Computing with Matter, Shapes, and Forces

Toward Material and Structural Primacy in Architecture

by

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ABSTRACT:

This thesis is motivated by my interest in addressing contemporary issues in architecture and design through historic inquiry. Taking a critical approach toward technology, a *slow* computation methodology will be proposed as a means of working between traditional architectural media: drawing and masonry construction. Working with compression-only material and constructive constraints offers a means of designing within the constraints of a masonry arch in a way that is neither mechanical nor deterministic. Rather, it is open-ended, imaginative and creative. By extracting rules from historic buildings, a new structural algebra (characterized by equilibrium constraints) will be specified that permits architects and designers to work visually and non-deterministically with material and structural primacy - **to feel the forces in shapes**. Although this methodological proposal does not extend to realizing complete designs, the rules are established with equilibrium constraints which offers a means of working that only produces build-able designs. This project is not about finding compression-only forms; rather it proposes to design [compute] with them. Learning to compute with matter, shapes, and forces, brings to light the relationship between current design technologies and methods, and the necessity to make breakthroughs in techniques of assembly and construction.

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This thesis would not have been possible with out the support and guidance from many invaluable mentors, advisors, colleges and friends.

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In the spring of 2016 (thanks to Prof. Ochsendorf) I had a chance to work on an installation for the Venice Architecture Biennale. It was an honor to work on team packed with such expertise. I am grateful that the experience led to being reunited and collaborating with Professors Fernando Vegas and Camilla Mileto from the Polytechnic University in Valencia, and Benjamin Ibarra-Sevilla from the University of Texas at Austin. I am grateful for new friendships and connections in Valencia, Spain: Salvador Tomas Marquez, Javier Gomez and maestro Salvador Gomis Aviño.

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I am drawn to **what I see when I look** up.

Fig. 0.1. The church of Santo Domingo Yanhuitlan, Oaxaca Mexico. Photo by the author.

Prologue

a note on history, fast computation, and making

This thesis will broadly fit into three areas of the discipline: history, construction, and computation. My objective is to demonstrate a way of working that promotes a greater understanding of the matter, shapes, and forces at play when designing architecture. I will not be developing any particular designs of things. That sort of exploration is better left to the design studio. Instead, I will present a new way of looking at unreinforced masonry structures to develop material, structural and constructive knowledge. Why study a historical construction system? In part, it's a matter of personal obsession: *I am drawn to what I see when I look up.* As I have pursued the topic however, it has opened up a rich territory to learn and talk about design.

My first scholarly research project was about a 16thC Gothic-style church in Mexico called Santo Domingo Yanhuitlan [Fig. 0.1]. Working as an undergraduate research assistant with Professor Benjamin Ibarra-Sevilla, I did an investigation of one of the unreinforced masonry vaults (we assumed the four in the church to be more or less the same). I became fascinated by the idea that without explicit knowledge of the forces in the structures, masons managed to work creatively and construct buildings in ways we still do not fully comprehend. We assume their construction methods were based on geometrical rules, material techniques, and sequences of assembly. The goal with the Yanhuitlan project was to look closely at the form of the vaults and find underlying geometrical rules to digitally reconstruct them. I became engulfed by the question of how the rib pattern may have been generated. I produced a series of drawings that described a speculative design system that located intermediate ribs on a four-pointed star plan [Fig 0.2]. The methods of master masons were rarely written down and often lost, so it is impossible to know if my rules resembled the actual method used by those who built Yanhuitlan. The significance of the investigation lies in being able to *see something new* when looking at

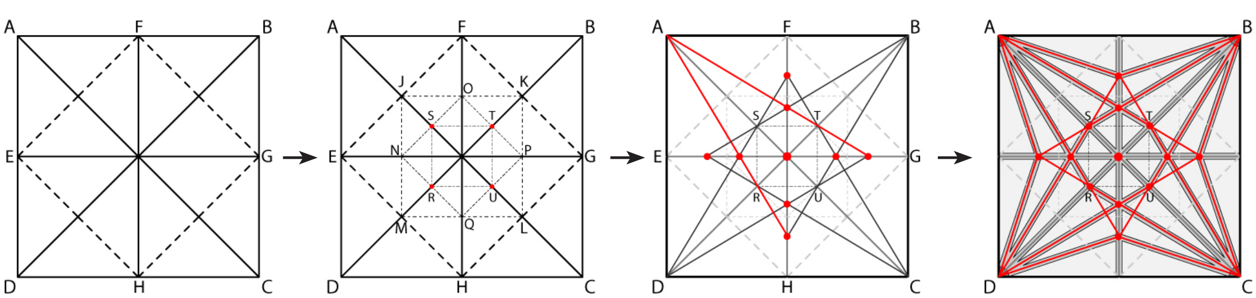


Fig. 0.2. Generating the Ribs at Santo Domingo Yanhuitlan. From [Dessi-Olive, 2010].

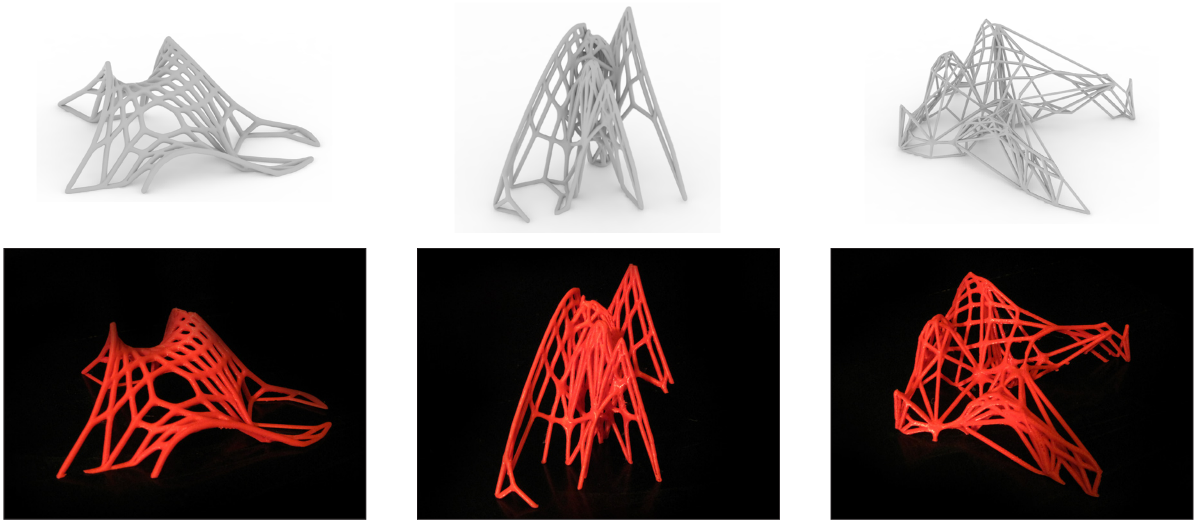


Fig. 0.3. Designs using fast computation design tools and PLA prints. From [Dessi-Olive, 2014].

a historical building. The rib generating drawing system provided a new way of looking at and talking about historical content in terms of creative design. The research experience motivated me to continue investigating this technologically constrained context.

My interest in unreinforced masonry structures grew after I learned about work by Professor John Ochsendorf and his legacy of students at MIT, who expertly demonstrate how intimate knowledge of historical building methods can lead to innovations in contemporary design and construction. By engaging directly with the materials, Ochsendorf, Block, and others were able to *do something new* using historical building techniques. They showed how tile vaulting, a more than 800 year-old construction system, can provide the means of efficiently constructing a wide range of compression-only shapes using minimal formwork, with less cost and material waste.

As a master of architecture student, I was immersed in a design studio culture at the University of Pennsylvania that was largely concerned with the rapid production of evocative geometry using digital modeling, simulation, and scripting techniques. I took issue with the focus on **fast computation** design tools and the complete disconnect between design and the physical world that resulted from working this way. To me it seemed strange that we were being tasked with modeling shapes with digital design tools (and sometimes 3D printing with rapid prototyping tools) without knowing if or how those shapes could actually be constructed at full architectural scale [Fig 0.3]. Thin-tile vaulting was proven to be forgiving enough to accommodate the construction of irregular shapes - even the kinds I was accustomed to see being made on people's computer screens around studio. My exposure to the work being done at MIT motivated me to learn to build tile vaults. Around the same time, I was introduced to two professors from Polytechnic University of Valencia (UPV) in Valencia, Spain who were visiting the University of Pennsylvania on sabbatical, and happened to be experts on thin-tile vaulting. Professors Fernando Vegas and Camilla Mileto taught me a few basics of the technique [Fig

Fig. 0.4. Building a mini thin-tile groin vault in Philadelphia. From [Dessi-Olive, 2014].

Fig. 0.5. Tile Vault Construction Workshop with Professor Franca Trubiano, PennDesign and students from the Charter High school of Architecture and Design (CHAD) in Philadelphia. Fall, 2013.

0.4] and continued to advise on the next few vaults I built with other architecture graduate students at PennDesign.

As we constructed vaults, a community of curious architecture students emerged who thought it might be valuable to learn to build as a part of our education. The work-site became a collaborative laboratory where we experimented, failed and learned together [Fig 0.5]. Whether with our hands or machines, we found *learning to build is challenging, yet joyful*. With each vault my masonry skills got better (cleaner) and more precise. I began to develop an intuition about the materials I was using, their properties, appropriate assembly sequences, and formal capacities of the system. This was a totally new form of tactile knowledge for me; a feeling I can only compare to playing a musical instrument. Building tile vaults provided a direct interaction with the intended materials and construction techniques of a design; an active, embodied feeling of the forces at play in the structures as they were being built. This is how I came to find out **making is inseparable from design**. Given that certain fast computation design tools are inherent to the professional architect's design process, it seemed worthwhile to bring to light the relationship between those tools and material making. For my M.Arch thesis [Dessi-Olive, 2014] at PennDesign, advised by Prof. Franca Trubiano, I proposed a design process that used thin-tile vaulting as a feedback mechanism for validating digital design - in particular, form finding and structural analysis techniques. I built ordinary thin-tile arches whose shape was generated with software. I demonstrated how digital work could be re-contextualized into physical reality and pointed out deficiencies of the software to sufficiently inform on concerns of material, assembly, or safety of the design.

To make up for the deficiency of the digital tools, tactile/material knowledge I developed by learning to build became eminently necessary as I transferred the digital design from the computer to physical material. Focusing on a simple and common shape - an arch - I logically speculated on the possibility of constructing strange, evocative, or imaginative forms. As the shapes I generated became increasingly complex and strange, they also became more difficult to evaluate and analyze. Irregular shapes "found" with software could likely be built, but I had very little to say about them critically or relative to historical or disciplinary contexts. Common fast computation tools for architecture design tend to lack an integration of intelligence to directly inform a designer about the material, structural and constructive capacity of their design. The lack of feedback promotes a practice of generating *immaterial form*, which has some merit on its own, but is limited in terms of what it can contribute to disciplinary or professional concerns.

This thesis is motivated in part by my own interest in addressing contemporary issues in architecture and design through historic inquiry as well as two observations I made in my previous research efforts regarding fast computation and highlight their shortcomings: *the tools alone are not enough to produce creative work; and they currently lack integration of material or constructive intelligence.* In response, I will implement the theories and mechanics of two visual computing methods that provide a means of making material, structural and constructive concerns explicit and visual. The first is graphic statics, which is taught by John Ochsendorf in his Building Structures course at MIT, will be discussed in chapter 1.2, used for the analysis in Chapter 2 on Palladio, and to form basic elements in Chapter 3. The other method is *shape grammars*, originally developed by George Stiny, which serve as the basis for a new structural algebra presented in Chapter 3. Stiny's notion of schemas has been especially important to the

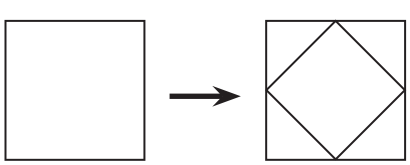


Fig. 0.6. A Shape Rule.

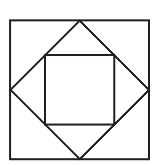


Fig. 0.7. A Shape.

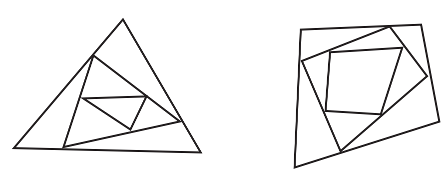


Fig. 0.8. Other Shapes.

a

b

c

d

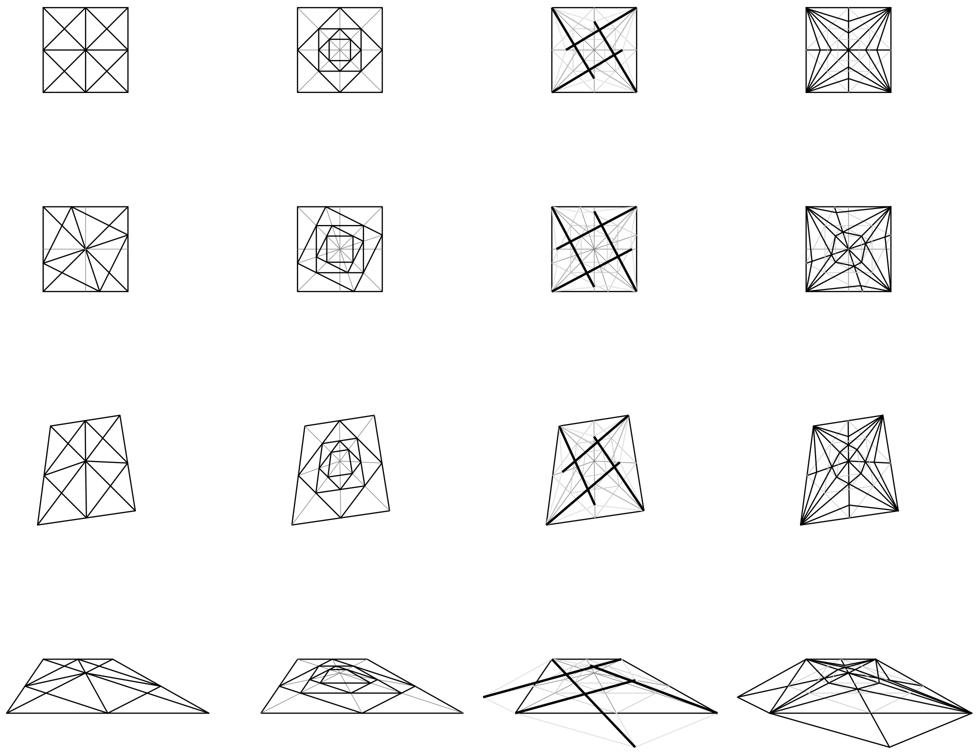


Fig. 0.9. Yanhuitlan rib patterns plans on other shapes by row: a. original pattern; b. twist; c. minor skew; d. major skew.

development of this design research. Schemas are universal rules of formation that can help one see the world in a new way and also suggest realms of possibility for making new designs. More precisely, the reason to identify a schema is to use it in new ways. Schemas suggest other kinds of interactions during the design process. The classic example given by Stiny to describe schemas is of two squares [Stiny, 2006, pg 127]. The shape rule [Fig. 0.6], defined by the schema **x → y** can produce the shape [Fig. 0.7] by applying the rule recursively. Schemas, also generate other shapes *like* the previous one [Fig. 0.8]. There is a striking *likeness* between Stiny's basic two-squares rule and the first step of the design sequence I drew to suggest the method of generating the rib patterns on the vaults of Santo Domingo Yanhuitlan. As shapes they are exactly the same. Although the vaults at Yanhuitlan were square, the drawing system can lay out the rib patterns for a rectangle or for ANY four-sided polygon [Fig. 0.9] The rules are specific yet flexible enough to produce visual variety and some surprises. Most importantly - they work.

