and compute the ranges of directions along which it is possible to separate the contacting parts in an assembly (Jimenez, 2013; Tai, 2012). The implementation is divided into three steps: (a) discretization of edge, (b) calculation of Local Translational Freedom (LTF), and (c) visualization of results.



(a) *(b)* *(c)*

Figure 33. NDFG of rule 01 (step) for piece on right), (a) discretization of edge, (b) calculation of LTF, and (c) visualization of results.

(a) First, we discretize the edge into its planar constituent parts –for linear edges-, or approximation of planar parts -for curved edges-. (b) Second, we find the local translational freedom of each interface by drawing the range of all possible three-dimensional vectors pointing from the center of a unit sphere to a point on the sphere in which the interface is free to move, or in other words, for each interface we find the vectors that describe a movement that is not blocked by another interface (Tai, 2013). Additionally, we compute a boolean intersection of all the resultant sections of the sphere that represent the local translational freedom of each interface. (c) The final intersection represents the local translational freedom (LTF) of the piece on the right. In this case, the result is the 25% of the initial volume of a complete sphere. This number would be useful in the case we want to compare different rules and results, the higher the percentage of freedom, the easier the assemblage of the piece (Figures 33-35).

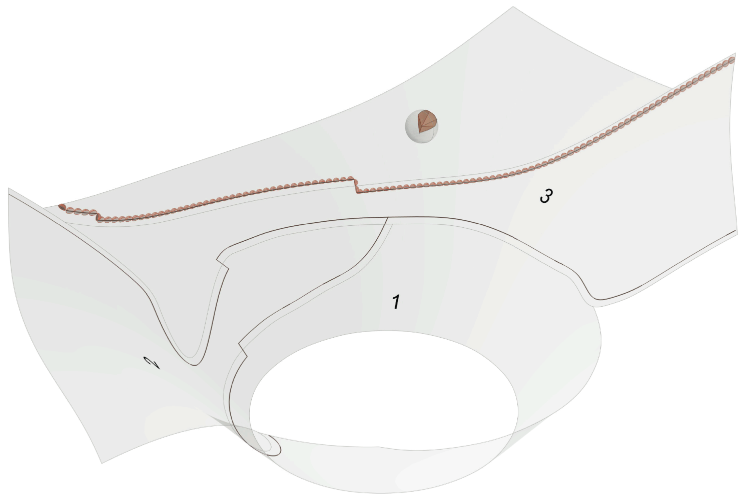


Figure 34. Local translational freedom of piece 05.

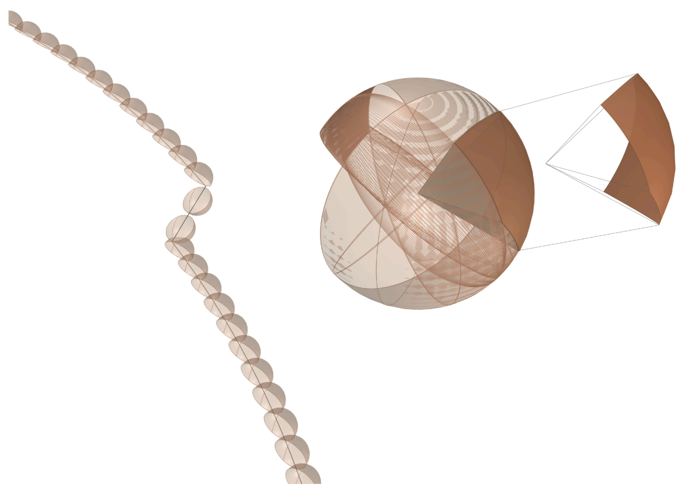


Figure 35. Local translational freedom (LTF) with range of assemblability of piece 05 (13%).

3.6 Materialization

The final step is preparing the instructions for the materialization of pieces, which includes the following steps explained below: (a) generation of volumetric piece, (b) tolerance and (c) securing homogeneous fabrication of parts. Ultimately, this step can also be included as part of the detail generation step by adding specific fabrication rules.

(a) The generation of volumetric parts implies defining a variable normal direction for the surface offset that can be performed in Rhinoceros with a command such as OffsetNormal, (b) defining the appropriate tolerance between parts according to the final material to be employed for the fabrication of parts, and (c) considering additional rules for placing, locating and manipulating the parts that maintains the structural quality as the one estimated in the FEA, i.e. if using a 3d-printing machine for the fabrication of parts, the direction of printing needs to be taken into account to assure the resistance of pieces.

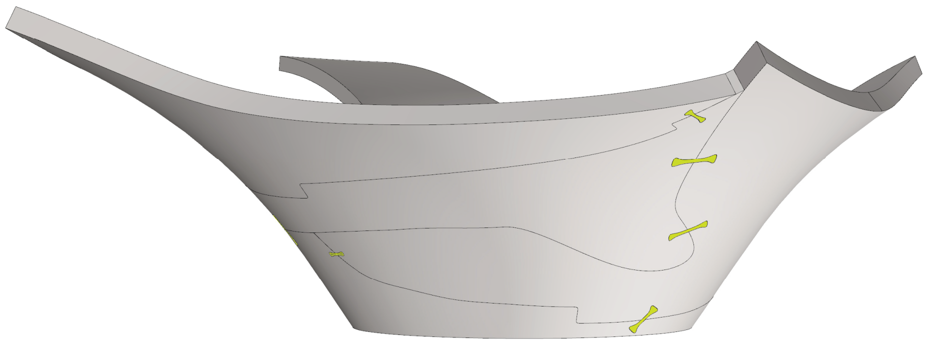


Figure 36. Volume, view.

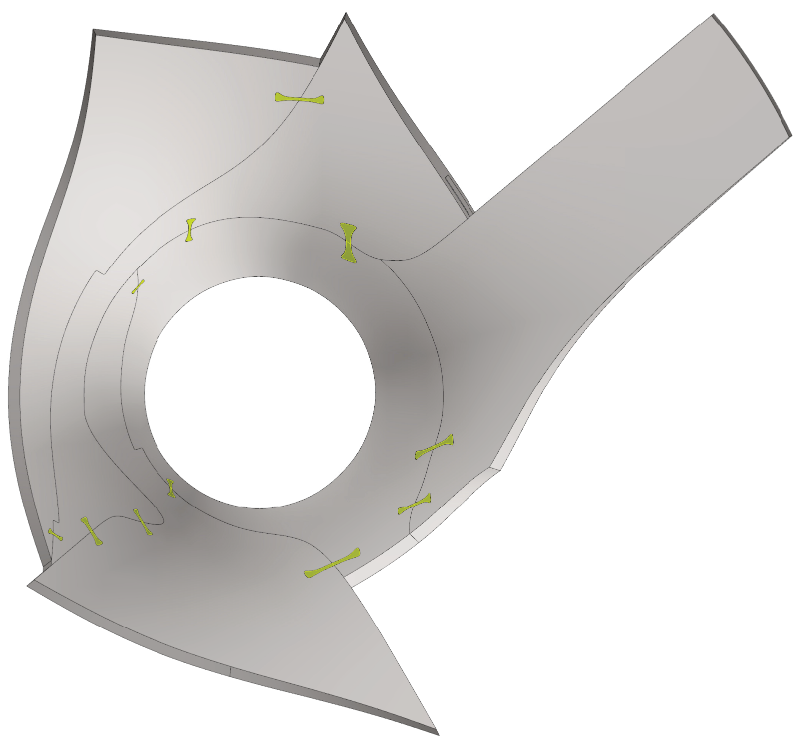


Figure 37. Volume, plan.

3.7 Summary

In this chapter we have seen how the synced detailing method can be applied to generate details based on the resolution of global and local constraints.