Seeing old work in an open-ended and new way captures the spirit of this thesis and the attitude it takes towards the nature architectural design. In particular that *design is visual and non-deterministic within constraints of material systems*.

Fig. 1.1. Beyond the Slab at Beyond Bending at the 2016 Venice Architecture Biennale. Constructed by Salvador Gomis, with Salvador Tomas, Fernando Vegas, Camilla Mileto, Benjamin Ibarra-Sevilla, Jonathan Dessi-Olive and John Ochsendorf. Photo by the author.

1. Introduction

1.1 On Material and Structural Primacy

A major portion of the world's historic buildings are made with unreinforced masonry. For the past two (or more) millennia, stone and brick have been used in remarkable ways despite strict material and structural constraints: they work only in **compression**. It is widely accepted that long before engineers had the means of calculating the stresses in built forms, medieval builders used proportion rules to design their structures. Their rules, of which there is absolutely no written record, were based on material knowledge - the same sort of knowledge I gained from building tile vaults.

Medieval builders had an intuitive understanding of the shapes and underlying geometries that make structures stand up. Their training was tactile and consisted of a lifetime of apprenticeships under more experienced builders through whom knowledge was transmitted. In time, a builder could become a master themselves, having embodied knowledge on material, geometry and assembly. Jacques Heyman, a British engineer who pioneered the modern approach to the analysis of historic masonry structures, suggests medieval design processes would have likely been a matter of "trial and error, by recording past experience and venturing, more or less timidly, into the unknown. Models were also used [...] to prove the stability of the finished full-scale structure" [Heyman, 1995, pg 141]. In the absence of any means of predicting failure by way of numerical (or graphic) calculation, there is little doubt an empirical approach was taken as a means of validating geometrical rules developed over hundreds, if not thousands of years. Despite constructive constraints (compression-only), history is nevertheless rich with evidence of invention and creativity. The builders' rules were essentially correct. They were usually sufficient and reliable enough to build structures that stood up, and yet flexible enough to allow for formal variety and innovation. Passed over generations, their techniques were tested to their limits as builders **slowly** evolved the constructive capacity of their material systems. This is most evident in the Gothic period, which saw some history's most creative and daring developments in unreinforced masonry construction. Tim Ingold, a British anthropologist who recently developed theoretical approaches toward the formation of "things", calls action-oriented and materially conscious creating, the *textility of making*. He describes it as "an ongoing generative movement that is at once itinerant, improvisatory, and rhythmic" [Ingold, 2010 pg 91]. The role of the practitioner, is therefore "not of imposing preconceived forms on inert matter but of intervening in the fields of force and currents of material wherein forms are generated" [Ingold, 2010, pg 92]. He summarizes this as a simple rule of thumb: *to follow the materials* [Ingold, 2007, p. 314]. For Ingold creativity is *in the making.*

This thesis argues in part, that a builder's perceptual understanding of *what* materials to use and *how* to put them together in space is at the heart expanding the creative capacity of a contemporary designer. A master builder's tactile experience working with materials gives way to a visual understanding of the relationship between form and forces, and a capacity to work creatively within the rules set by their materials. This section will show that over history the nature of architectural design has changed. In particular, how or when creative design occurs, and which medium is used for working. **Material and structural primacy** is about promoting a way of designing architecture that uses a greater understanding of the matter and forces at play to catalyze creative production of designs that can be built.

The common belief is, until the establishment of architecture as a *discipline* - roughly between Leon Battista Alberti's <u>On the Art of Building in Ten Books</u> (1443-52) and the founding of the Ecole des Beaux Arts (1682) - buildings were designed by builders from knowledge of known construction practices. Beginning in the Renaissance, it was the role of the *architect* to conceive building designs in advance of construction and describe them in their entirety using a medium that is now inherent to the field: **lines and drawings**. This shift is often attributed to Alberti, whose treatise on architecture begins with the function of what he calls the *lineaments of buildings:*

> "Let us therefore begin thus: the whole matter of building is composed of lineaments and structure [...] It is the function and duty of the lineaments to prescribe an appropriate place, exact numbers, a proper scale and a graceful order for whole buildings and for each of their constituent parts, so that the whole form and appearance of the building may depend on the lineaments alone. Nor do lineaments have anything to do with material [...] It is quite possible to project whole forms in the mind without any recourse to the material, by designating and determining a fixed orientation and conjunction for the various lines and angles. Since that is the case, let lineaments be the precise and correct outline, conceived in the mind, made of lines and angles and perfected in the learned intellect and imagination." [Alberti, 1988 pg 7]

Engineers who study history often see the shift toward design in advance of construction as a “collapse” that is “reflected in the absence of structural interest” [Heyman, 1995 pg 2]. Others suggest, “the Gothic rules were so complicated that no one who had not served a long apprenticeship and spent years of practice could master them; whereas the rules of Vitruvius were so easy to grasp that even bishops could understand them and princes could try their hand at design on their own” [Harvey, 1958]. However, Vitruvius must have been essentially correct with his proportions, which should (and for a large portion of history, did) suffice for building safe and stable structures.

Alberti recast design and creativity as a matter of the **mind**, as opposed to hand or material. According to him, buildings could be formed through a process of thinking and representing as opposed to making (forming). Tim Ingold points to Alberti’s text as the turning point in history where the nature of design changed from the *textility of making* to *hylomorphic formation*. He observes, “the tactile and sensuous knowledge of line and surface that had guided practitioners through their varied and heterogeneous materials, like wayfarers through the terrain, gave way to an eye for geometrical form, conceived in the abstract in advance of its realization in a now homogenized material medium” [Ingold, 2010 pg 92]. Material and structural *primacy* - inherent to the builders’ process - was replaced by the idea that buildings could be produced in advance. Any educated person who could represent buildings in abstract form with the homogenized material medium: the lineaments. The *architect* could leave aside questions of *what* and *how* in favor of producing building forms from pure geometric exploration.

Today, the architect’s medium has not really changed. Indeed - more and more architects are writing scripts and algorithms to conduct rapid generation, and often giant catalogs of geometry such as [Blanciak, 2008], [Moussavi, 2009], [Di Mari & Yoo 2012], and [Di Mari, 2014]. These could be based on any number of predetermined constraints or objectives (structural, environmental, functional, etc). No matter the approach, tools and processes in architecture design are still geared toward the ultimate production of <u>lines</u> that describe (in advance) the form of a building. Though shifting paradigms of making have seen the rise of computer-controlled tools for fabrication and assembly, the role of the architect is nevertheless to produce *instructions for making* (whether in the form of drawings or lines of code for a machine). This has led to a trend of buildings that are conceived of entirely without consideration for material and structure during the creative stage of building design resulting in buildings that are overly heavy structured, waste material, cost more financially, and are more environmentally harmful - all facilitated by the lack of relevant feedback from fast computing tools. Today it is ethical and essential to work toward designing more efficient buildings and constructing them with sustainable materials.

Of course, architects are not universally unaware of the value of knowing the “what” and “how” in architecture. Within the tradition of Modern architects who worked with masonry, Louis Kahn famously (and humorously) inquired with a brick:

You say to a brick, ‘What do you want, brick?’ And brick says to you, ‘I like an arch.’

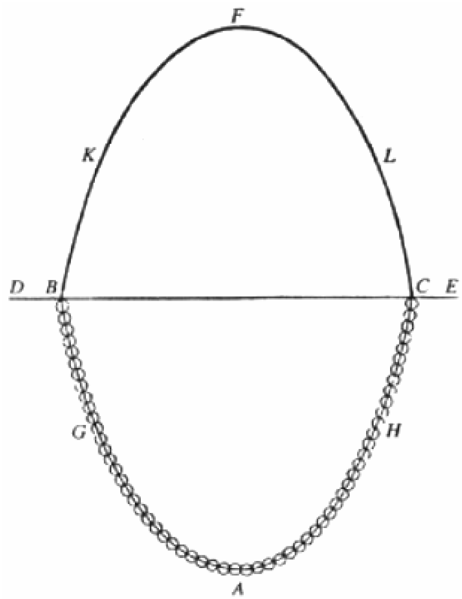


Fig. 1.2. Hook's Hanging Chain. From [Heyman, J. 1995 pg 7].

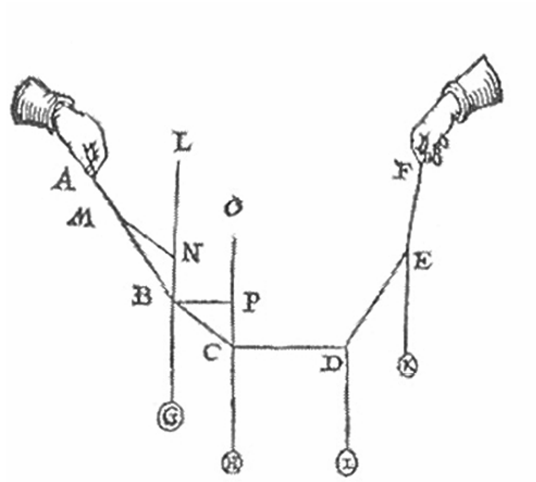


Fig 1.3. A drawing by Stevin of force equilibrium of hanging weights on a string (1586). From [Block, DeJong, Ochsendorf 2006].

Kahn's exchange [Kahn, 1971], though silly, suggests architects should find form by understanding materials the way a master builder would. After all, a mason knows a brick likes an arch, because masons work directly with bricks. Architects do not work with bricks, so rather than *follow* the material, as Ingold would say, they tend to resort to using a preconceived ideas (the lintel). This is illustrated in the second half of Kahn's exchange with brick:

> *And you say to brick, 'Look, I want one, too, but arches are expensive and I can use a concrete lintel.' And then you say: 'What do you think of that, brick?' Brick says: 'I like an arch.'*

Material and structural primacy is a call for the discipline of architecture to rethink the relationship between its media of conception and media of construction. The *lineaments of buildings* [Alberti, 1988] are inherent to how buildings are made today; the tradition is ingrained. The problem with architecture's shift to *hylomorphic formation* [Ingold, 2010] is the lines, drawings, and other forms of geometric production used today lack material and structural intelligence, which in turn, limits the capacity of what architects design and how buildings are constructed. For designs constrained to compression-only, embedding greater material and structural awareness into the lines can help a designer can work intuitively the matter, shapes, and forces at play. Working within the constraint benefits from the possibility to only produce designs that can be built. This is important to address concerns in a discipline where material demonstration is inherent.

1.2 On Equilibrium and Design

This section will demonstrate how to embed an understanding of *what* and *how* in masonry construction into the common lineaments design. The *what* [brick] and *how* [arch] are known, but to embed material and structural knowledge into the lineaments for designing unreinforced masonry, it will be necessary to make visible *why* brick likes an arch.

The reason *why* brick likes an arch is based on the concept of *equilibrium*. An anagram written in 1675 by English scientist Robert Hooke noted the relationship between a chain hanging under self-weight and an arch are equal and opposite [Fig. 1.2]. It read, "as hangs the flexible line, so but inversed will stand the rigid arch" [Heyman, 1995, pg 7]. The forces of the chain are all in tension, and the forces in the arch are all in compression. Hooke's discovery was the first formal understanding of a funicular line - commonly known as a catenary. The basic principles of equilibrium serve not only as a means of analysis for historic buildings, but also as a learning tool for developing a heightened understanding of the relationship between form and forces in masonry structures. Working within this constraint will prove to have some exciting design implications: compression-only shapes are nearly infinitely scalable; they can be built with materials that are low-strength and have low embodied energy; and most critical to this project, the forces in shapes can be computed visually.

There has been extensive work that demonstrates how Hooke's simple concept is sufficient for understanding the structural behavior of brick arches. All unreinforced masonry structures "derive their stability and strength from their shape" [O'Dwyer, 1999]. Scholars who use an equilibrium approach to the analysis of historic structures tend to use *limit analysis* as a theoretical framework, which makes three basic assumptions about the behavior of masonry: i. masonry has no tensile strength; ii. due to low stresses, masonry has effectively infinite compressive strength; and iii. there is no sliding within masonry assemblies. Jacques Heyman, Santiago Huerta, and John Ochsendorf are notable figures who have pioneered the scholarship on the analysis of historic masonry structures, and use limit analysis to demonstrate principles of masonry construction.

Studying the behavior of unreinforced masonry arches - *why* brick likes an arch - brings to light simple yet powerful concepts that offer profound visual feedback about the stability and safety of historical buildings. An arch is safe, according to Heyman, "if any equilibrium state can be found, that is, one for which a set of internal forces is in equilibrium with the external loads, and, further, for which every internal portion of the structure satisfies a strength criterion" (Heyman, 1995, pg 11). Any stable masonry structure has a "family" of thrust lines that can be found embedded in the assembly of the shape [Fig. 1.4]. Furthermore, the *geometric factor*

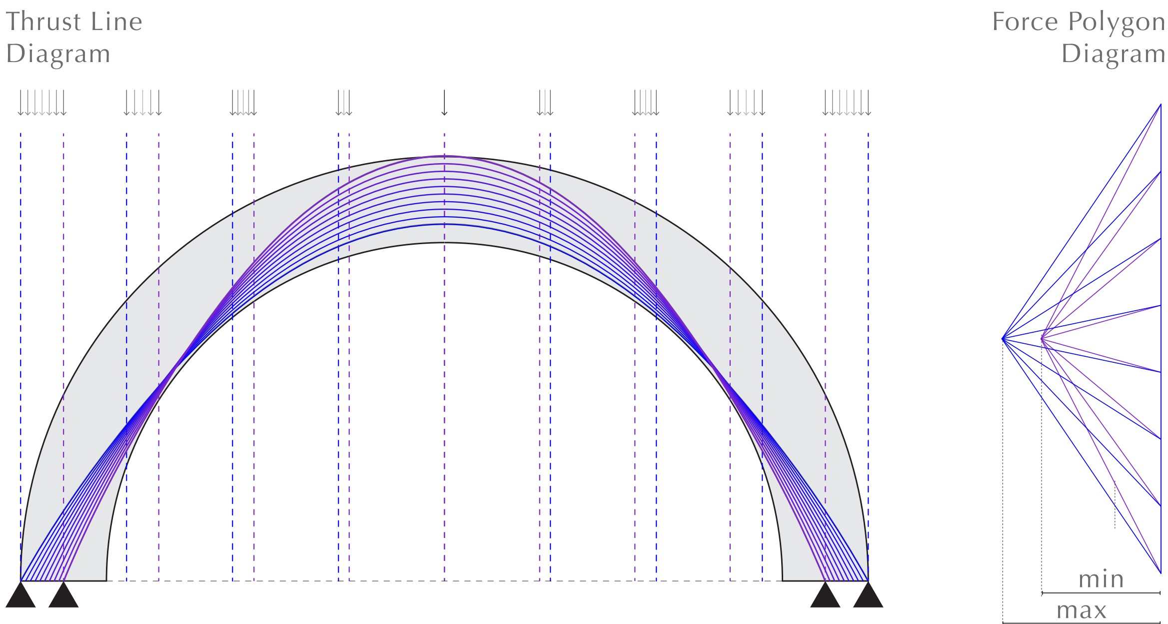
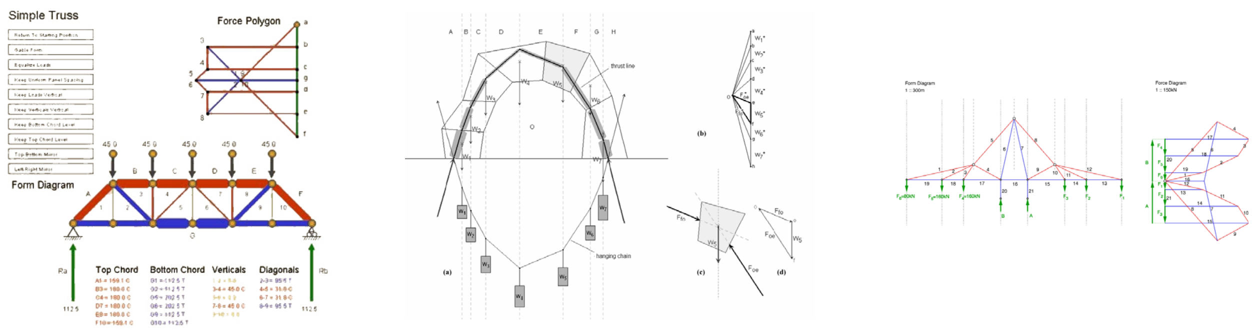


Fig. 1.4. *left,* "Family" of thrust lines embedded in an arch; *right,* Force polygon for generating thrust lines showing minimum and maximum horizontal thrust.

of safety of a structure can be assessed by identifying the maximum and minimum thrusts in the shape. Limit analysis is commonly applied using a graphical method of visualizing one or more lines of thrust passing through the material assembly of a structure. The origins of *graphic statics* are attributed to Simon Stevin's parallelogram rule [Fig 1.3], which made it possible to describe equilibrium graphically using force vectors and closed force polygons [Stevin, 1568]. It was later formalized by Culmann (1866). The method was used by master architects and engineers such as Antoni Gaudi, Gustave Eiffel, Robert Maillart and Raphael Guastavino Jr. to design their masterpieces. Graphic statics grew to be the most common method of computing equilibrium structures until the 1920's when it was replaced by the theory of elasticity [Block, et. al, 2006]. Although graphical analysis is not a replacement for gaining material knowledge through experience building with materials, the drawing method provides immediate visual and analytical feedback about the safety and stability of the design, which stone, bricks and other building materials cannot do. For more background on limit analysis for masonry structures and graphic statics, the reader is encouraged to refer to Heyman (1995); O'Dwyer (1999); Huerta (2004); Block, DeJong, and Ochsendorf (2006); Allen, Zalewski, et al. (2009).

Recent work by a small but growing community of researchers who are interested in leveraging compression-only as design constraint, have developed methods to help designers work with a heightened material and structural awareness. A portion of this work has focused on developing intuitive computational form-finding and analysis tools. As powerful as graphical



a b c

Fig. 1.5. *a*. Edward Allen / Simon Greenwold. Active Statics (early 2000's); *b*. Philippe Block. Thrust Line Analysis (late 2000's); c. Block Research Group. eQuilibrium 2.0 (mid 2010's).

analysis is for generating form with forces, the technique is extremely tedious to do by hand. Computational structural design and analysis tools have seen widespread use since the 1970's*, but only recently have tools been developed based on principles of geometry-based form finding (graphic statics). The first notable example of computer-controlled graphic statics was developed by Edward Allen and Simon Greenwold at MIT call *Active Statics* [Fig. 1.5a]. The web-based software was primarily a learning tool that consisted of a set of interactive (parametric) drawings that were based on graphic statics "for maximum transparency and creative potential" [Greenwold and Allen, 2003]. The software let the user "experiment with the relationship between form and forces" by seeing the changes between the reciprocal form and force diagrams. As the user made changes to the form diagram or increased the loading on the structure, the force diagram was automatically revised. Perhaps importantly though, *Active Statics* suggested how computational methods could be used for the analysis of masonry structures. For his SMArchS thesis at MIT [Block, 2005], Philippe Block produced "applets" of interactive drawings for masonry structures inspired by *Active Statics*, including thrust-line analysis of a random arch [Fig. 1.5b] and animated kinematics to show the behavior of an arch on spreading supports. These 2D research efforts were further developed into his PhD dissertation, which introduced the Thrust Network Analysis (TNA), as a 3D extension of the work on computational graphic statics-based form-finding and analysis. More recently, Tom Van Mele of the Block Research Group (ETH Zürich) built a web-based learning platform using GeoGebra called eQuilibrium [Fig. 1.5c] that has a very similar functionality as Active Statics, but has a much larger set of pre-made interactive 2D equilibrium drawings. TNA was eventually developed into a plug-in RhinoVault, which is a form-finding plug-in that lets users explore

* GROWLTIGER, a software package that emerged from Project Athena - was widely available at MIT. Even Sutherland's Sketchpad in 1963 had a structural analysis component for analyzing trusses based on finite elements.

Fig. 1.6. Armadillo Vault at Beyond Bending. ODB Engineering, Block Research Group and the Escobedo Group. 2016 Venice Biennale. Photo by the author.

complex compression-only shapes in 3D, generated from specified boundary conditions. Since the software is not based on not simulation but rather geometry, it provides an intuitive means of exploring vault forms, and relevant feedback about the of forces in those forms. The tool is a major step toward promoting material and structural primacy in contemporary design and has proved play a significant role in expanding the formal capacity of stone and brick structures.

Intimate knowledge of historical building methods and advanced fast computation form-finding tools have lead to innovations in contemporary masonry construction. In particular, a small-scale free-form tile vault by Laura Davis at the ETH [Davis, et al. 2011]; a large-scale free-form tile vault by David López López in Barcelona [López López, et al. 2016]; most recently the impressive Armadillo Vault [Fig. 1.6] by Ochsendorf, DeJong and Block Engineering, the Block Research Group and the Escobedo Group at the 2016 Venice Biennale [Van Mele, et al. 2016]. This series of increasingly larger, more daring prototypes and pavilions use the principles behind 2D graphic statics and the 3D extension [RhinoVault] to find novel forms based on support conditions, and extending the constructive capacity of bricks and stone to build these forms by relying on digital fabrication technologies to produce complex formwork or accurately

Fig. 1.7. Mapungubwe Interpretive Center, South Africa. Peter Rich Architects with John Ochsendorf, Michael Ramage, Henry Fagan, Philippe Block.

cut stone voussoirs. These examples also benefit from the scalability of stability problems [Block, 2005] by incorporating small-scale rapid prototype assembly models. Recent work has shown that *following* brick can produce successful results from environmental and sustainable perspectives, but also from an aesthetic point of view. Since material strength is essentially negligible they can be built with materials that are low-strength and have low embodied energy (such as earth or aerated concrete) has shown the potential for compression-only masonry forms in contemporary architecture. A material that has seen recent promise is earth - first used at the Mapungubwe Cultural Center in South Africa by Peter Rich Architects, Michael Ramage (Cambridge University), Henry Fagan and John Ochsendorf [Ramage et. al. 2009]; and more recently a proposal for a “Droneport” by Sir Norman Foster [Foster & Partners, 2016] as well as in a prototype for a sustainable floor system at the 2016 Venice Biennale [Fig 1.1].

To summarize, the principles of equilibrium serve not only as a means of studying the structural behavior of historic buildings, but also as a learning tool for developing a heightened understanding of the relationship between form and forces in masonry structures [primacy]. The structural behavior of bricks can be described - visually - to find equilibrium states by computing

Ok Brick, so you like an arch...**now what**?

Fig. 1.8. “Cowboy Construction” [not to be attempted except under strict supervision]. Constructing an extruded arch (barrel vault) without support in Philadelphia. From [Dessi-Olive, 2014].

lines of thrust that pass through a shape. Graphic statics are a means of accessing the principles of equilibrium, thus working with structural awareness, designers can *explore material form through Alberti's lineaments*. The benefits of programming variable graphic statics drawings using fast computation tools are quite clear: "applets" and interactive drawings provide a rich platform for learning about the principles of equilibrium; for more efficiently analyzing historic structures; and generating design content with real-time visual feedback of the stability and safety of a structural shapes working in compression.

Computational graphic statics tools tend to have one major drawback in common: the drawings are preconceived [fixed], which means the range of possible shapes are known from the start - the true flaw of any parametric system. In a publication on the findings of his SMArchS project at MIT, Philippe Block notes, "for the methods employed here, all graphic constructions are prepared in advance, so that the user is not hindered by the need to construct the force polygons." [Block, Ciblac, Ochsendorf, 2006]. The interactive drawings can generate design content that is based on principles of equilibrium, but only let the designer see the forms and forces changing that particular drawing. Predetermined systems have little creative value on their own because a designer is incapable of exploring possibilities outside of the bounds of parametric variation without completely re-programming the system according to other variables, goals, and or boundary constraints. Although graphic statics drawings implemented in fast computation tools promote a means for architects to work with an awareness of the matter and forces at play, **awareness alone is not evidence of a creative capacity**. A builder's tactile understanding of *what* materials to use and *how* to put them together in space (or *why* they stand up) are vital, though technical forms of knowledge. Calculating the shape of a stable structure is a mechanical task, not a creative act. A design is much more than the forces that can be found in it, so the goal should be to develop a means of designing that uses material and structural primacy to *catalyze creative production***.**

1.3 On Slow Computation

A brick likes an arch. *What* material is being used and *how* to put it together in space is pretty clear. The basic principle of equilibrium described by Robert Hooke's anagram, answers the question of *why* - or for design purposes - *if* brick likes an arch. The medieval builders knew brick wanted an arch. That was given by their material knowledge gained from working with bricks. It's what they did with bricks forming arches that counts.

Earlier, the term **fast computation** was introduced to describe a design enterprise concerned with the rapid production of evocative geometry using digital modeling, simulation, and scripting techniques; often satisfied with rapid prototype models as proof of concept for building designs. More now than ever before, digital computing power allows designers to fully enumerate and visualize results within the bounds of preconceived variables, goals, and constraints. Two shortcomings were identified in regard to the productive role of fast computing tools for designing with masonry structures:

a. common digital design environments lack necessary integration of material, structural intelligence to directly inform full-scale construction and thus promotes a practice of generating immaterial form.
b. computational tools alone are not enough to produce creative work.

Section 1.2 *On Equilibrium and Design*, showed how graphic statics is *like* working with the matter, shapes, and forces of masonry, and fast computation makes doing that work...faster. Form-finding is an active though mechanical process that generates design content. The focus on enumeration using fast computation has drawn architects' attention toward programming tools to make families of design possibilities. Even if all those possibilities are generated with material and structural *primacy*, the results are still routine design possibilities within preconceived boundary conditions. Following forces to make forms is evidence of material knowledge, but not itself a creative act. This thesis takes a critical approach toward technology in the context of doing creative design and proposes a methodology that leverages an awareness of the matter, shapes, and forces at play in masonry structures to catalyze creative production. The goal is to leave aside obsessions with giant catalogs of related of forms and SLOW DOWN.

In the last decade the value of slow-ness has started to be promoted among designers. Carolyn Strauss defined the "Slow Design Principles", which outlines the generation notions and benefits of slowing down design activities. The first principle, which says "slow design reveals experiences in everyday life that are often missed or forgotten, including the materials and processes that can be easily overlooked in an artifact's existence or creation", [Strauss, 2008] resonates quite well with the idea of material and structural primacy being promoted in this thesis. The shortcoming of Strauss' article, is it does not offer a particular attitude toward technology. Terry Knight's chapter on teaching generative design with *shape grammars* using "slow computing" which "promotes the unique visual/perceptual, non-digital, and expressive features of shape grammars and gives students mastery over rules, computations, and their outcomes." Knight concludes that although fast computation is often needed for design, their successful use "always depends on slow, reflective thinking of the kind engendered by slow computing" [Knight, 2012]. Shape grammars were first defined by Jim Gips and George Stiny [Stiny and Gips, 1972] and later generalized to parametric shape grammars [Stiny, 1977]. Research on shapes and shape grammars has been on-going since and have been developed for design analysis and synthesis in many fields such as architecture, landscape architect, craft, as well as art and structural design. For more background on limit analysis for masonry structures and graphic statics, the reader is encouraged to refer to journal articles by George

Stiny (1980a, 1980b, 1985, 1989) as well as Stiny (2006). Other notable contributions to shape grammar research by other scholars include Koning and Eizenberg (1981), Downing, F. and U. Flemming (1981), Knight (1989, 1999), Durate (2005), and Muslimin (2010).

Slow computation, as it its being defined here expands the reach of Knight's definition to include methodologies that bring to light issues of material and structural primacy. It is an intentionally named antithesis of the fast enterprise, to describe any graphic, visual, or haptic computing method that promotes creativity through open-ended exploration. Good design does not happen quickly, and is usually less concerned with generating content. A Medieval builder's creative capacity was in their ability to work *with* technical knowledge. Their creativity manifested in the way they saw new ways of using the rules set by their material worlds. Slow computation is a practical context for systematically looking at historical content as well as a theoretical context for design and research. It's a means for designing with primacy in a visual and open-ended way. Slow computation methods are relatively easy to learn, intuitive and generative (in the sense that they provide designers with infinite possibility within the rules that regulate of their respective media). Their graphic, visual, or haptic nature is vital because it requires some form of sensorial feedback during design/exploration (calculating) processes. Examples of these methods that are traditionally done in 2D drawings include shape grammars and graphic statics, which will serve as the basis for analysis, design and discussion in the next two chapter of the thesis. In the context of compression only design, this definition of slow computation also includes analog form-finding computers - such as hanging chain or soap bubble models famously used by masters such as Antoni Gaudi, Heinz Isler, and Frei Otto - which offer a scalable means of designing with physical material. Lastly, construction at full-scale is also included in this definition of slow computing. Though ambitious, the ultimate goal behind these analysis and design activities is to gain an intuition for matter, shapes, and forces and shift how (with which media - digital or not) and when creative design occurs (is design preconceived or action-oriented?).

1.4 Problem Statement

A brick likes an arch - these are the *what* and *how*, central to a builder's material knowledge. The basic principles of equilibrium explain *why* brick likes an arch. Graphic statics make visible the nature of the material world and describe the relationship between form and forces. This is useful to find out *if* brick likes a design. As the master builder's sensory understanding of *what* materials to use, and *how* to put them together was lost to a disciplinary approach to architectural design in the Renaissance, a body of work emerged conceived of without consideration for material and structure. The current lack of integration of material and constructive intelligence in contemporary design methods has resulted in buildings that are overly structured and wasteful. Today it is ethical and essential to work toward designing more efficient buildings and constructing them with sustainable materials. Working immaterially is counter-intuitive and limits the capacity of what architects design and how buildings are constructed.

Problem Statement (in the context of creative design with compression-only material systems): *Though fast computation can generate content with material and structural primacy, the tools alone are not enough to produce creative work because they lack a means of working that is open-ended and based on visual intuition, rather than mechanical formation.*

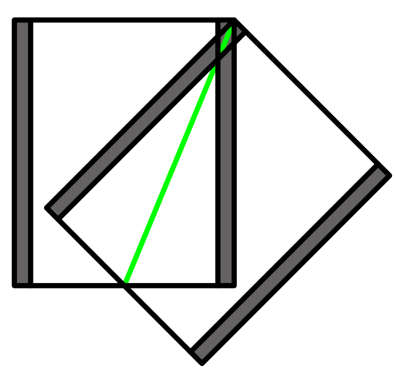
This thesis is motivated by my own interest in addressing contemporary issues in architecture and design through historic and constructive inquiry. My contention is by working within a compression-only constraint, there is a possibility to develop a way of working that only produces designs that can be built. **This project is not about finding compression-only forms - rather - designing WITH them.**

1.5 Thesis Statement

A new structural algebra - characterized by equilibrium constraints - will be specified that lets architects and designers to work visually and non-deterministically with material and structural primacy; to feel the forces in shapes. By extracting structural design rules from history with slow computation methods, it is possible to produce creative yet build-able designs that expand the capacity of what architects design and how buildings are constructed in the future.