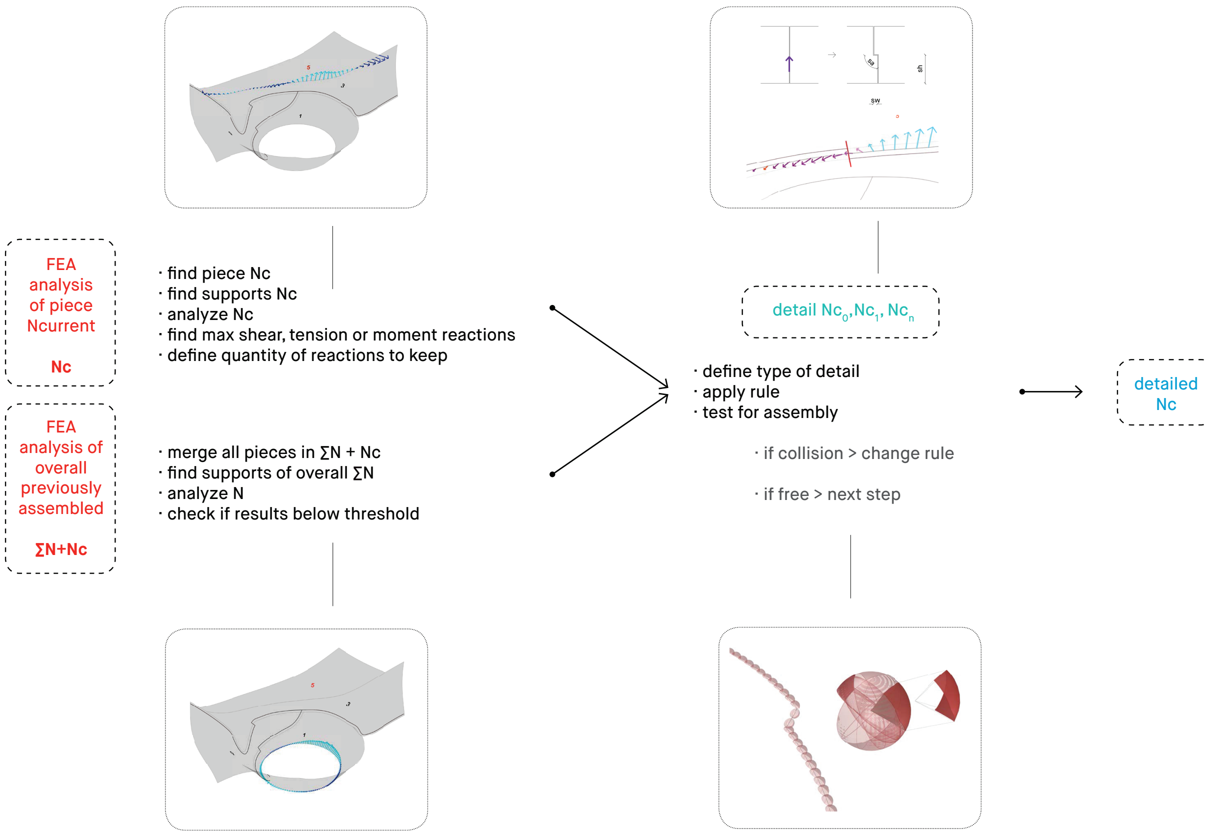


Figure 38. The synced detailing method.

4. Results

This chapter demonstrates how the synced detailing method introduced in Chapter 3 can be used for the design and assembly of complex structures. The method is particularly appropriate for solving the construction of self-supporting structures where a simple reconsideration of the detail strategy, the addition of tension at interfaces, can avoid the use of scaffolding. The chapter begins by an overview of the different test prototypes, then describes its specific challenges and detail results, and finally presents a completed prototype that illustrates the realization of the method.

4.1 Overview

The case study described in chapter 3 is materialized as a 20 in. diameter, 5 in. height discretized funicular funnel shell supported by a 4 in. diameter base and continuously tied with a tension ring at the open higher edge. We have tested different iterations of the method in 5 prototypes making variations on the quantity/size of the pieces. Prototypes 01 and 02 are decomposed in 66 pieces; prototypes 03, 04 and 05 in 16 pieces. The thickness of the pieces is constant across all prototypes (0.36 in / 9.1 mm). The physical models were 3D printed with a ZCorp ZPrinter 350, using a high-performance composite of zp151 powder and zb63 clear binder solution. None of the prototypes were impregnated with any strengthening material.

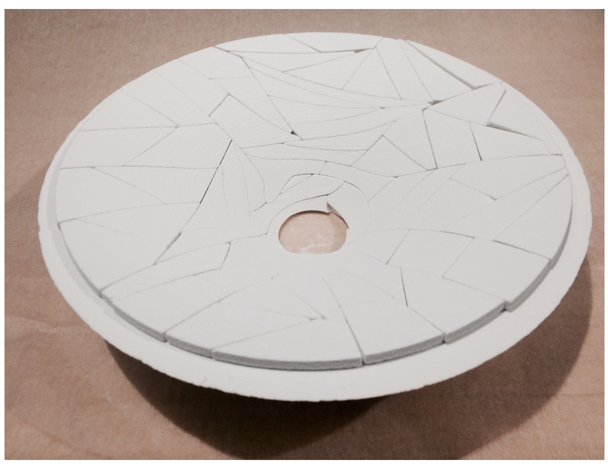


Figure 39. Case study assembled with the use of scaffolding and no details.

4.2 Detail results

This section describes the specific detail results (analysis, generation and physical models) of each of the prototypes in order to display a range of different detail solutions that can be achieved with the synced detailing method.

Prototype 01

The first prototype shows the basic workflow of the method. In this case, we analyze and assemble the first two of the sixty-six pieces. In Figure 40 we can see the analysis (a), detail generation (b) and physical model of the prototype before it is assembled (c). The latter shows how the pieces are not stable by themselves. Once the detail is applied, both pieces work as one sole piece. (Figure 41)

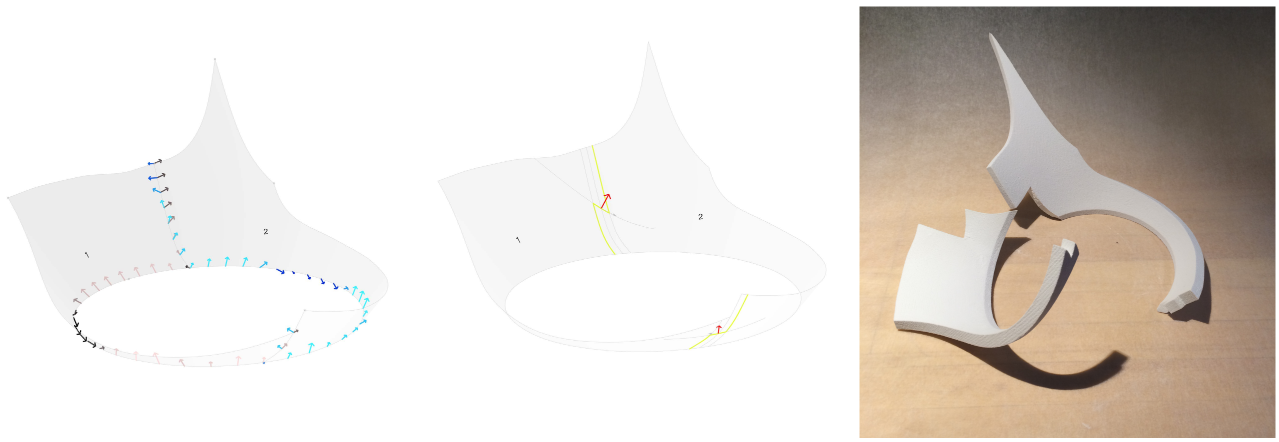


Figure 40. Prototype 01: (a) analysis, (b) detail generation and (c) disassembled physical prototype.