This thesis takes a critical approach toward technology and proposes a slow computation methodology that uses an awareness of the matter and forces at play to catalyze creative production. At the scale of architecture, structure is unavoidable. Having the capacity to intuit structure would make it possible to improvise and to design directly with the "stuff" of architecture [matter, shapes, and forces]. I will not be developing any particular designs of things, nor will I construct any new masonry structures. That sort of exploration is better left to the design studio.

In the next chapter, *An Inquiry into Palladian-ism,* I will take a closer look at a well known historical building, designed by the Italian Renaissance architect who wrote what could be considered the first comprehensive architectural design textbook: Andrea Palladio and I Quattro Libri dell' Architettura, first published in 1570. From a scholarly perspective, very little work has been done in terms of looking at the stability and safety of Palladio's buildings as unreinforced masonry structures - and yet, the villas in particular were made primarily out of brick that was plastered over and often painted to look like stone [Ackerman, 1966, pg 68]. An inquiry into the Villa Foscari, "La Malcontenta" will seek to develop material, structural and constructive knowledge. In the third chapter, *A New Structural Algebra*, design rules will specified according to that historical knowledge and define the generative machinery for a slow computational design system. The methodology is inspired by the theories and mechanics of shape grammars and graphic statics **as means of working between traditional architectural media: drawing and masonry construction.** The contention is working this way offers a means of designing masonry structures that bares on contemporary disciplinary concerns by showing how designing within the constraints of a masonry arch does not have to be mechanical or deterministic, but rather is open-ended, imaginative and creative. Although the methodology proposed does not extend to making designs, the way the rules are set up within equilibrium constraints results in the possibility to construct anything in the algebra of shapes. Learning to compute with matter, shapes, and forces, brings to light the relationship between current design technologies and methods, and our necessity to make breakthroughs in techniques of assembly and construction.



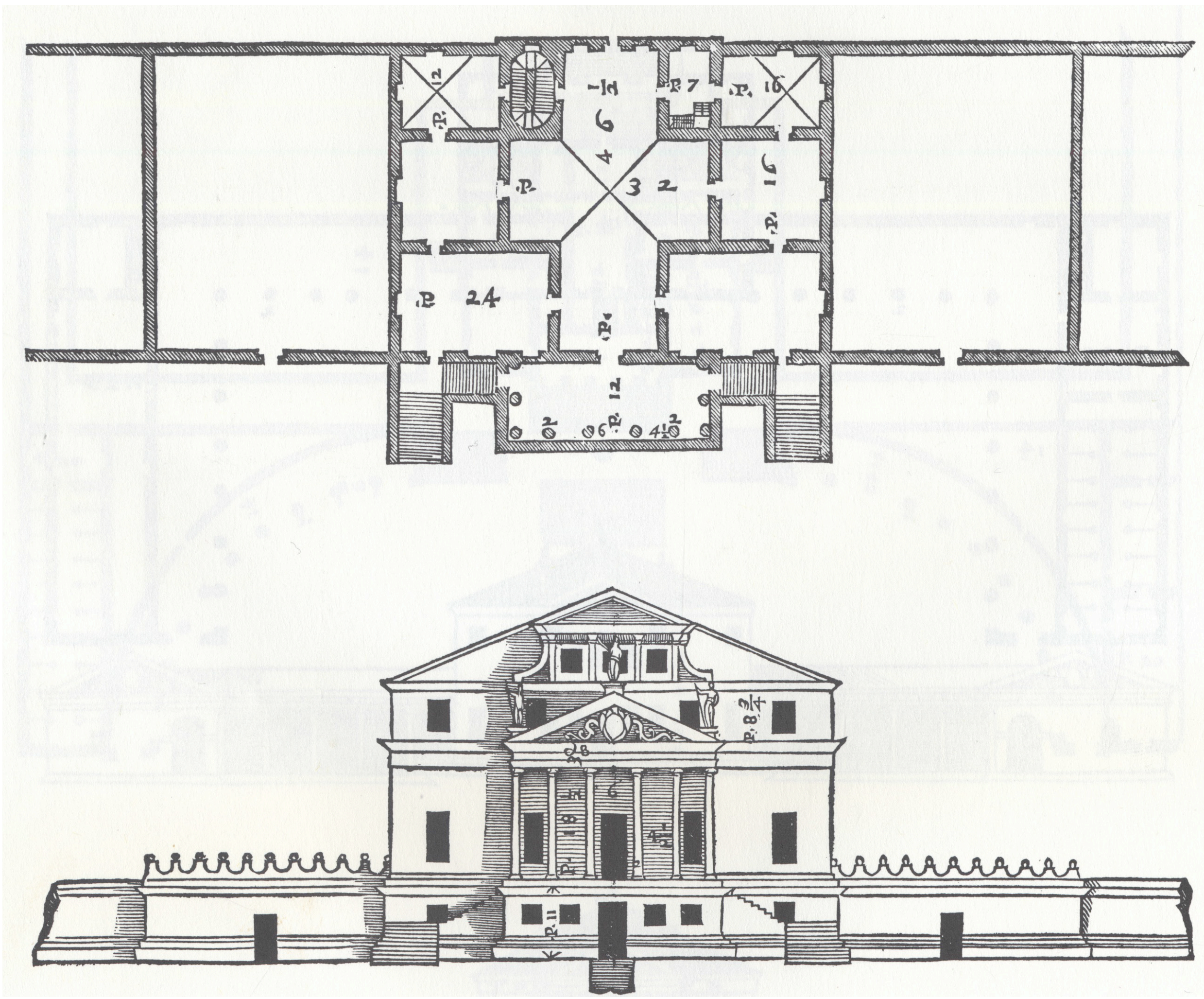


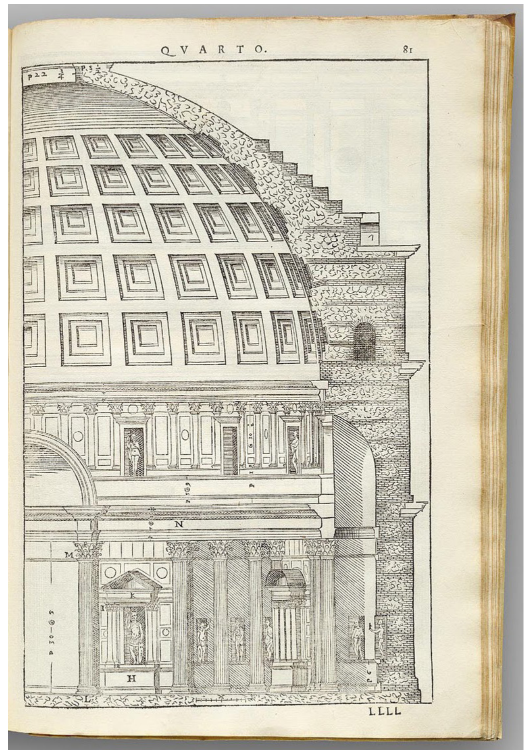
Fig. 2.1. Woodcarvings of Villa Foscari, “La Malcontenta” from Palladio, Quattro Libri.

2. An Inquiry into Palladian-ism

2.1 Why [re]Study Palladio?

Earlier, the Renaissance was identified as a period in history when the nature of architectural design changed with the establishment the *discipline* - between Leon Batista Alberti's On the Art of Building in Ten Books (1443-52) and the founding of the Ecole des Beaux Arts (1682). Architecture became a *matter of the mind* (not material). Alberti was very clear that the *lineaments of buildings* were immaterial [Alberti, 1988 pg 7]. When and where creative action occurred in the process of making buildings was shifted by the architect. The intentional disconnect between design and the matter, shapes, and forces of physical world was adopted as tradition and is ingrained in how architects work and how buildings are made today. At the time of this shift, the builder's perceptual understanding of *what* materials to use and *how* to put them together MUST have been translated into significant Renaissance texts. Of all the architects from the Italian Renaissance, Andrea Palladio is perhaps one of the most studied and imitated. Throughout Europe and North America his influence is unmistakable: symmetrical facades with columnated porticoes topped by pediments; some of key features that mark the *Palladian style*. This is especially true for late 18th and 19th century architecture in England and the United States. Palladio's buildings have been regarded by many generations to be the perfect embodiment of classical traditions, in part because of his overt references of the classical Greek and Roman antiquities. His imitators, such as Thomas Jefferson whose buildings are essentially undecorated imitations, are drawn to a certain aesthetic harmony [Ackerman, 1966].

Aside from his buildings around the Veneto built over his fifty-year career (a number of which still standing today), Palladio's most significant disciplinary contribution is his treatise, I Quattro Libri dell' Architettura (The Four Books on Architecture), published in 1570 [Palladio, 1997]. He lived and worked at a unique moment in history where scholarship and technology permitted him to study the past and develop his own *architectural system*. The *Quattro Libri,* serve both as a textbook on historic building design, construction history, and a manual on



a b

Fig. 2.2. Palladio's historical analysis: a. the Temple of Vesta in Tivoli; b. the Pantheon in Rome; Pages from the *Quattro Libri*.

how to design and construct new buildings. Palladio distilled historical building knowledge and his scholarship of classical architecture - seen with his eyes and measured with his own hands [Palladio, 1997, pg 3]. He demonstrated how intimate knowledge of historical buildings and construction methods could be used for making new designs. **Rules** were extracted (the generative machinery) to define a "usable system of measurements and proportions" [Ackerman, 1966, pg 29]. Many of the rules were likely taken from Alberti and Vitruvius, and presented as a set of instructions; a written provision of the essential principles of architecture that "must be followed by all intelligent men eager to build well and gracefully" [Palladio, 1997, pg 3].

Palladian scholars are particularly fascinated by the architect's rigorous use of proportions, not only as visual tools for aesthetics, but also to control the width, depth and height relationships of spaces [Appendix A]. Ackerman describes the interrelationship between the various parts of the design being "tightly knit as an organism" [Ackerman, 1966, pg 161]. Palladio conveyed his system in the *Quattro Libri* both in written text and in drawings - adhering to Alberti's assertion that, "the whole matter of building is composed of lineaments" [Alberti, 1988 pg 7]. Palladio's designs, were essentially motifs that demonstrate the capacity of his system to produce a variety of buildings of different uses and scales. Palladio copied history to make new designs and he expected his readers to copy him in the future.

Although his system may not have had clear structural or constructive *primacy* (both engineers and architectural historians tend to claim Renaissance architects lacked any interest in structure, compared to the Gothic builders), the fact is Palladio and his contemporaries were equally constrained as their predecessors from a technological and constructive standpoint. The same rules governing construction during the time of Vitruvius and middle ages still applied during in the Renaissance. How complex, technically heroic, or dangerous a building was to construct are insufficient measures of the knowledge or interest in structural principles during a particular historical period. The extensive use of masonry and vaults in Palladio buildings mean structural principles could not be totally disregarded. Compared to his Gothic predecessors, whose daring structures were carved entirely of stone for the Church, Palladio's private clients likely had neither the time, budget, nor acceptable risk of failure to use stone in such a manner. The rise of a wealthy, educated middle-class of clients meant Renaissance architects had to meet a greater demand for new forms of buildings - notably the villa, for which Palladio is perhaps most famous. It may have been out of practical necessity that architects sought solutions for faster, cheaper, and safer construction in rough brickwork, coated in stucco, rather than push the formal (and structural) capacity of stone.

As one of the most studied architects in history, the scholarship on Palladio is vast and voluminous. It seems worthwhile to address the question: **why [re]study Palladio?**

(1) Preservation - his buildings are important to preserve not only as symbolic or social heritage (art, culture, economics). Many of Palladio's buildings are still standing some 400 years later, so there is a unique opportunity to study a Renaissance master both in theory [the *Quattro Libri]*, and in practice. A systematic method of analyzing the stability and safety of Palladio's buildings (especially the Villas) should be developed.

(2) Design - those who study Palladio have tended to focus on the context that permitted him to produce so much work compared to his contemporaries, whether the buildings are true to his own system, or seek some hidden essential truth - an ideal - in his drawings and proportional relationships. Few, however, have commented on how the system in the Quattro Libri addresses concerns of construction and structure. This project is attempting to work like Palladio: to extract concepts of masonry/historical construction to bring an awareness of the matter, shapes, and forces at play between masonry structures to contemporary design. Though design is constrained to compression only, history also demonstrates how the technology is generous enough to allow for creativity and innovation.

a

b

Fig. 2.3. a. Portrait of Palladio; b. Cover page from *I Quattro Libri dell' Architettura, 1570*. Both images from [Palladio, 1997].

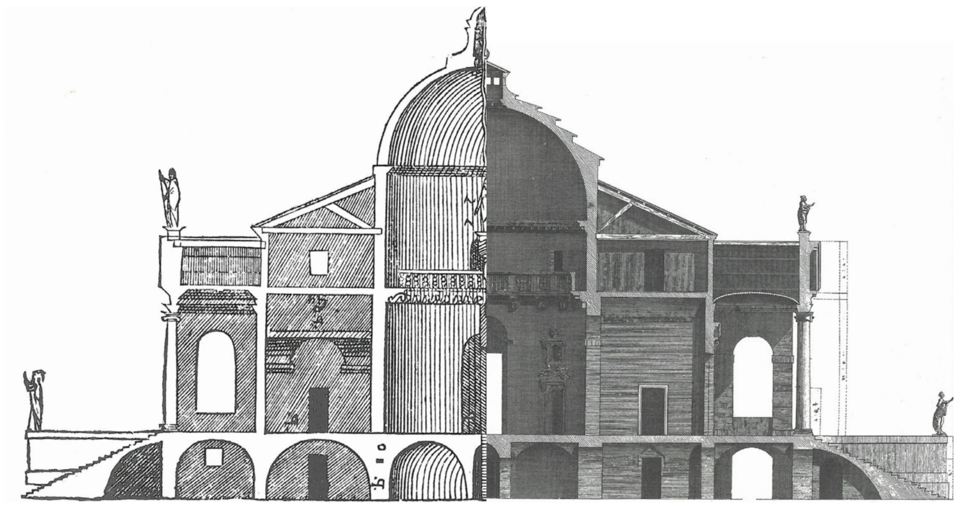
2.2 Background on Palladio & the Quattro Libri

Born Andrea di Pietro dalla Gondola in 1508 in Padua, his career is marked by historians to have begun at age thirteen, when he began an apprenticeship as a stone mason [Mitrović 2004, pg 13]. In the late 1530's, he came into contact with the Count Giangiorgio Trissino, a Vicentine aristocrat, humanist scholar, poet, and an amateur architect. During his time in the entourage of Trissino, he was given the name Palladio, introduced to architectural scholarship (especially that of Vitruvius, but also Bramante, Serlio, and others), and traveled to Rome on numerous occasions to study and draw buildings of antiquity. During his travels, he sketched and measured buildings, usually drawing them in flat projections to accurately record their design as opposed to their visual impression [Ackerman, pg 26]. Although this was becoming common practice among architects in the late Renaissance, it is significant because prior to this time, the main source of information on buildings and building design had to be pieced together from written description (Vitruvius and Alberti are exceptions to this), rather than clear, dimensioned graphic representations as we are accustomed to today.

The significance of Palladio's scholarship is the way he used history as the source of knowledge for basic design and construction principles to derive his architectural system. His treatise has come to be one of the most influential architecture books from the Renaissance and has been studied extensively since its publication. The *Quattro Libri* covered: fundamentals of architecture and the orders; domestic design (mostly his own designs); public and urban design and engineering; and temples. The books were meant to simplify (not extend) the understanding of ancient architecture [Ackerman,1966, pg 29] and were written in the form of clear and economical instructions. The drawings accompanying the writing are of buildings he designed [Fig. 2.1] and of classical buildings he had saw and documented on his trips to Rome [Fig. 2.2]. He used woodblocks, though an imprecise means of reproduction and likely the cause of later scandal, to teach his usable system of measurements and proportions [Ackerman 1966, pg 29]. Palladio's expectation was that by offering his experience in this form, others after him could use their own intellectual acuity to make creative designs that were historically and economically relevant.

Palladio's professional ambition differs substantially from his predecessors and contemporaries - neither of whom documented their work and scholarship so rigorously, nor worked on as many buildings. Alberti, who inspired Palladio quite heavily, developed a complete theoretical basis for design [Alberti, 1988] but did not produce a body of built work to demonstrate its use in the field. Brunelleschi and Bramante's exceptional works (the duomo in Florence, St. Peter's, etc) are unique and singular examples of their design and technological genius largely due to the nature and scale of their commissions [Burns, 1975, pg 205]. Regarded the most system conscious architect of the Renaissance [Burns, 1975, pg 7], Palladio is an example of how a systematic approach to design, which provides spatial, aesthetic, constructive rules (and also structural, as this paper will attempt to prove) can be developed in theory and practice. The rules can be specific without being restrictive, which produces a diverse and creative body of built work at a wide variety of scales, whether a villa or a Basilica.

Palladio's early works (1540s) were primarily a series of villas for patrons around Vicenza. Although these projects do not exhibit the level of refinement in his use of the system, they nevertheless demonstrate a clear stylistic and cultural differentiation when compared to villas by his contemporaries in other regions of Italy. These early years were formative though because by the 1550s Palladio shows maturity and refinement in the way he deploys his system. He went on to design eleven more villas (surviving) including villa Foscari (discussed at greater length in this paper) and perhaps his most famous building, the villa Rotonda. Palladio's late career, until his death in 1580 was dominated by nine Palazzos in the Vicentine region, public buildings in Vicenza - the Basilica (1549) and the Theatro Olimpico (1579) in Vicenza are perhaps his most famous. He also built a number of ecclesiastical buildings in Venice, such as the church of San Giorgio Maggiore (1565), Il Redentore (1576) and the Tempietto at Maser (1579). The reader is encouraged to see [Ackerman 1966, pg. 14] for a complete list of the surviving works of Palladio.



Andrea Palladio, 1570 Ottavio Bertotti Scamozzi, 1786

Fig. 2.4. Sections of Villa Rotonda - split to show discrepancy between Palladio's drawing from the *Quattro Libri* (left) and as-built measurements by Scamozzi (right).

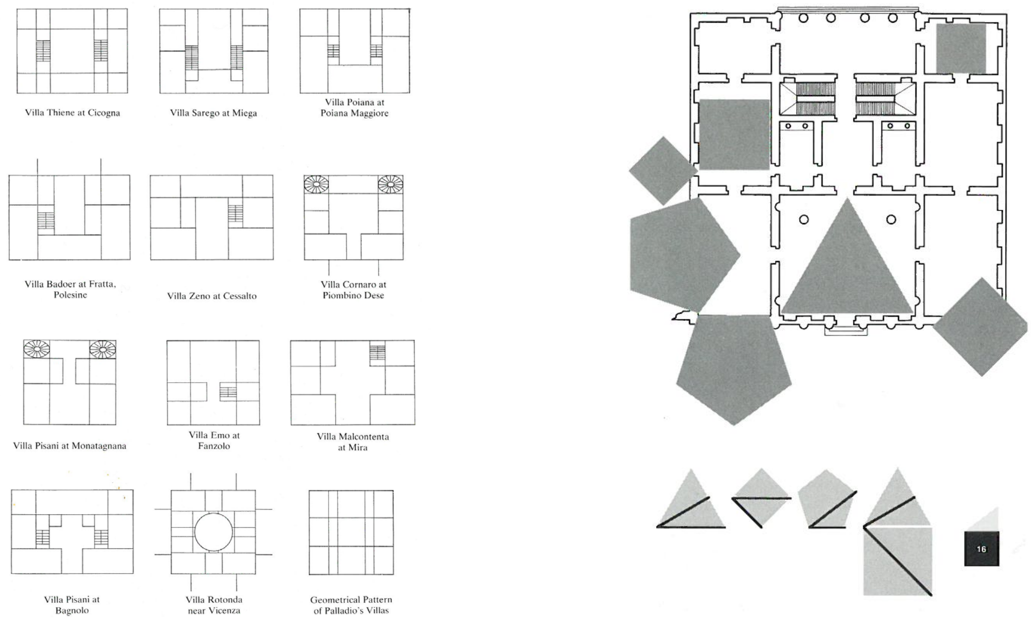
2.3 Review of Historical and Analytical Literature

The scholarship on Palladio and his work is vast and varied. A complete review of all the literature on Palladio is an undertaking that would take an entire career to complete; a task some architectural historians have chosen. Since the focus of this paper is on the structural aspects of Palladio's system, a section of the scholarship has been selected that focuses on the buildings themselves and primarily take the form of speculations on how the works were designed and built and, their formal properties. The goal of this literature review is to demonstrate that the major authors tend to avoid specific questions relating to the structural performance of Palladio's buildings, whether due to lack of expertise or because of the widespread opinion that Renaissance architects were completely uninterested in questions of structure. Though structure may not have been the *primary* concern of Renaissance architects (with the obvious exception of Brunelleschi), it could not be ignored altogether considering the technological and constructive limitations of the time.

Compared to the other great architects of the Renaissance, there is one distinct advantage to studying Palladio: his *Quattro Libri* are an invaluable primary resource that provide a wealth of information and give a unique window to how the architect thought about design, construction, and how he saw those rules being deployed. Although many of his buildings have survived, very few reliable documents of his buildings exist. The first extensive collection of surveys was made by Ottavio Bertotti Scamozzi, just over two-hundred years after Palladio. Scamozzi's dissertation [Scamozzi, 2014] first published in 1786, is a unique record of Palladio's buildings in reality as opposed to how the architect drew them in the *Quattro Libri.* Scamozzi's motivation for such an undertaking stemmed from the observation that there were major discrepancies between Palladio's designs as they were depicted in print and how they were built. Many scholars tend to dismiss Scamozzi due to the inaccuracy of his drawings, but they can nevertheless be valuable historical artifacts for developing preliminary hypotheses about Palladio's designs and for developing a systematic method for analyzing his buildings. Recently, Professor Takehiko Nagakura (MIT), whose work in part focuses on digital heritage, has led teams of students on pilgrimages of Palladio's buildings around the Veneto to document and capture them with 360 degree video and photogrammetric building scans [Nagakura, 2015]. These scans are a valuable resource and could play an important role in preserving Palladio's buildings, which are monuments of architectural heritage. Future work should involve applying the proposed method of analysis (section 2.4) to those scans to determine (and validate) the safety and stability of the buildings.

There are many 20th C historians whose biographies of Palladio are noteworthy, but tend to lack any emphasis on technical issues. Howard Burns, is an eminent Palladian scholar, who provides an in-depth analysis of the context Palladio worked, his education, development and adherence to a design system in Andrea Palladio 1509-1580: The portico and the farmyard (1975). Only in the final paragraph of a short section on "Building Materials and Structural Solutions", does he briefly mention structural solutions. Palladio's use of brick for constructing vaults is included in one single sentence: "When possible, Palladio employed vaulted ceilings, which diminish the fire risk" [Burns, 1975, pg 209]. Beyond their utility for fireproofing, the author does not comment further on Palladio's use of vaults (which are above the basement and first floors of most of his villas). Perhaps the most well known and widely referenced book on Palladio is James Ackerman's short yet thorough biography simply titled, Palladio (1966). Ackerman focuses on the architect's uniqueness as a designer, provides an overview of his body of work, and the surrounding social and cultural context in the Veneto. In his final chapter on the principles of Palladio's architecture Ackerman notes the architect's use of proportions is often conditional. He explains, "whatever their source, numbers related by proportionality are indicated in every design in the *Quattro Libri,* though in many cases structural or utilitarian needs demanded the inclusion of unrelated measurements" [Ackerman, 1966, pg 162]. No examples of these special structural cases are given however - he only briefly explains that Palladio would break his own proportional rules because he could be "as practical as he was abstract" [Ackerman, 1966, pg 165]. Italian historian Lionello Puppi (like Ackerman and Burns) focuses on the context of Palladio's work and the social and economic environment in Vicenza in Andrea Palladio (1975). These experts on Palladio provide (at best) a vague mention of the structural elements of the buildings and no mention of the necessary structural considerations or rules Palladio must have had and used in order to construct them.

Rudolf Wittkower's Architectural Principles in the Age of Humanism from 1949 looks at the compositional aspects of Palladio's designs. Like Scamozzi before him, Wittkower looked for



a b

Fig. 2.5. *a*. Wittkower's schematized Palladian Plans; b. Palazzo Antonini, Udine by Palladio with regular polygons defining the principal proportions. From [March, L. 1998, pg 238].

an adherence to classical conventions in Palladio's work. He searched for truth and order in the drawings. For example, in discussing symmetry he invokes Vitruvius' definition of 'symmetria' but discusses it only in terms of aesthetics - taking for granted that Palladio's buildings consist of clusters of masonry vaults that may require symmetry as a structural and constructive solution. Wittkower believed by looking at a few "typical plans ranging over a period of about fifteen years [he could] prove that they are derived from a single geometrical formula" [Wittkower, 1988, pg 68]. His formula was a generic "pattern" he believed acted as the "fundamental geometrical skeleton" for systematically generating Palladian villa plans [Fig 2.5a]. The fundamental flaw in Wittkower's hypothesis is building plans have wall thickness. From the standpoint of making architectural plans (or actual buildings, for that matter), Wittkower's pattern does not suffice to inform or comment on questions of design, structure, or construction. Wittkower also has a hypothesis about Palladio's intent to use musical theory harmonic proportions, which Ackerman also makes reference to [Ackerman, pg 162] but it is a controversial interpretation. Wittkower inspired a number of scholars after him to outright reject his claims about design in the Renaissance. Some responses rejecting Wittkower's claim attempted to clarify the mathematics of the proportion systems they saw in the *Quattro Libri* [Fig 2.5b] including, Architectonics of Humanism (1998) by Lionel March, and Learning from Palladio (2004) by Branko Mitrović. Both

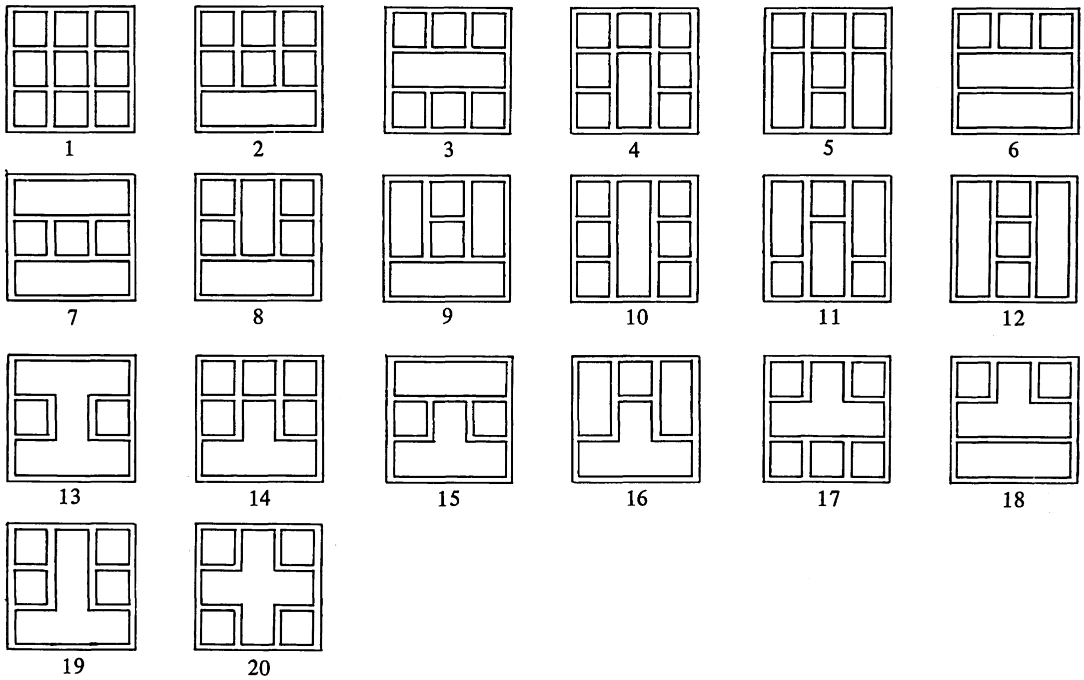


Fig. 2.6. The enumeration of all 3x3 plans using the *Palladian grammar* rules from [Stiny & Mitchell, 1978b].

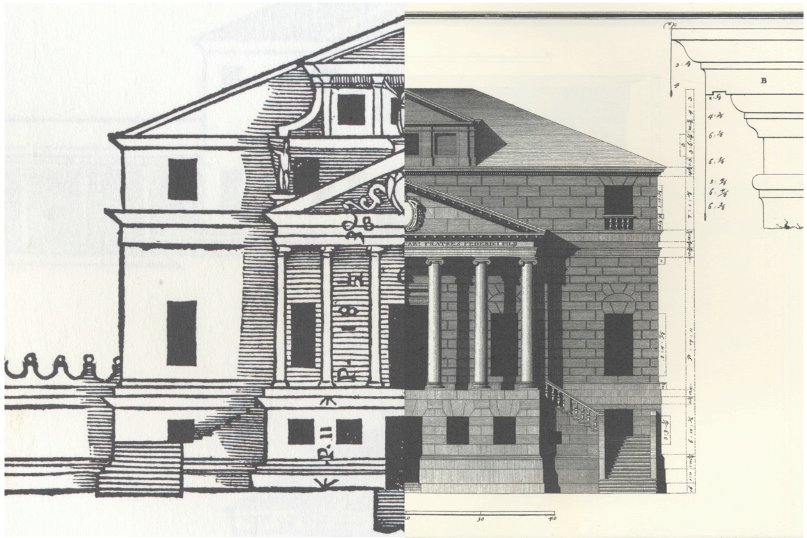
authors' analyses of Palladio are interesting and enjoyable, but neither addresses questions of material, structure, or the buildings themselves outside of the classic question that lingers about the discrepancy between the buildings and the designs in the *Quattro Libri*.

Lastly - and most influential for this thesis - is an article by George Stiny and William Mitchell called *The Palladian grammar* (1978a) that reexamined Palladio's architectural language from the *Quattro Libri*, "in a modern, generative form." Stiny and Mitchell clearly state their focus on studying Palladio's villa *plans* (as opposed to other aspects of the system), as a response to typical Palladian scholarship (in particular Ackerman and Wittkower), which overwhelmingly suggests "the distinguishing feature of Palladio's villas is the 'systematization of the groundplan'" [Stiny & Mitchell, 1978a]. Palladio's system is treated as a *generative mechanism* for villa plan designs based on geometry, but general assumptions are made about dimensions - notably the thickness of the walls. A *parametric shape grammar* was specified consisting of *rules* based on what the authors saw when they looked at examples of villa plans. The rules [Fig 3. 2] are categorized into eight computational "stages" and generate the different parts of the floor plan drawings of Palladio's villa designs as they are found in the *Quattro Libri*. In the article, the floor plan of the villa Foscari is computed as an example. The authors also suggest the possibility of computing other, new plans they contend are in a "family" of designs in the Palladian style [language].The grammar - which is not defined to suggest Palladio's process, rather to show the generative possibility of systematic design - is used to enumerate new possibilities of plans [Fig 2.6] that look *Palladian* [Stiny & Mitchell, 1978b]. The Palladian grammars are evocative because they demonstrate a *new way of looking at historical content* and invite a discussion about design based those observations. The specifics of the Palladian grammar will be discussed further in Chapter 3 and serve as the schematic foundation for the structural algebra being proposed in this thesis.