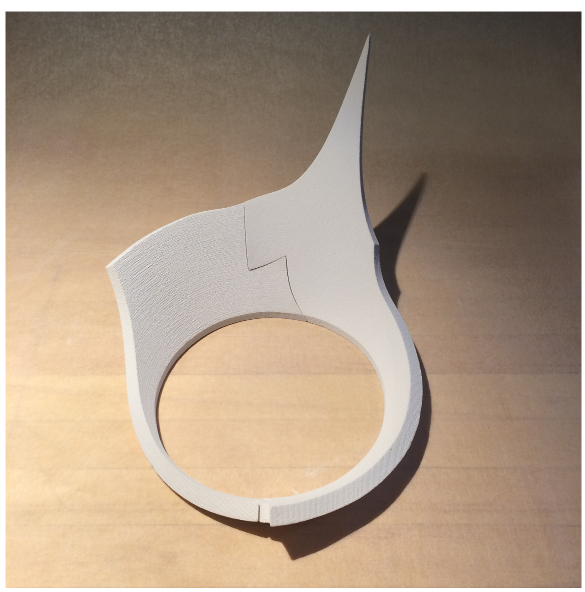


Figure 41. Prototype 01: assembled physical prototype.

Prototype 02

The second prototype shows the diversity of possible detail solutions to solve instability. In this prototype, we extend the method for the first eight of the sixty-six pieces. In Figure 42 we can see prototype 02 in the process of being assembled. In addition to the step presented in prototype 01, rings and bow-ties are introduced to handle tension reactions as shown in Figure 43. Figure 44 shows the analysis (a), detail generation (b) and physical model of piece 03 of prototype 02 (c).

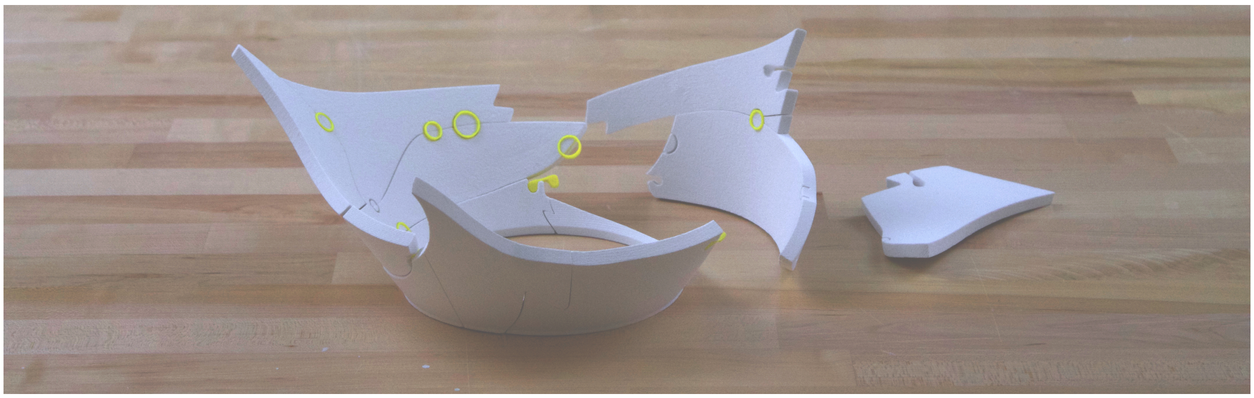


Figure 42. Prototype 02 during assembly.

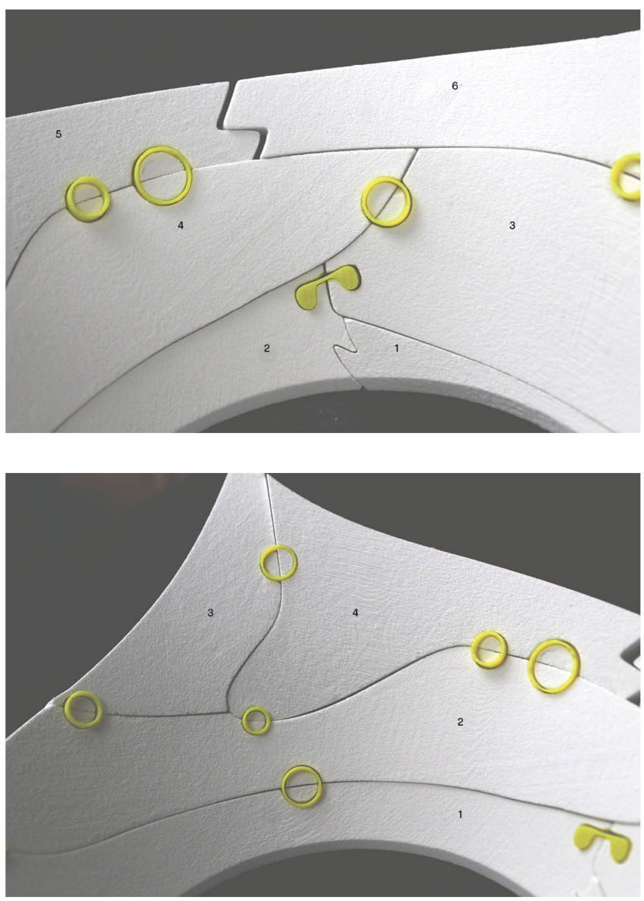
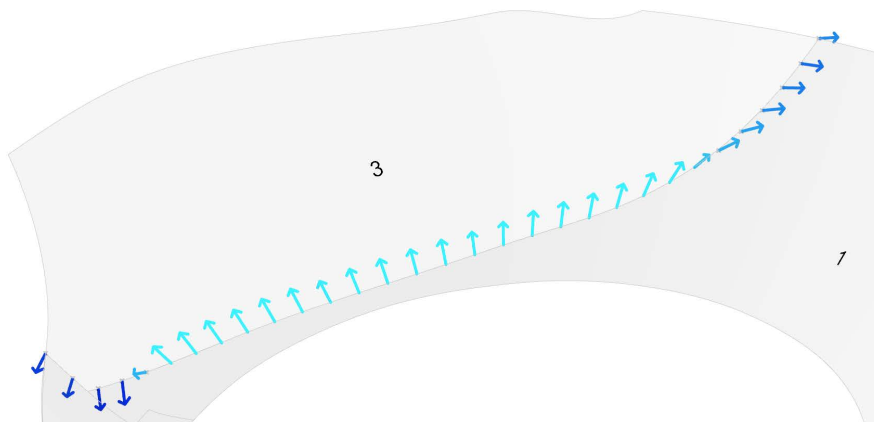


Figure 43. Tension reactions of prototype 02.



(a)

(b)

(c)

Figure 44. (a) FEA, (b) detail generation, and (c) physical model.

Prototype 03

In the third prototype we have changed the number of discrete elements during the decomposition process. Prototype 03 is composed by the first five pieces of a total of 16 pieces, which average size and weight are larger than the averages of the pieces of prototypes 01 and 02 resulting in more extreme support conditions. In this prototype we have introduced a rule (tongue and groove) to handle moment reactions between pieces 03 and 04. The application of this rule results in a very constrained assembly of piece 04 and the need to change the tolerance to allow piece 04 slide inside piece 03.

In this prototype we also simplified the use of tension rules, providing a unique rule (bow-tie) for all tension reactions. This step simplifies the diversity of solutions inside the script and the decision making process at each stage.

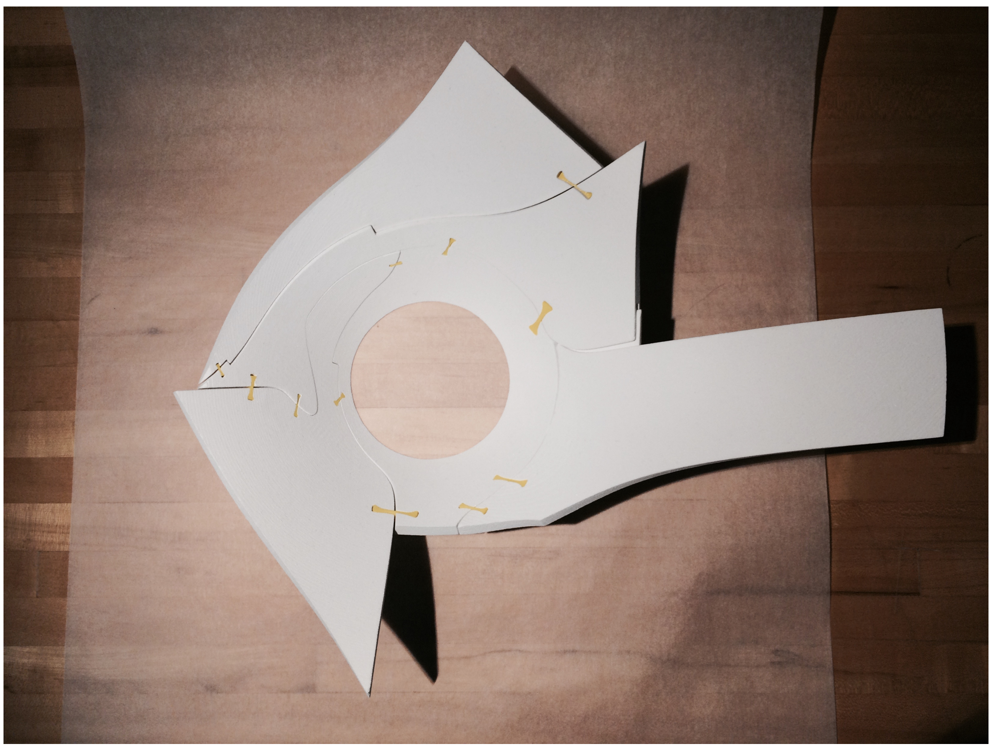


Figure 45. Prototype 03.

Prototype 04

The fourth prototype shows some of the limitations of the method. This prototype contains 16/16 pieces and is the first completed prototype. In this case we have replaced the tongue and groove rule with a combination of step and tension rules, increasing the range of possible assembly vectors between pieces. We have also modified the values of some parameters of the tension rule description, which has resulted in insufficient tension to support most of the pieces during assembly.

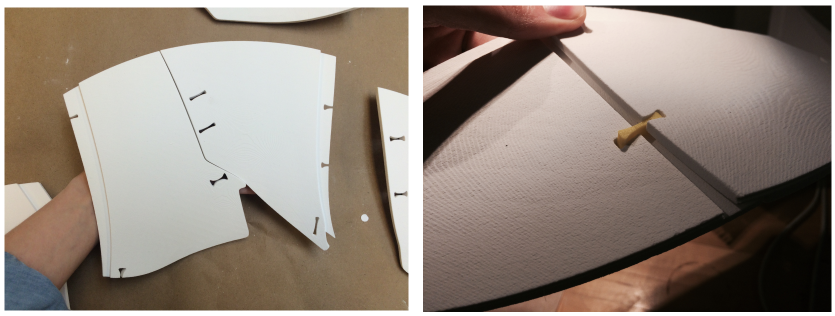


Figure 46. Insufficient tension.

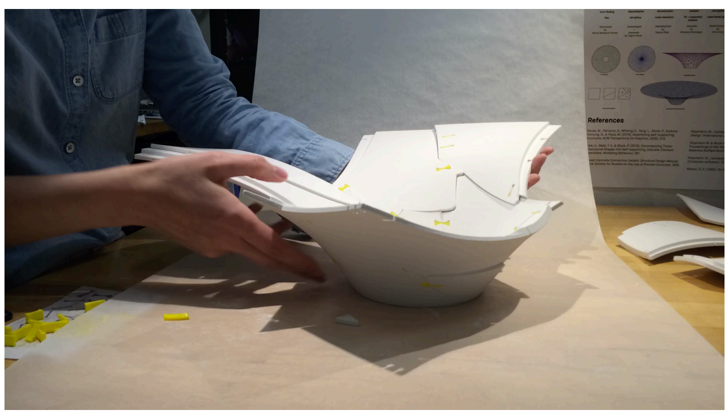


Figure 47. Need of external supports during assembly.

Prototype 05

In the final prototype we have incorporated the lessons learned in the previous prototypes regarding simplification of rule descriptions, interdependence and proportional definition of rule parameters and correct material tolerances. The result is a successful assembly that is stable at each stage without the need of scaffolding (Figure 48-51). Figure 49 shows the analysis (a), detail generation (b) and physical model of piece 05 of prototype 05 (c).

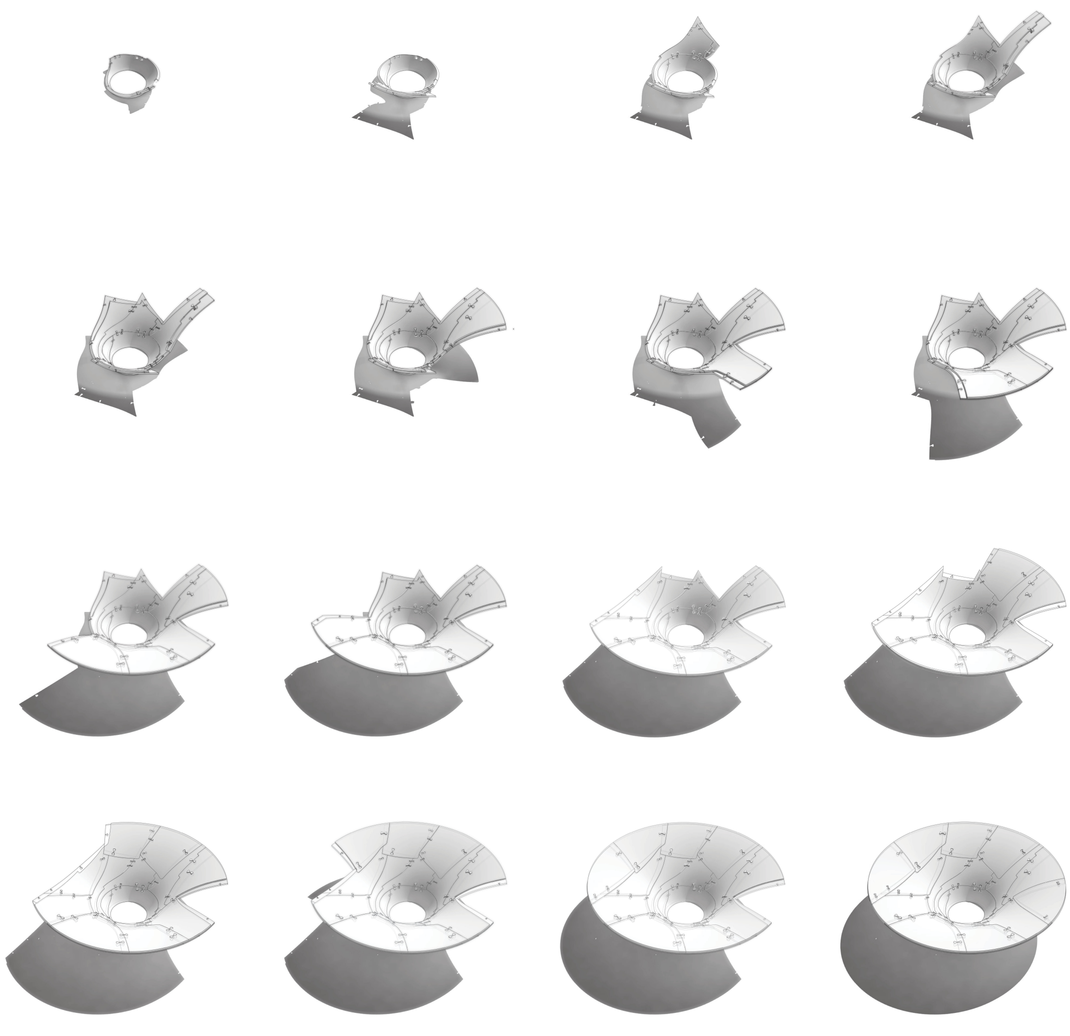
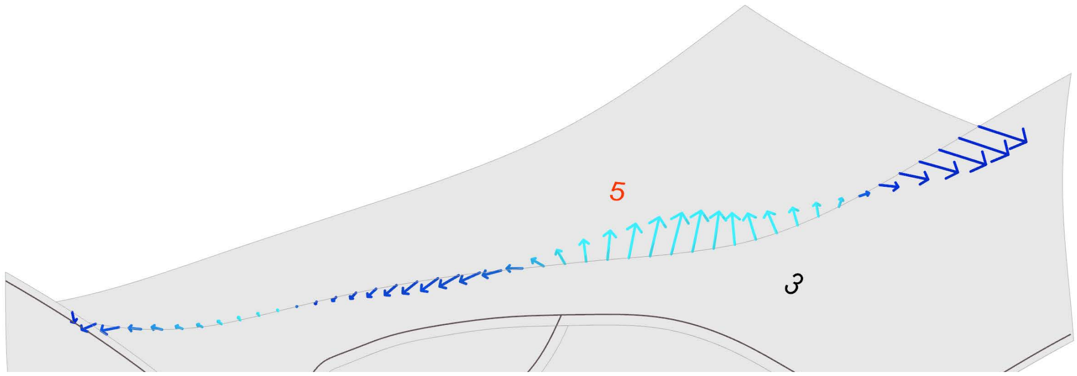
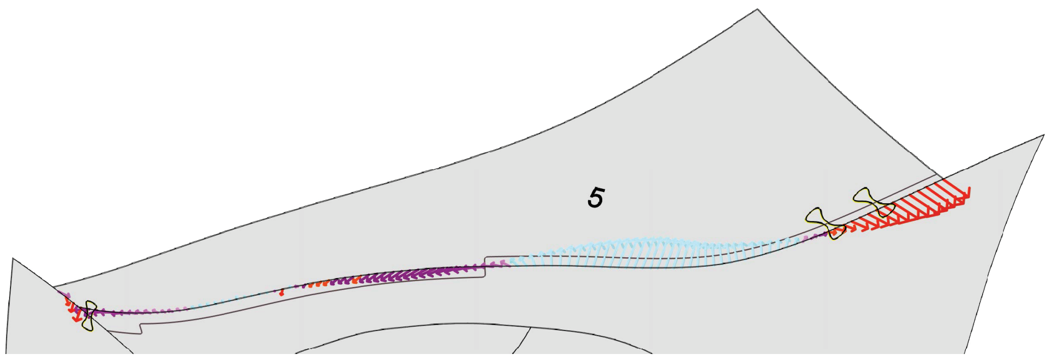