With the exception of Stiny and Mitchell's analysis of Palladio that brought to light the generative capacity of his design system, the historical and analytical scholarship on Palladio (*Palladian-ism*) is overwhelmingly concerned with making speculations on the Renaissance architect's process, narrative about social, cultural, and economic context; or investigations seeking to find proportional [mathematical] ideals in the drawings. The major authors on Palladio do not discuss the validity of the drawings (or the written design rules) from the *Quattro Libri* in terms of their forms and forces. The buildings that today still stand over four-hundred years after Palladio, are proof that his architectural system worked - somehow. Though the majority of authors, in particular Scamozzi, note the discrepancy between the designs and the real buildings. The next section will - slow down - take another look at the plan Villa Foscari, through the lens of material and structural primacy. In addition to Stiny/Mitchell's example computation of the villa in *The Palladian grammar* (1978), Foscari is described at length by Ackerman (1966), Burns (1975), and Puppi (1975), and analyzed by Wittkower (1949), March (1988) though purely in terms of its underlying geometry, not its material and structural principals. By looking at forms and forces implied in drawings by Palladio and Scamozzi, the goal is to gain a formal and compositional intuition of how unreinforced masonry vaults interact next to each other in a design. Furthermore, it will serve to validate the shape rules in George Stiny and William Mitchell's Palladian grammar rules and form the basis for masonry vault schemas.

2.4 Another Look at Villa Foscari

Palladio's drawings in the *Quattro Libri* are evidence of the shift from *textility of making to hylomorphic formation* [Ingold, 2010], almost exactly in between Alberti's treatise (1443-52) and the founding of the Ecole des Beaux Arts (1682). Though some of the drawings included by Palladio were retrospective, many were also speculative, which implies design occurred before construction. Although its is quite true that structural concerns may not have been *primary* for Renaissance architects - as it was for their Gothic ancestors - the constructive constraints still applied during the Renaissance. At the time Palladio first published the Quattro Libri in 1570, there was no means of analysis to determine the safety and stability of masonry assemblies. Robert Hooke's discovery of the inverse relationship between tension and compression in a



Andrea Palladio, 1570 Ottavio Bertotti Scamozzi, 1786

Fig. 2.7. Elevations of Villa Foscari - split to show discrepancy between Palladio's drawing from the Quattro Libri (left) and as-built measurements by Scamozzi (right).

funicular curve was not for another 100 years. Palladio's experience as a mason would position him perfectly to translate material knowledge and formal intuitions from learning to build, through the lessons from Vitruvius and Alberti, and deliver an architectural design system that can translate accurately to built form. If the *lineaments* (which make shapes) can represent unreinforced masonry vaults in plan, then *the rules of formation for those shapes need to be more materially and structurally informed in accordance to the rules of formation of the material world.*

<u>Research Question</u> (and sub-questions):
The larger question is, do the drawings and written rules in Palladio's proportional design system sufficiently promote build-able design? This will be addressed by taking another look at the Villa Foscari, *through the lens of material and structural primacy*, to determine if and why the building design is stable and safe using graphical equilibrium methods. Assuming the villa is made of brick vaults below the second floor, the structure should behave only in compression.

- Can states of equilibrium be found in the structure the building?
- How does Palladio handle the thrust of the vaults in the core of the building?
- How are does Palladio keep his walls so thin?
- What happens at the outer edge of the buildings?
- Palladio does not provide any buttressing on the exterior of the buildings and yet, there are often vaults that line the perimeter of the villas. Though often thicker than the inner walls, how does Palladio manage to keep the exterior walls so thin and still resist the thrust of the vaults along the outer edge?

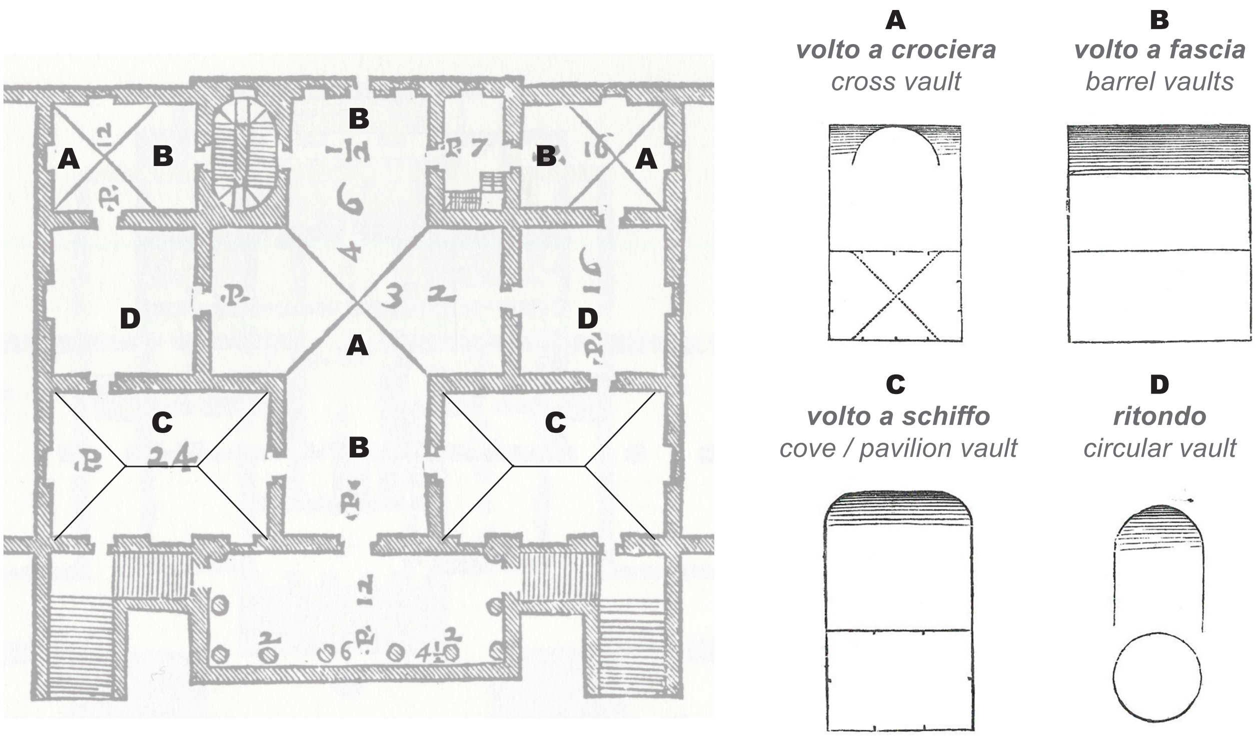


Fig. 2.8. Vault types in the villa Foscari. Images from [Palladio, 1997].

Hypothesis:

For the core of his buildings, Palladio uses rules for distributing vaulted, first-story spaces that bare the true structural intelligence of his system: orienting the vaults so they counter-thrust and buttress each other. At the perimeter, Palladio controls the height of the second floor walls relative to the first floor to provide enough weight to re-direct the thrust of the vaults edge vaults through the thickness of the wall. The solution is comparable to a buttress, though obviously quite different formally.

Methodology:

The primary goal is to see the plan of villa Foscari in a new way by considering questions of material and structure. Built between 1555 and 1561 [Beltramini, 2009, pg 130], Villa Foscari, sometimes called “la Malcontenta” is a rich example of Palladio’s use of room ratios and vault types [Appendix A]. Without access to building scans, this analysis of the villa Foscari is strictly speculative. Assumptions were made about the vaults based on drawings, and photographs.

The internal distribution is arranged vertically with the service rooms at the top and bottom and the grand living spaces on the first floor. The smaller rooms on the first floor (as well as the lower level) have all vault ceilings - always in different forms (cross, cove, and domical)

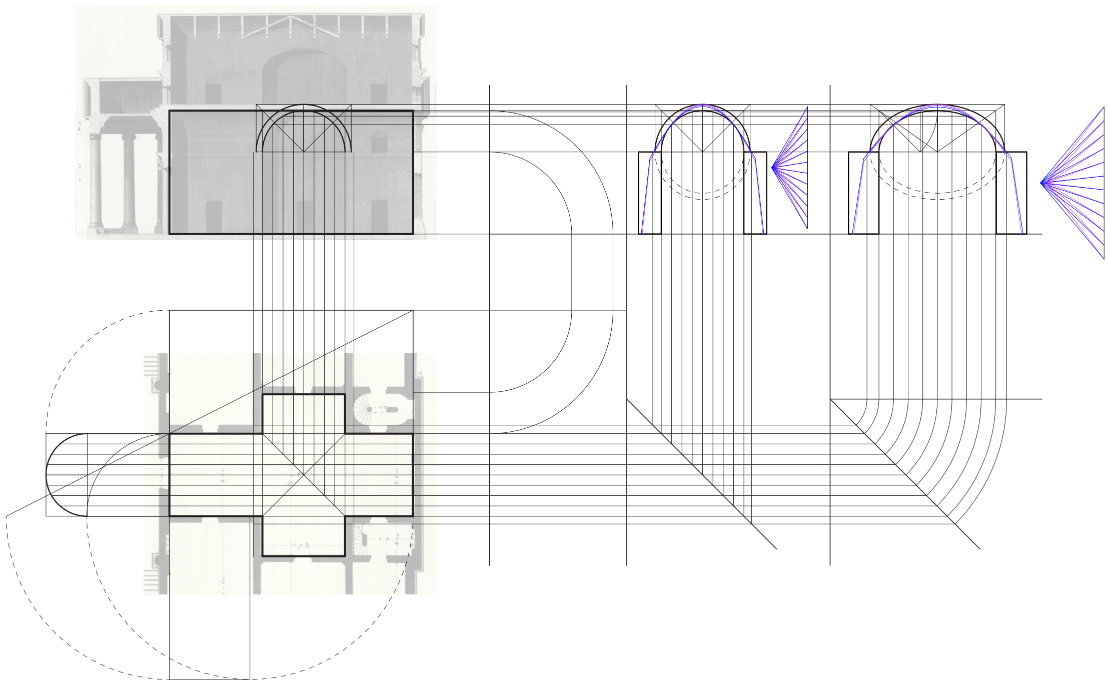


Fig. 2.9. Graphical analysis of the central cross-vault at the villa Foscari.

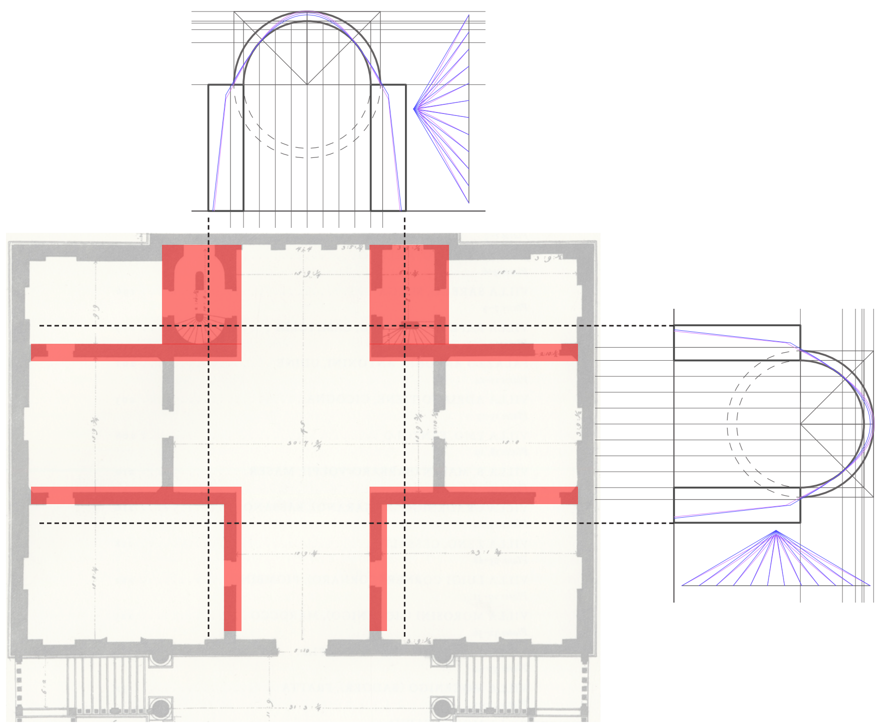


Fig. 2.10. Comparison of minimum abutments given the horizontal thrust of the central brick at villa Foscari with the walls as they are drawn in the Quattro Libri.

which, together with the varied heights, create a complex spatial experience culminating in the large *sala* covered by a tall cross vault [Beltramini, 2009, pg 133]. The main cross vault of the sala will be examined to address how Palladio handles equilibrating the core of his building by distributing smaller vaulted spaces around the large central vault. This will show how unreinforced masonry vaults interact next to each other; an inquiry into how to design *with* unreinforced masonry structures. The four types of vaults assumed to be used above the first floor of the villa [Fig. 2.8].

The geometry of the groin vault can be determined based on basic dimensional assumptions made from Scamozzi's drawings. From Scamozzi's section and plan drawing, it is possible to approximate the curvature of the vault as well as its thickness and span using descriptive geometry to transfer plan and elevation information and draw two sections of the groin vault [Fig 2.9]: one through an intersecting barrel vault and one through the diagonal - "the groin". Although it is known that these drawings contain inaccuracies, they are nevertheless useful tools for testing the hypothesis.

Limit analysis (see section 1.2) is applied to bring to light the relationship between form and forces in the villa Foscari. As demonstrated by [Block et al., 2006] graphic statics are most appropriate for visually calculating lines of thrust that lie in the section of the vault. Finding maximum and minimum horizontal thrusts identify the families of thrust lines that pass through the section of the vault. The technique can also predict potential collapse mechanisms by identifying where thrust lines touch the material boundary of vault's section [Block, et al. 2006]. The minimum required thickness of the walls holding up the vault will be calculated in order to comment on a contentious topic that is typically is either ignored or generalized (as Stiny and Mitchell did).

<u>Results:</u>
Super-imposing the "necessary" abutments need for the cross vault over Palladio's plan, it is easy to see that the central vault could not stand on its own - the internal walls holding up the vault would have been insufficient [Fig. 2.10]. In the text, Palladio shows he has an understanding of structural behavior from the standpoint of spatial organization. He says:

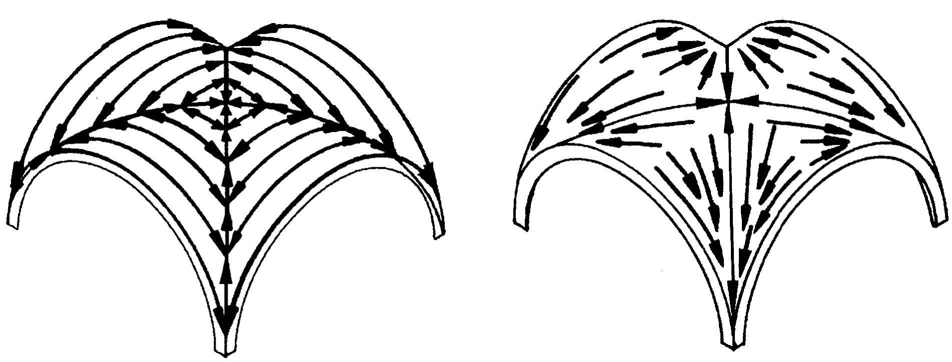


Fig. 2.11. Two possible load paths for a groin vault. From [O'Dwyer, 1999].

Fig. 2.12. Photo of the sala at villa Foscari. From [Beltramini & Burns, 2008, pg 133].

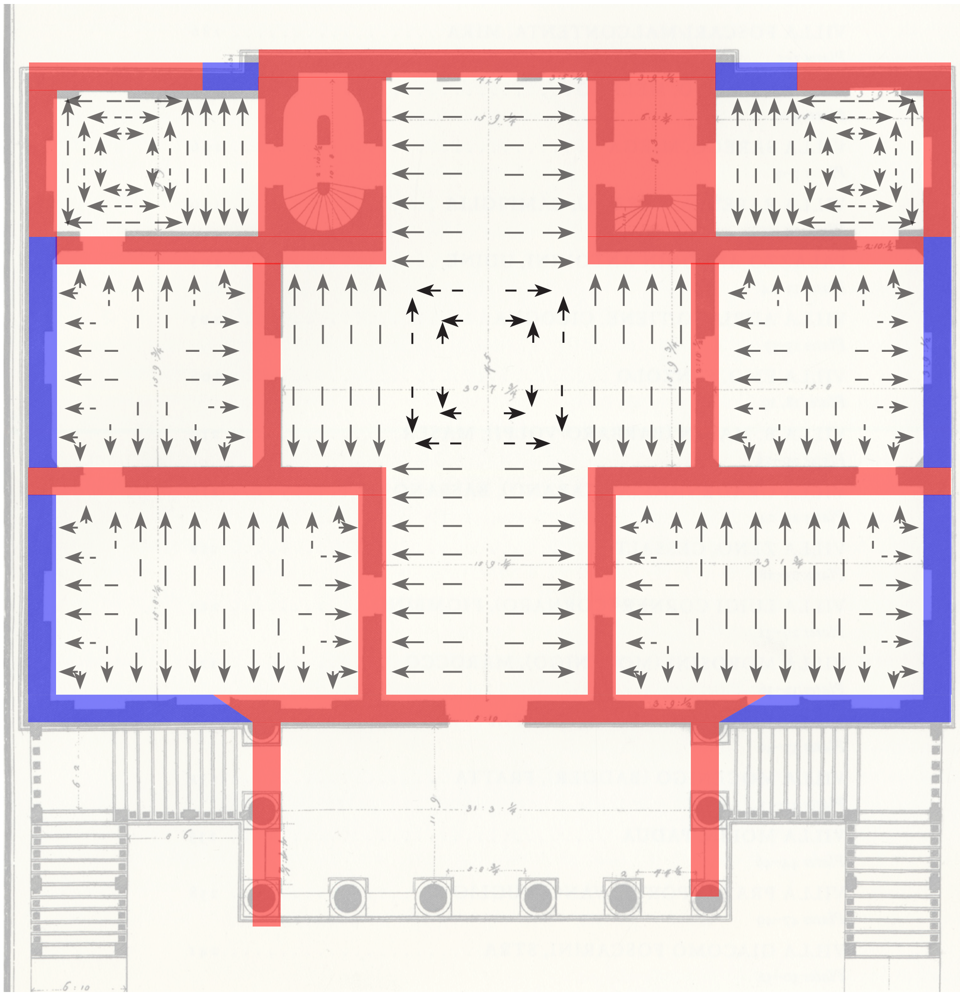


Fig. 2.13. Mapping of possible force paths in the vaults of villa Foscari.

> “Rooms [stanza] must be distributed at either side of the entrance and the hall and one must ensure that those on the right correspond and are equal to those on the left so [...] will take the weight of the roof equally; the reason is that if the rooms on one side are made large and those on the other side small, the former will be more capable of resisting the load because of the thickness of their walls, what the latter will be weaker, causing grave problems”. [Palladio, 1997, pg XX]

This assumption, though vague, is essentially correct when thinking about providing adequate buttressing for the vaulted central halls of buildings. Carefully selecting the types of vaults that surround the main space, clustering and orienting them to counter-thrust the central vault (along with the weight of the walls above), the core is essentially stable. Masonry structures are indeterminate to the infinite degree, but as a general rule of thumb, O'Dwyer suggests it is safe to assume that the forces follow the curvature of the masonry structure [Fig. 3.11]. Following O'Dwyer's example, a possible mapping of forces can be made for the central groin vault [Fig. 3.12] at Villa Foscari as well as for the other rooms, based assumed shapes of the vaults. The counter thrusting forces at the core of Palladio's design are mapped over the plan of Villa Foscari [Fig. 3.13]. Exactly what occurs at the edges of the building is still not totally clear, but a quick sectional study superimposed on Scamozzi's elevation [Fig. 3.14] suggests that the height of the outer walls to the top of the second story plus the weight of the roof baring on them is sufficient to handle the horizontal thrust from the outer vaults by applying additional vertical loads to pull the resulting force vector back into the section of the thin outer wall.

<u>Summary and List of Contributions:</u>

Palladio's rule about distributing vaulted, first-story spaces proves the architect had an awareness of the structural interactions taking place as he distributed spaces formed from vaulted masonry structures. Mapping the forces of the vaults in plan shows how the structures counter-thrust and buttress against each other to create a stable core around which the building is organized. This mapping technique is not only easy, but repeatable for any Palladian building and could serve as a primary check of the safety and stability of the building. Although the hypothesis about the height of the outer walls and the weight of the roof serving to work against the horizontal thrust of the outer vaults still needs to be proven with more rigor, the sketch shows promise of a structural rule that can handle edge conditions of buildings that use clusters of vaults. The rule would identify an edge condition (in blue) and prompt a sectional design study where the outward thrust is managed by a range of formal solutions: either by increasing the height of the wall above the vault or with a buttress. This brief analysis is just the beginning of what could be an extensive study of Palladio's buildings with material and structural primacy. So far the contributions have been:

- a rationalist way of seeing Palladio's building plans by directly engaging questions of "forces and flows of materials [Ingold, 2010].
- development of a systematic method of analysis to better understand the structural/constructive literacy of Palladio's proportional design system.
- an observation about how Palladio uses vaulted structures in his architecture without external buttressing.

This study of Palladio has opened up a rich territory to learn and talk about compression-only design and suggested a theoretical method for looking at masonry buildings in a visual and intuitive manner. Though current revelations have been valuable, the methods should be tested using content from 3D scans in order to shed light on the safety and stability of these monuments of architectural heritage.

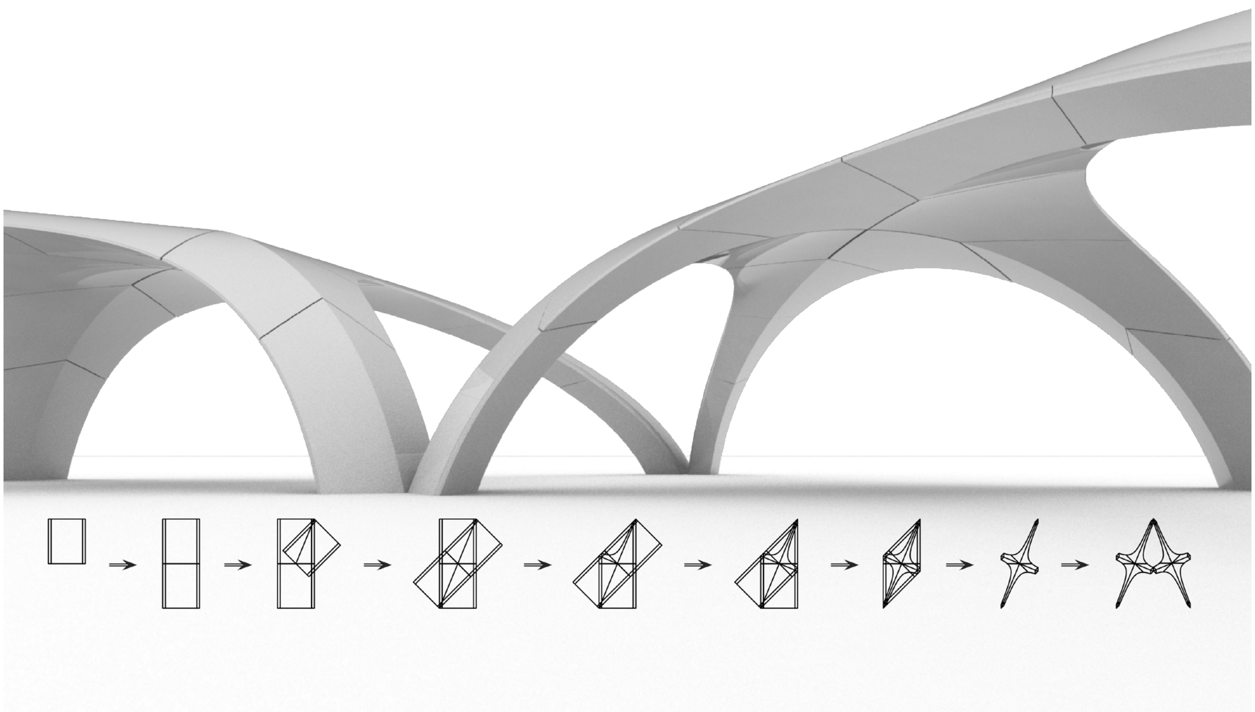


Fig. 3.1. A computation from the barrel vault grammar.

3. A New Structural Algebra

3.1 Introduction

A new structural algebra - characterized by equilibrium constraints - will be specified that permits architects and designers to work visually and non-deterministically with material and structural primacy; to feel the forces in shapes. By extracting structural design rules from history with slow computation methods, creative yet build-able designs can be produced that expand the capacity of what architects design and how buildings are constructed in the future.

3.2 Background on Structural Grammars

There is a brief history of scholars who have used the theories and mechanics of shape grammars and applied them to structural design. The earliest example is William Mitchell (1991) “Functional Grammars”. A shape annealing approach to grammatical structural design was developed by Kristina Shea and Jonathan Cagan (1999) “Languages and semantics of grammatical discrete structures”. More recently, Caitlin Mueller (MIT) included a chapter on “Trans-typology structural grammars” in her PhD dissertation (2014) in which a grammar was written to generate designs of bridges. A year later, Juney Lee (ETH) wrote a master’s thesis on “Grammatical Design with Graphic Statics” (2015). To date no grammars have been published for designing masonry structures. This chapter presents the a first attempt at grammatical design for compression-only shapes.

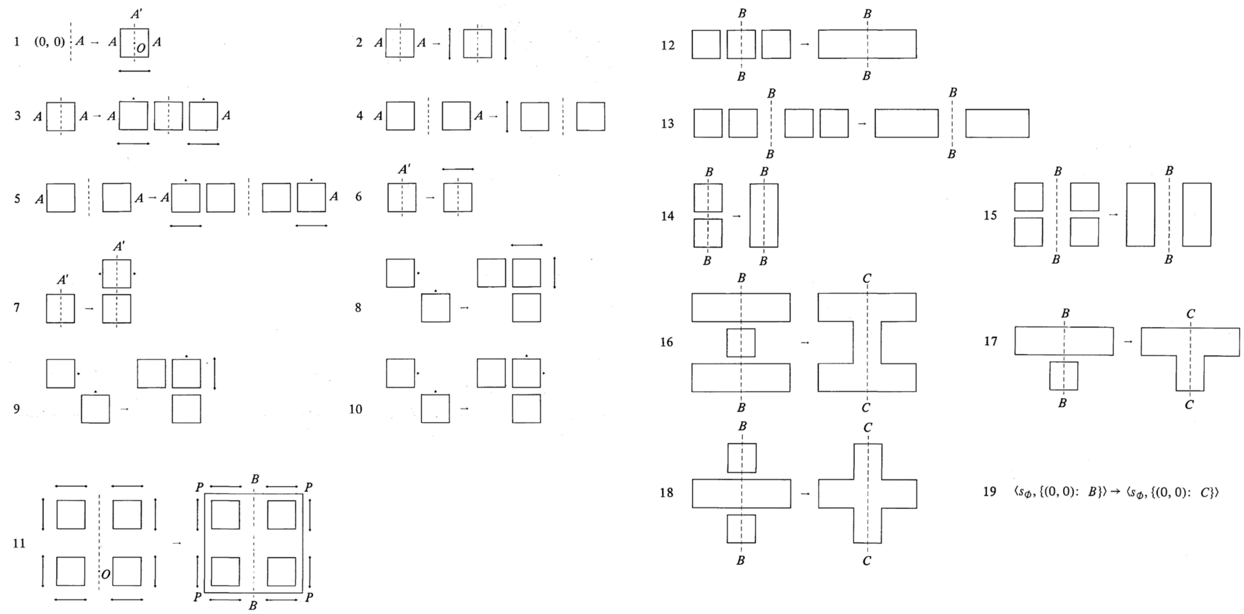


Fig. 3.2. Stage 1 shape rules from [Stiny & Mitchell, 1978a].

3.3 The Palladian grammar [REVISITED]

Earlier, a paper by George Stiny and William Mitchell was described within a body of scholarly work on Renaissance architect Andrea Palladio. *The Palladian grammar* (1978a) is evocative because it suggests a new way of looking at historical content (through the lens of shape grammars) and invites discussion about design based on those observations. The rules, imply the possibility of an open-ended design system that uses principles learned by slowing down and taking a closer look at history. Stiny was interested in what Palladio drew because he sees building plans as “shapes before they’re plans” [Stiny, 2006, pg 341]; his goal is to calculate with *shapes*. This section seeks to revisit a portion of the shape rules (particularly first 3 stages of computing) in the grammar, look at them through the lens of material and structural primacy, and re-write them so they are more flexible for designing other configurations or arrangements of unreinforced masonry structures.

The authors interpreted Palladio’s architectural language “in a modern, generative form” and updated previous scholarship on systematizing the drawings of different villa plans (in particular Ackerman and Wittkower). They define a *parametric shape grammar* that combines the powerful notion of parametric design, with the generative, rule-based design. Parametric shape rules, now more commonly known as *schemas,* were first introduced in [Stiny, 1977] and take the form **x → y**, where x and y are variables that can be assigned any parametric shape. A

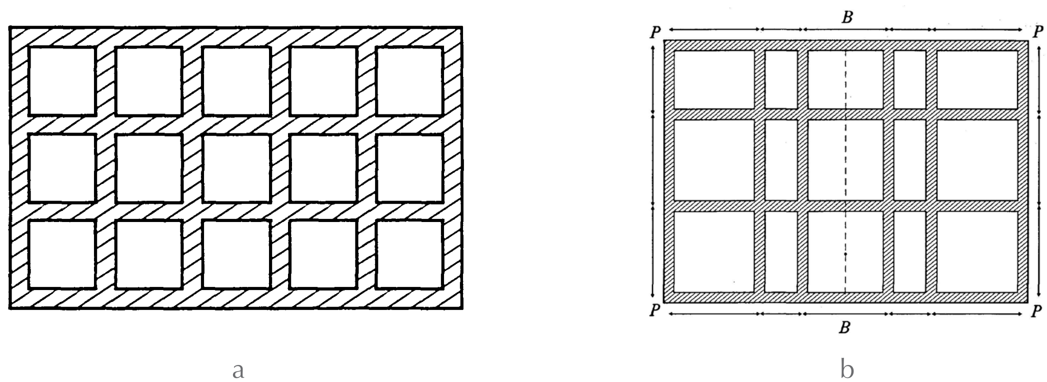


Fig. 3.3. a. Example of a basic 5 x 3 grid at the end of stage 2; b. Basic 5 x 3 grid proportioned for computing the underlying wall pattern for the Villa Foscari.

shape rule is written when the variables are given assignments, which are shapes. According to Stiny and Mitchell, the shape □ is defined as variable according to “any consistent well-defined set of dimensioning and proportioning rules” [Stiny & Mitchell, 1978a]. Any proportioning rules for making rectangles can be applied to □ in order to fit the shapes to Palladio’s designs. Palladio’s actual room proportioning rules are shown in Appendix A. The basic schemas are assigned with a generic value □ to write shape rules [Fig 3.2] that are applied recursively to generate the basic spatial configurations Palladio’s villa designs as they are found in the *Quattro Libri.* Other assignments make rules that generate the different details of floor plan drawings such as porticoes, doors and windows. The plan of the villa Foscari is computed as an example.