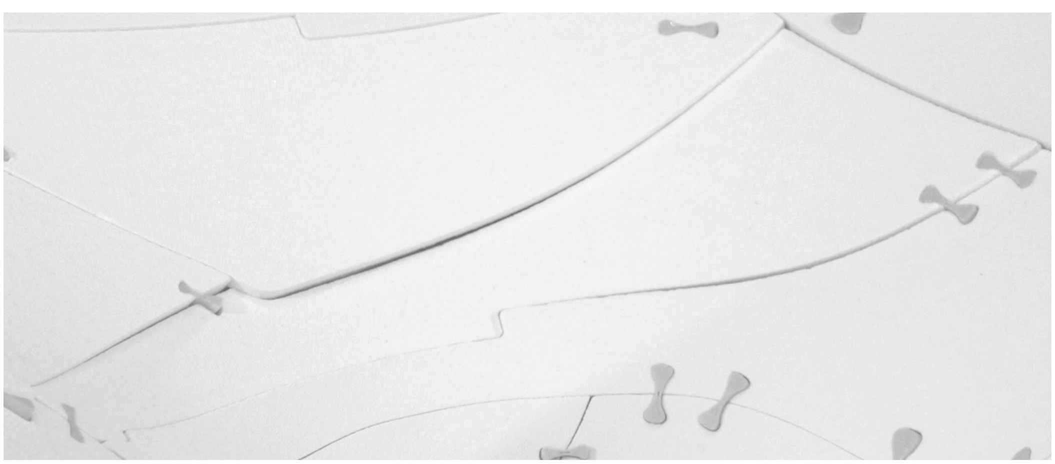
Figure 48. Assembly sequence.



(a)



(b)



(c)

Figure 49. (a) FEA, (b) detail generation, and (c) physical model.

Figure 50. Prototype 05.

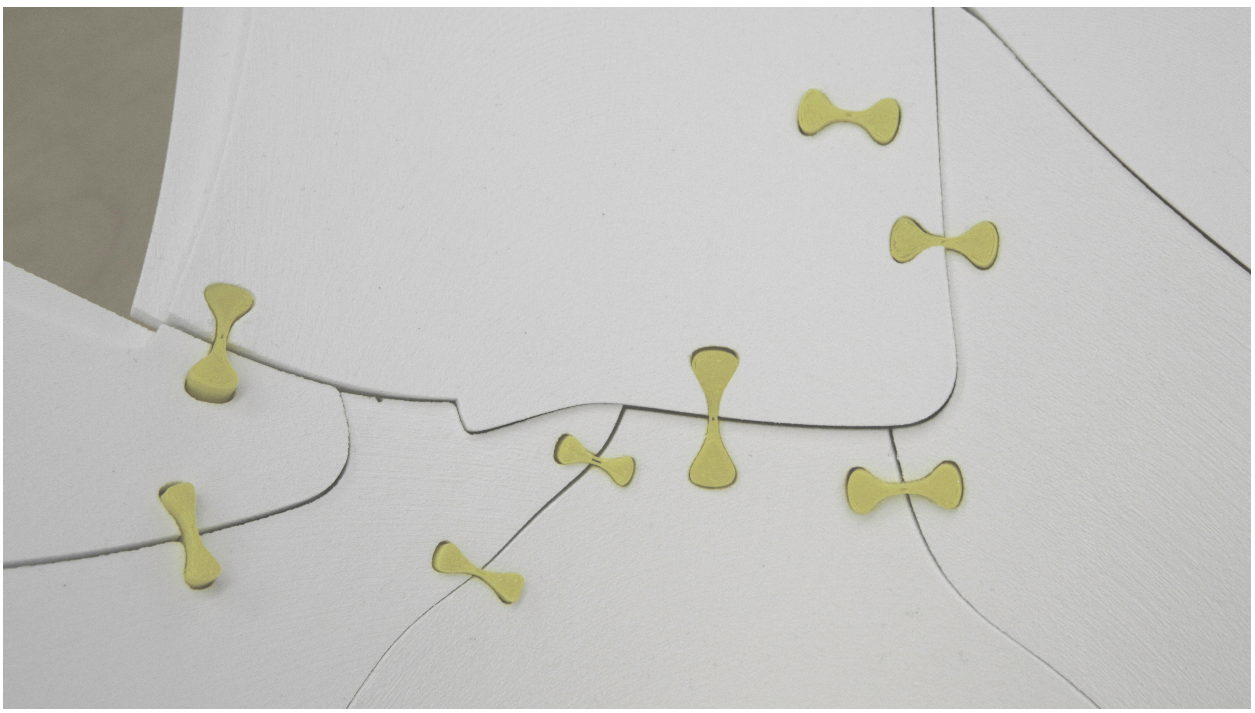


Figure 51. Prototype 05, detail.

4.3 Discussion

So far we have demonstrated how the synced detailing method can be used to resolve conflicting constraints such as the ones presented by the instability, assembly and fabrication of discrete element structures in the details. The method has been tested in the construction of a structurally challenging assembly, a discretized funicular funnel shell, to prove that novel detail solutions can solve challenging construction problems that standard detail solutions have not been able to solve yet.

In respect to the calculation of stability with reaction forces and moment at supports, the method shows a novel approach and an intuitive tool to identify and measure instability. The accuracy of results depends on the precision of the model set-up including material properties, loads, support conditions and discretization for analysis (remeshing). Special attention needs to be paid to the local orientation of the support conditions as well as to the correct visualization of the resulting reaction forces and moments vectors in the same locally oriented condition.

Concerning the detail generation based on a detail grammar, the results show a flexible and real-time method that can be expanded and updated during the design process. While the manual application of the grammar favors interaction allowing designers to make decisions on-the-fly in regard to the selection, order and reciprocity of rules, a partially automated rule application, where rule matching, parameter setting and rule application are automatically executed by the computer, could benefit the design process at an early stage by quickly exploring the detail design space (Mueller, 2014).

With regard to the assemblability check, the implementation of the LTF can be effortlessly integrated into the workflow giving valuable information about the expected assembly performance. At this point, we have only used the LTF information as a boolean check (yes it is assemble/no it is not assemblable). However, further parametric detail definitions could use the result of the LTF calculation as an input in an optimization routine to find the most assemblable detail geometry. The implementation in Grasshopper shows its limitations at the stage of the boolean operation due to the need of high-tolerance calculations. This can be overcome by the addition of a specialized script that can handle a separate and specific tolerance parameter for the boolean operation.

4.3.1 Physics and assembly results

As shown in the previous section (4.2), prototype 05 demonstrates that the synced detail method can be used to generate novel detail strategies to solve intermediate instability of complex structures. In our case we have calculated each interface sequentially, with no regard for the altered conditions of every previously calculated interface. The structure can fail at the base or at any of the previously calculated joints. A comprehensive stability check should include three analyses at each stage of the assembly (a) local stability of edge, (b) local stability of each previously calculated joint, and (c) global intermediate stability at the base. A combinatorial challenge of checking each previous state can be tackled with an extension of the detail generation step with additive rules to avoid erasing what has been previously calculated.

We can identify some patterns of distribution of loads and associated patterns in the application of rules that are legible at the higher edge of the structure. These patterns correspond mainly to the radial symmetry of the case study and to the specific geometry of the decomposition step.

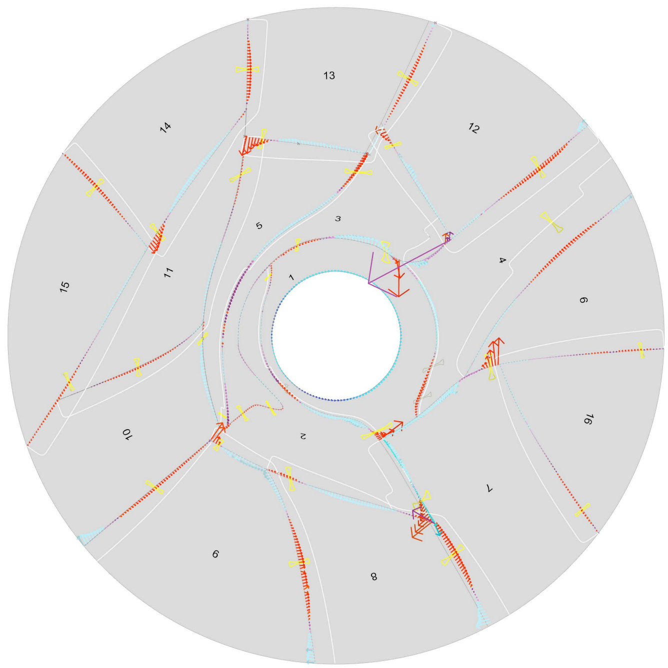


Figure 52. Patterns.

Conflicting constraints such as the need of tension, shear or moment details at the extremes of pieces have been solved with an interdependency rule that modifies successive geometries according to the joints that have been previously placed. The rule remaps the edge geometry according to the distance to previous joints.

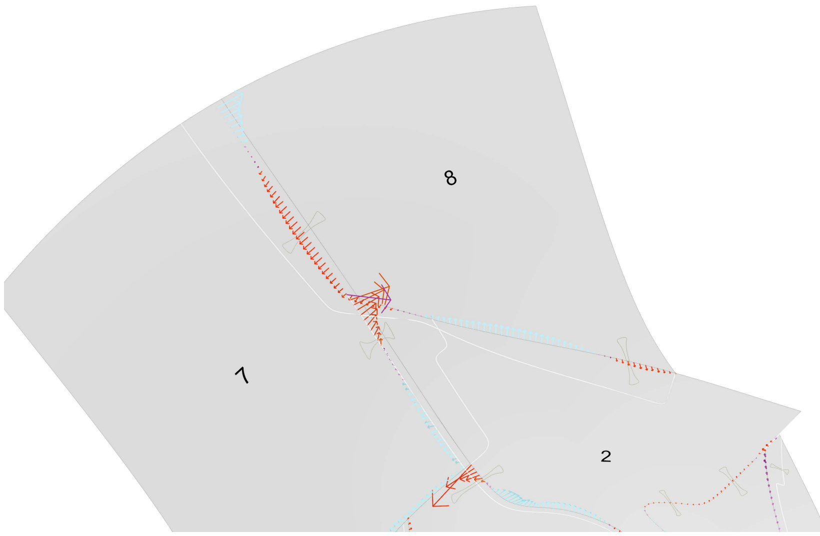


Figure 53. Interdependency.

4.3.2 Visual results

According to the specific sequence of assembly and the support conditions that we define during the analysis, the type, distribution, and size of details might change completely. In this respect, the synced detail method allows users to read and interpret building information such as a specific sequence of assembly in the physical object.

The compoundable and extensible properties of the grammar, such as the possibility of adding rules one on top of the other, in combination with the synchronized analysis show that novel and unexpected detail solutions can be created. More heterogeneous geometries can generate more variable results; additionally rules can be applied less homogeneously.

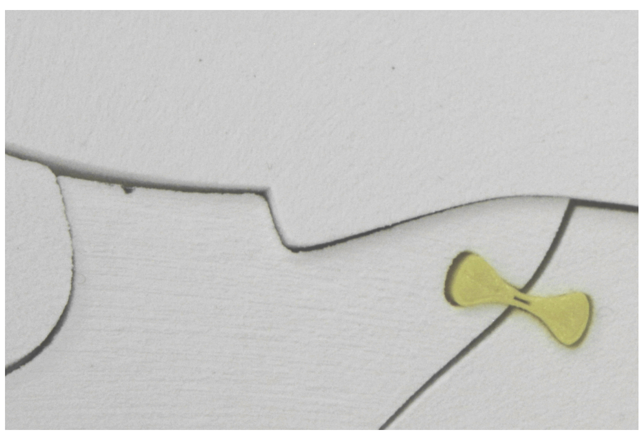


Figure 54. Visual results.

Because constraints can be solved in multiple ways (applying different or additional rules, changing sequences of assembly, etc.) there is no one unique standard solution to solve a problem. The flexibility of the method allow very different visible solutions for the same type of constraints such as the ones illustrated in Figure 55: (a) equilibrium is taken solely from the inside of the piece while the exterior does not show how the stability is solved and (b) tension details use the full thickness of the piece to stabilize the pieces during assembly, resulting in a visible solution from the exterior.

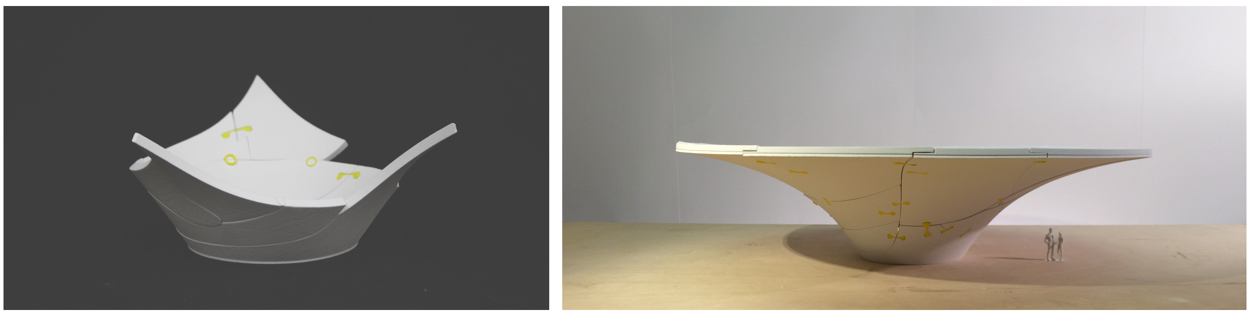


Figure 55. (a) Prototype 02 and (b) prototype 05.

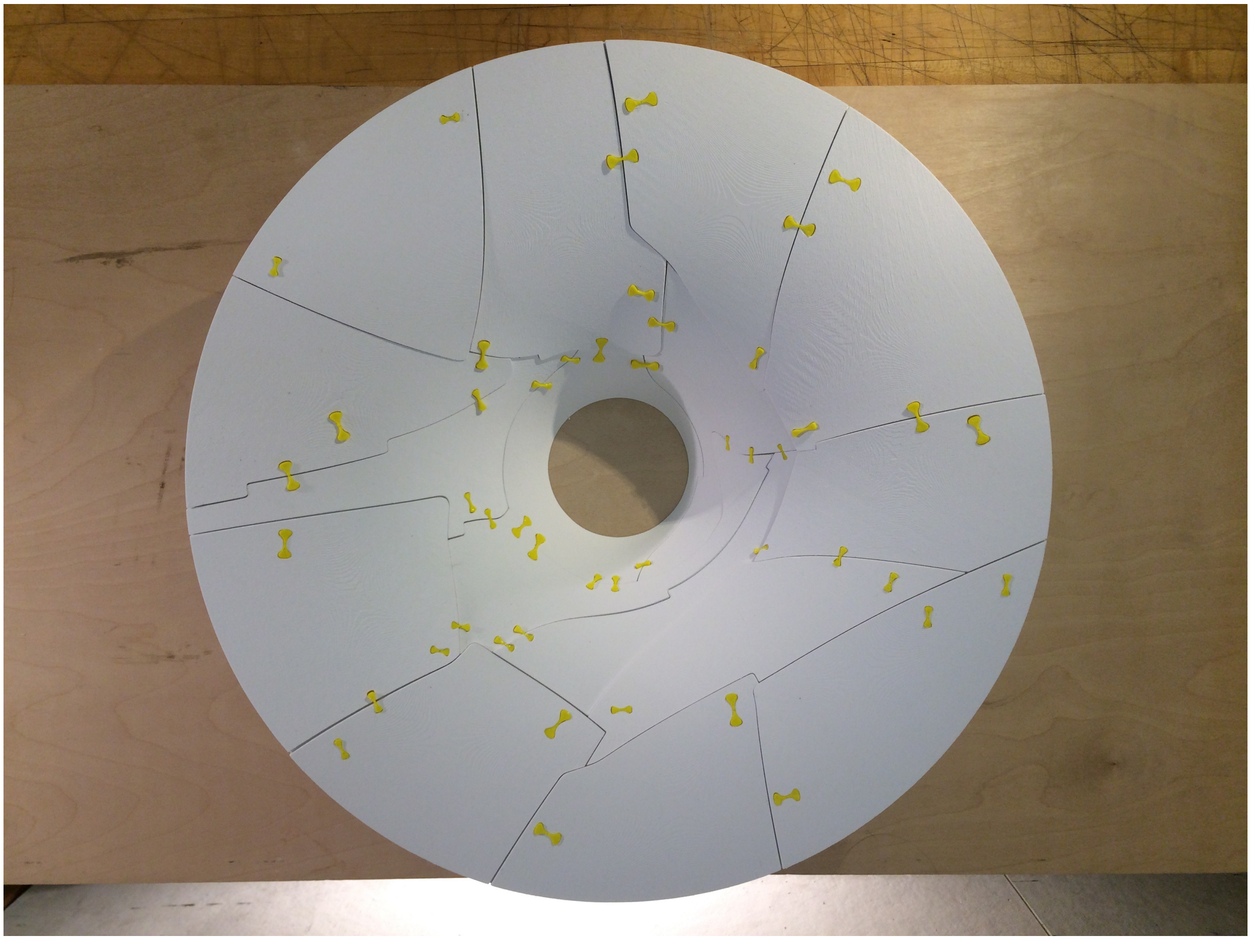


Figure 56. Prototype 05.

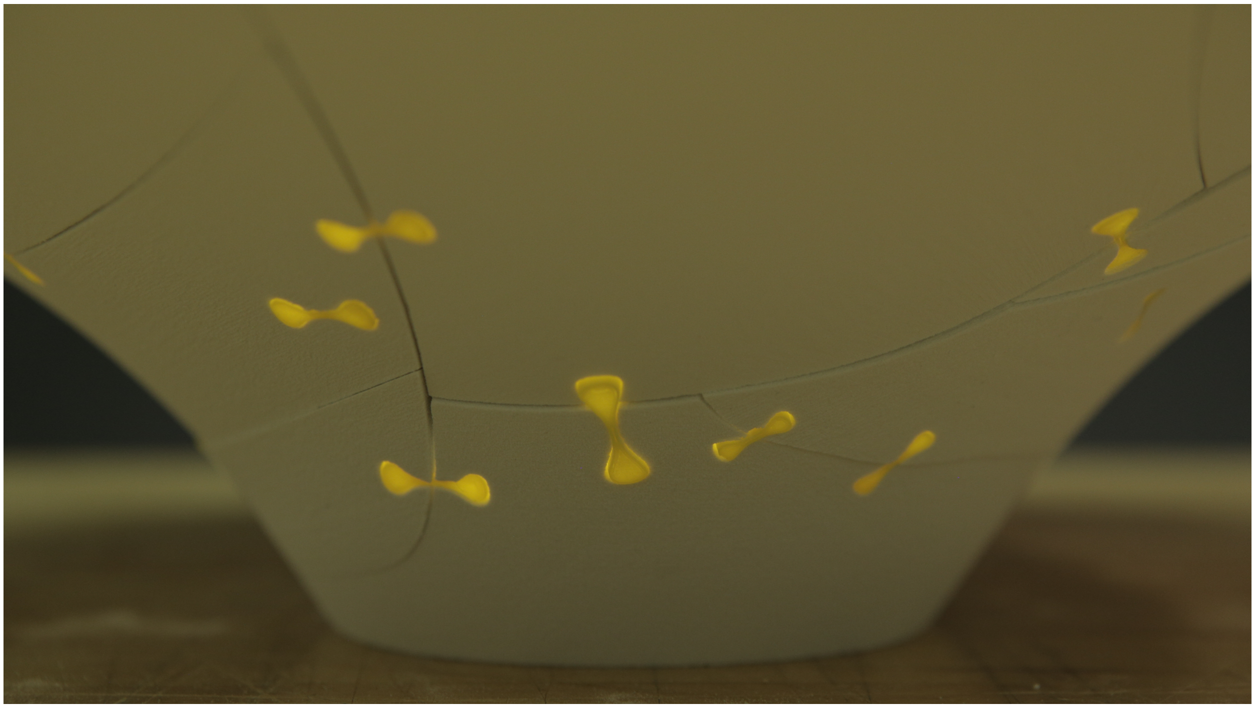


Figure 57. Prototype 05.

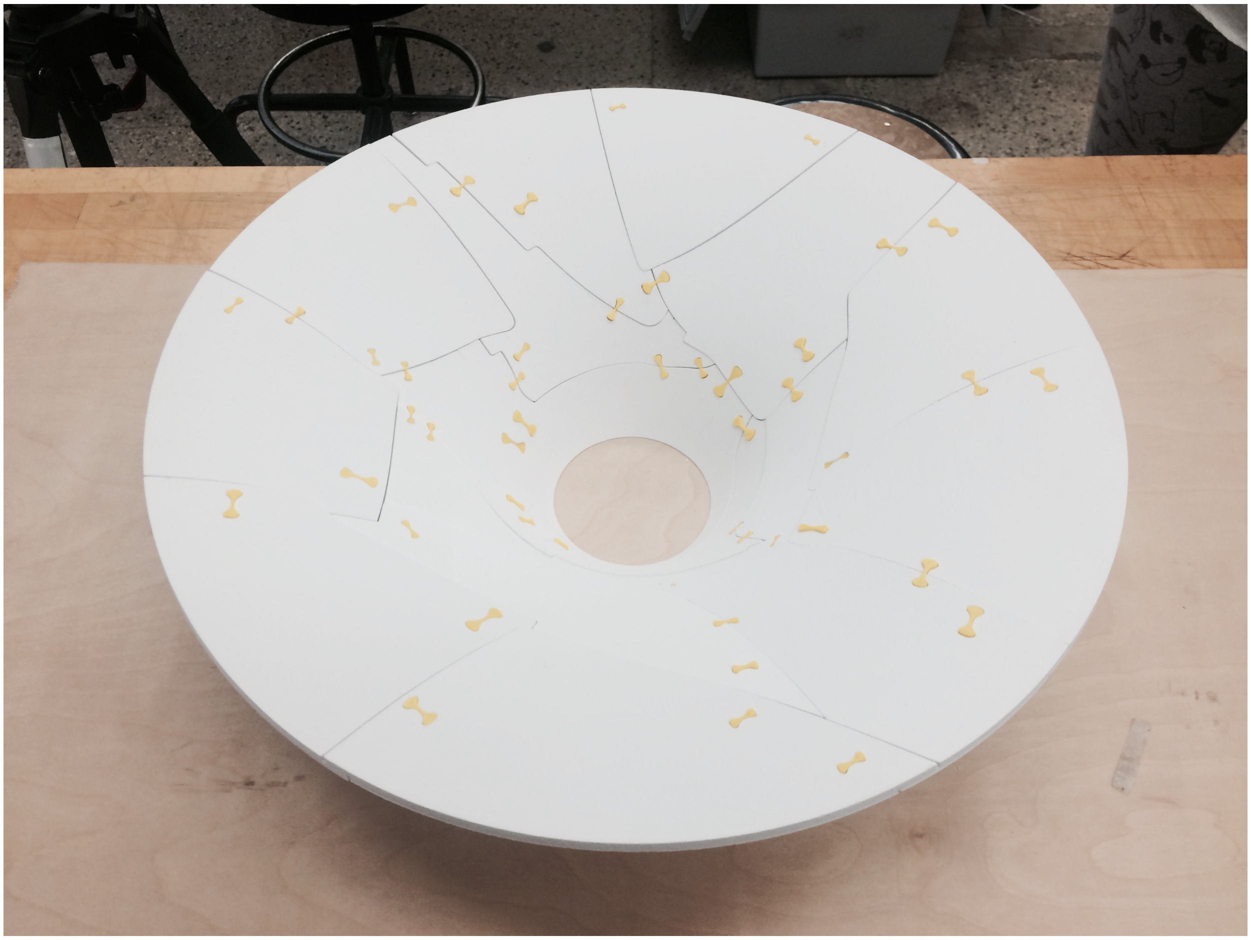


Figure 58. Prototype 05.

Figure 59. Prototype 05.

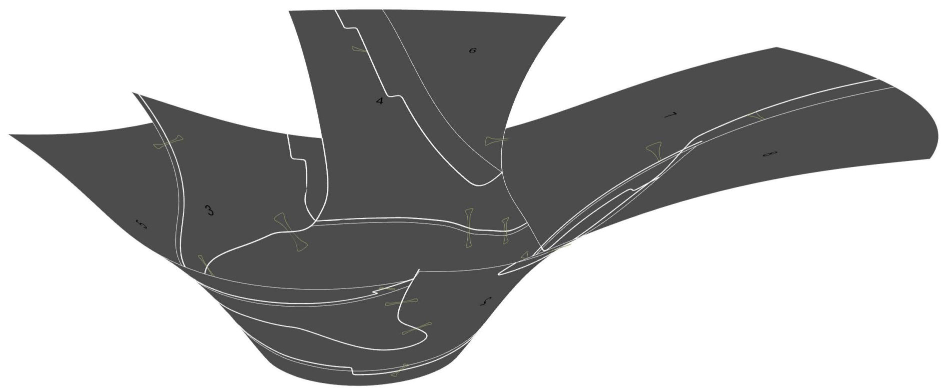


Figure 60. Prototype 04: intermediate equilibrium state.

5. Conclusions

This thesis presents a new computational strategy for designing details informed by local and real-time analysis of structural and assembly results. In chapter 1, this thesis has argued about the need of new detail strategies by presenting the limitations of current detail approaches, which can potentially hinder the development of novel non-standard material assemblies. In chapter 2, this thesis presents a revised literature on detail definitions, strategies and main modes of access to detail knowledge. In chapter 3, we introduce the synced detail framework, which presents the steps of the new computational strategy for designing details. In chapter 4, we have exposed and discussed the results of the application of the framework, opening a series of promising future work. This chapter summarizes the contributions of the thesis, and discusses potential impact and a range of possible directions for future work.

5.1 Summary of contributions

The contribution of this thesis are summarized as follow:

· Outline a new interactive framework for designing details for discrete element structures that incorporate physics and assembly constraints.

The framework includes local and global real-time stability analysis by studying the reaction forces and moments at supports of each element during the assembly sequence; the implementation of a visual assemblability check that shows the range of assembly vectors for each element; the study and encoding of geometrical principles in compoundable shape rules which combined define a detail grammar; and a real-time workflow that informs designers how to apply the detail rules.

· Design a new strategy for the construction of self-supporting structures based on intermediate detail solutions.

The self-supporting structure case study illustrates the value of the synced detailing approach. Until now, both continuous and discrete complex structures have relied on the availability of labor and resources to allow its construction relying on the use of scaffolding. This thesis introduces an alternative approach where the analysis of local conditions merged with a novel understanding of details as coordination of data can solve the intermediate equilibrium of these structures during the construction process.

5.2 Directions for future work

Building from the synced detailing framework introduced in this thesis, there are several areas that can be developed further:

In respect to the theoretical aspects of this thesis, the synced detail method can be generalized to other types of constraints, including other structural demands beyond stability such as the strength of materials and the friction at interfaces of parts; fabrication constraints such as the size, geometry and manufacture of pieces and details; economical limitations tied to constructability aspects; water and air control analysis at the interfaces; etc.

Regarding the implementation aspects of the method, the framework is flexible enough to incorporate additional and comprehensive steps of analysis: local analysis at every new interface, local analysis at each previously analyzed interface and global intermediate analysis at the base. Additionally, a combinatorial study of the most optimal assembly sequence can be performed at the beginning and at each stage of the assembly sequence to find most expressive and optimal detail results.

In relation to the further development of the digital workflow, the categorization and simplification of data inputs and outputs could allow clustering of processes and rules resulting in faster interaction and evaluation of results.

5.3 Concluding Remarks

Current advances in digital design and fabrication processes are allowing material information to drive design intent based on new measurements of data. Still, our current approaches for using and interpreting this data are greatly segmented by the specificity of different fields of knowledge. In the light of this availability of information into our design processes, there is a risk of losing design intent and assuming creativity in the flow of data. In this respect, there is a need for new approaches that help us coordinate information in intelligent and creative ways. This thesis proposes a novel approach to look at details in a creative way as points of coordination of material information.

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