The rules are categorized into eight computational stages. According to Stiny and Mitchell’ rules, computing any Palladian-style plan begins by generating “labeled rectangular ‘tartan’ grids with bilateral symmetry relative to the north-south axis of the coordinate system” [Stiny & Mitchell, 1978a]. Stage 1 (grid definition) computes labeled tartan grids, which set up the basic spatial relations of rooms in Palladian designs. Rule 1 introduces the basic element □. Rules 2, 4, and 6 label shapes with letters designating the computing stage and dimension strings which are used to locate doors and windows in stage 7. The other six are shape rules that show how to calculate with the shape □ to <u>only</u> generate grids with bi-lateral symmetry. Rules 3 and 5 copy and move □ left and right according to different axes of symmetry. Rule 7 copy and moves □ upward. Rules 8, 9, and 10 fill in corners to complete the grids.

Palladian plans are drawn with wall thickness. Unlike Wittkower, whose plans are reduced to single lines [Fig. 2.5.a], Stiny and Mitchell use stage 2 to draw the exterior wall, around the symmetrical grids made of □. By the end of stage two, the underlying wall pattern for a villa plan is generated. The essence of computing *Palladian* plans lies in stage 3 where rules 12-18 lay out various configurations of rectangular, I-shaped, T-shaped, and +-shaped spaces [Stiny & Mitchell, 1978b]. Applying rules in different ways can produce new and sometimes surprising results. Stiny & Mitchell demonstrated the potential to compute new compositions of

Fig. 3.4. Simplified shape rules from the Palladian grammar.

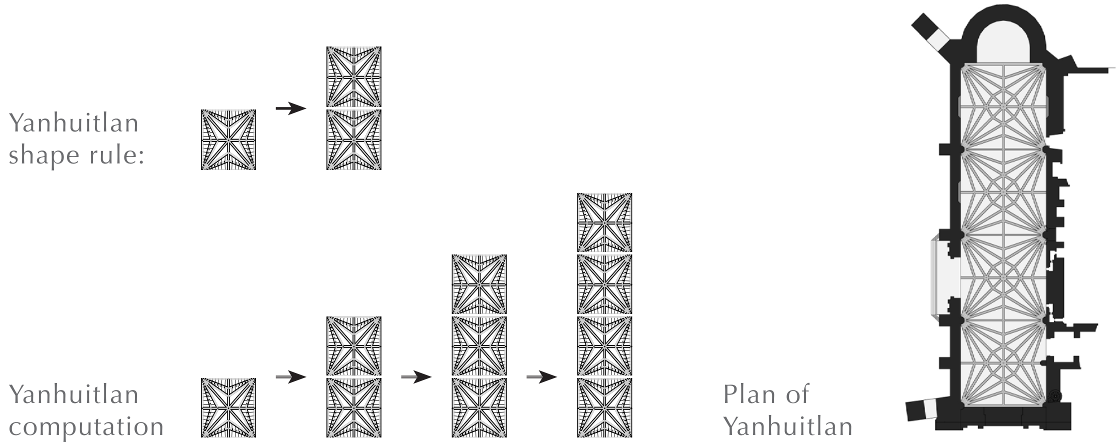


Fig. 3.5. Shape rules using reflected ceiling plan at Santo Domingo Yanhuitlan.

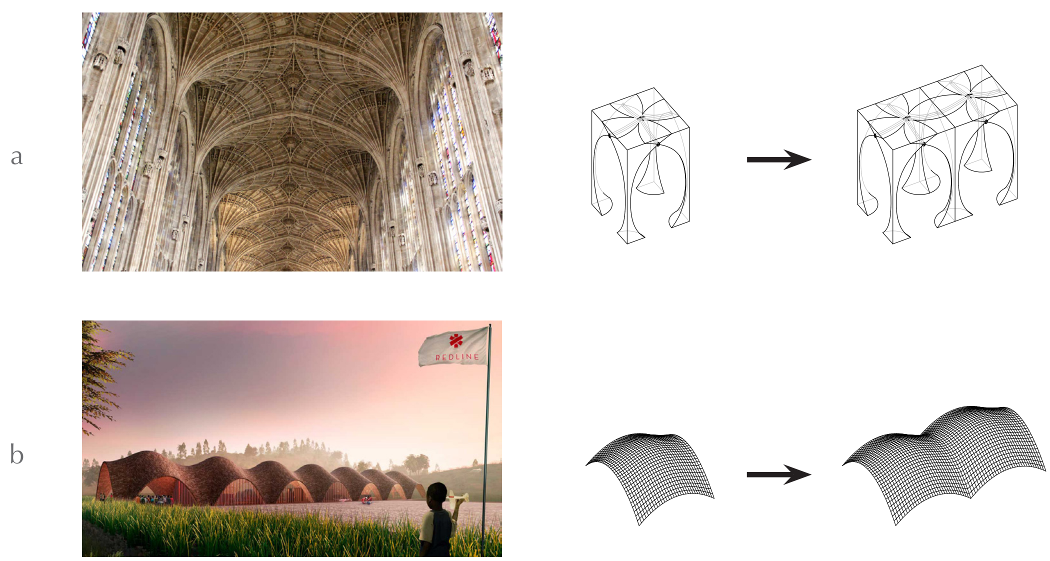


Fig. 3.6. a. King College Chapel in Cambridge, England; b. Droneport proposal by Foster + Partners.

spaces in plan by enumerating all the possibilities of plans organized on 3 x 3 [Fig 2.6] and 5 x 3 tartan grids, which include most of the villas in the *Quattro Libri,* as well as other, new plans in a family of possible designs using the Palladian grammar rules.

Although the current rules are sufficient for producing **copies** of Palladian plan drawings from the Quattro Libri and other new plans in the same language, the rules have not been tested for making anything other than drawings that have a Palladian aesthetic. If parts of the grammar were going to be used for computing other configurations or arrangements of unreinforced masonry structures, the rules would need to be generalized so that they do not constrain arrangements of shapes to bilateral symmetry and tartan grid formation. Rules 3, 5, 7, 8, 9, and 10 can be simplified to just two basic rules [Fig. 3.4]. Both rules copy and move shapes, described by the schema: **x → x + t(x)**, where **x** is a variable shape, and **t** is any Euclidean transformation of the shape (including mirroring, scaling or skewing shapes). In this case t is simply a copy and a translation of x, which in the rule is □, either to the right or up. Although the shape rules are different, the schema shows how they are related. Schemas are universal rules of formation that can help reveal these relations. More precisely, the reason to identify a schema is to use it in new ways.

The shape □ is only one of an infinite number of values of shapes that can be assigned to the variable x, in the schema **x → x + t(x)**. For example, the reflected ceiling plan of Santo Domingo Yanhuitlan (discussed in the prologue) can easily be substituted. If the rule is applied three times, it computes a basic diagram of the nave which describes the spatial relations of the vaults in the nave of the plan of Santo Domingo Yanhuitlan [Fig 3.5]. No matter the assignment to these two shape-rule schemas, which replaces □ with any other drawing of a rectangular vault in plan, it is possible to describe the spatial relations in a surprising amount of buildings made with masonry vault shapes. Santo Domingo Yanhuitlan is an extremely simple example of Gothic-style church designs but even those with more complex vault shapes or rib patterns can be described by one of the two shape rule schemas. The impressively thin fan vaults at King's College Chapel in Cambridge, England are arranged in exactly the same manner, and can be described - generatively - by the schema **x → x + t(x)** [Fig 3.6a]. In the mid-20th century Uruguayan architect Eladio Dieste [Anderson, 2004], championed the use of **x → x + t(x)** for the buildings he designed [Fig. 3.7]. Though he changed the value of the assignment, his designs often consisted of a masonry vault shape copied and translated over and over. Recently, there has been renewed interest in building with unreinforced masonry, and even these can be described by the same schema. Sir Norman Foster proposed a project in Rwanda for a "Drone-port" [Fig. 3.6b] that would be constructed of earthen tile vaults [Foster+Partners, 2015]. His design follows precisely the same schema as Yanhuitlan, Dieste and the King's College chapel. Each of these buildings are unique and bare very little resemblance to each other. Yet through the lens of the shape schema **x → x + t(x)** they are undoubtedly related. Each design selects a vault shape and repeats it. The two basic rules that describe grid formation of Palladian plans are outstandingly powerful tools for describing commonality between many buildings made with masonry vaults throughout history.

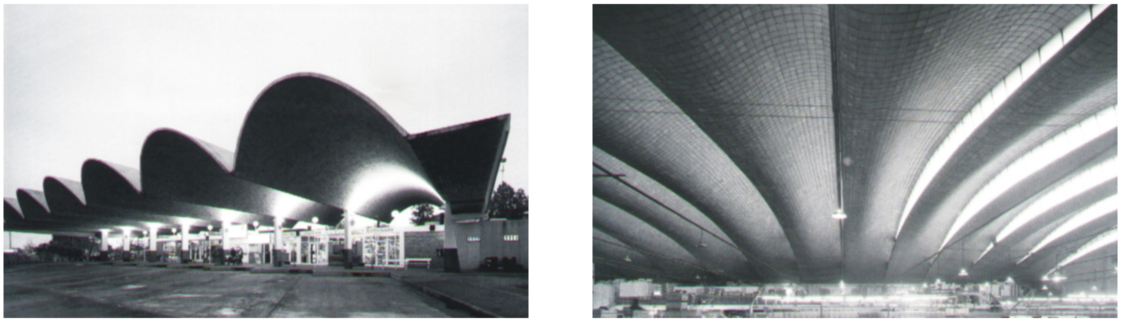


Fig. 3.7. Two examples of buildings by Eladio Dieste from [Anderson, 2004].

Stiny and Mitchell's generalized shape rules free arrangements of shapes from bilateral symmetry and grid formation, which made it possible to describe a majority of buildings with masonry structures. Designing with unreinforced masonry shapes has a lot to do with adjacencies. In order to use the shape rule □ → □□, to compute new designs of structures that can be constructed - particularly if those structures are to made of bricks, as they are in Palladio's buildings - the assignments need to be more specific to better describe the types of structural interactions taking place between the shapes. Updated rules will take into account more than just the relationship between the spaces under the vaults. The type of vault, its shape in section, its support conditions, and possible force paths will be considered and drawn with labels in the new shapes rules used for computing.

The most basic vault type is a barrel vault, which Alberti describes as "a series of arches added one to the other, or like a curved beam stretched laterally, and hence it may be compared to a wall bent over our heads for protection" [Alberti, 1988, pg 84]. As discussed earlier, any arch section can be visually evaluated for its stability and safety by looking for families of thrust lines passing through it [Fig 3.8]. Limit analysis can be used as a generative design tool as well as evaluative one by finding the maximum and minimum thrusts of a shape. The barrel vault plan is parametric in the sense that arch sections can varied as long as families of thrust lines to show their stability and safety are validated and represented in plan drawings. When that shape is extruded [Fig 3.9a], the result is a barrel vault. Based on O'Dwyer's method of mapping potential force paths, any barrel vault could be drawn in plan [Fig. 3.9b]. The drawings are labeled with arrows that represent possible load paths, which give a better of a sense of the shape of the vault in plan. In simple shapes (in barrel vaults, for example), this information is fairly straightforward.

The the plan of villa Foscari with an overlaid mapping of the forces (end of Chapter 2) suggests the different kinds of structural interactions that can safely be used when designing clusters of unreinforced masonry vaults. Each of these interactions can be described through the lens of shape grammars by seeing the same schema **x → x + t(x)**, and writing shape rules to describe those interactions. At the core, Palladio formed and oriented vaults in different ways so they would counter-thrust against each other - indicated in the plan [Fig 2.13] by arrows pointing

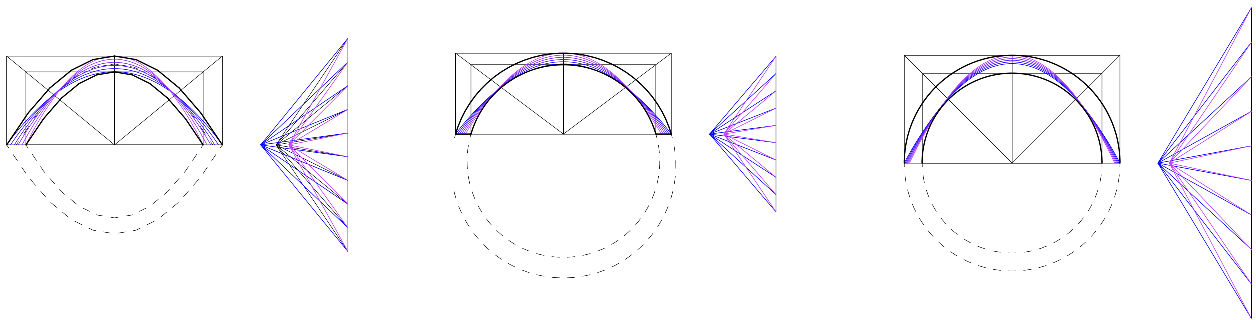


Fig. 3.8. Three types of arches that could be used to begin computing with barrel vaults.

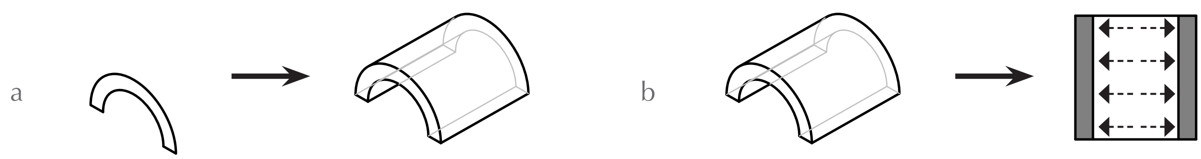


Fig. 3.9. a. Extruding an arch to make a barrel vault; b. Representing a barrel vault in plan.

toward or perpendicular to each other. All of Palladio's vault types are based on extrusions or rotations of arches, so the basic shape rules of the form □ → □□ can be re-written in terms of labeled barrel vault plan drawings to describe each of the interactions in Palladio's plan.

These specific rules extracted from Palladio's buildings bring a heightened sense of material and structural primacy to the design process. The thickness required at the wall is drawn to show the location, shape and dimension of the supports of the vault. As the rules are deployed for computing arrangements of structural shapes, it becomes important to keep track of this information and will serve to check interactions between vault shapes. Shape rules that "copy and move" take the form $\mathbf{x} \rightarrow \mathbf{x} + \mathbf{t}(\mathbf{x})$. Based on the Palladio plan of villa Foscari, three types of interactions can take place with adjacencies. Rule 1 extrudes the original shape, which can be either above or below the original shape by reflecting the rule. Rule 2 copy and moves the shape laterally so the forces in the vault are counter-thrusting. This rule can also be reflected so the "copy-move" can either be left or right. Rule 3 copies, moves and rotates the original shape. In this case, **t** is a compound transformation. The key contribution here, is the basic elements for computing have been updated to show the matter and forces at play in shapes when they are being used for computing designs with masonry structures.

The defining feature of villa Foscari is the groin vault, which was looked at in the previous chapter. The original Palladian grammar rules used room layout rules (12 through 18) to carve away at the grid to make configurations of rectangular, I-shaped, T-shaped, and +-shaped spaces. The +-generating rule used to make villa Foscari makes a groin vault in the actual building. Heyman gives a straight-forward explanation of how groin vaults are formed: “the simplest form of groin vault results from the intersection of two equal semi-cylindrical barrels; the resulting bay of vaulting is square in plan, and the diagonals of the square define the location of the groins” [Heyman, 1995, pg. 51]. He explains that groins are areas of large stress concentrations because “a crease in a shell introduces a discontinuity in the force field; the smoothly changing stresses have to change direction suddenly at a crease, and this cannot be achieved without the generation of large forces. The discontinuity is a line of weakness in

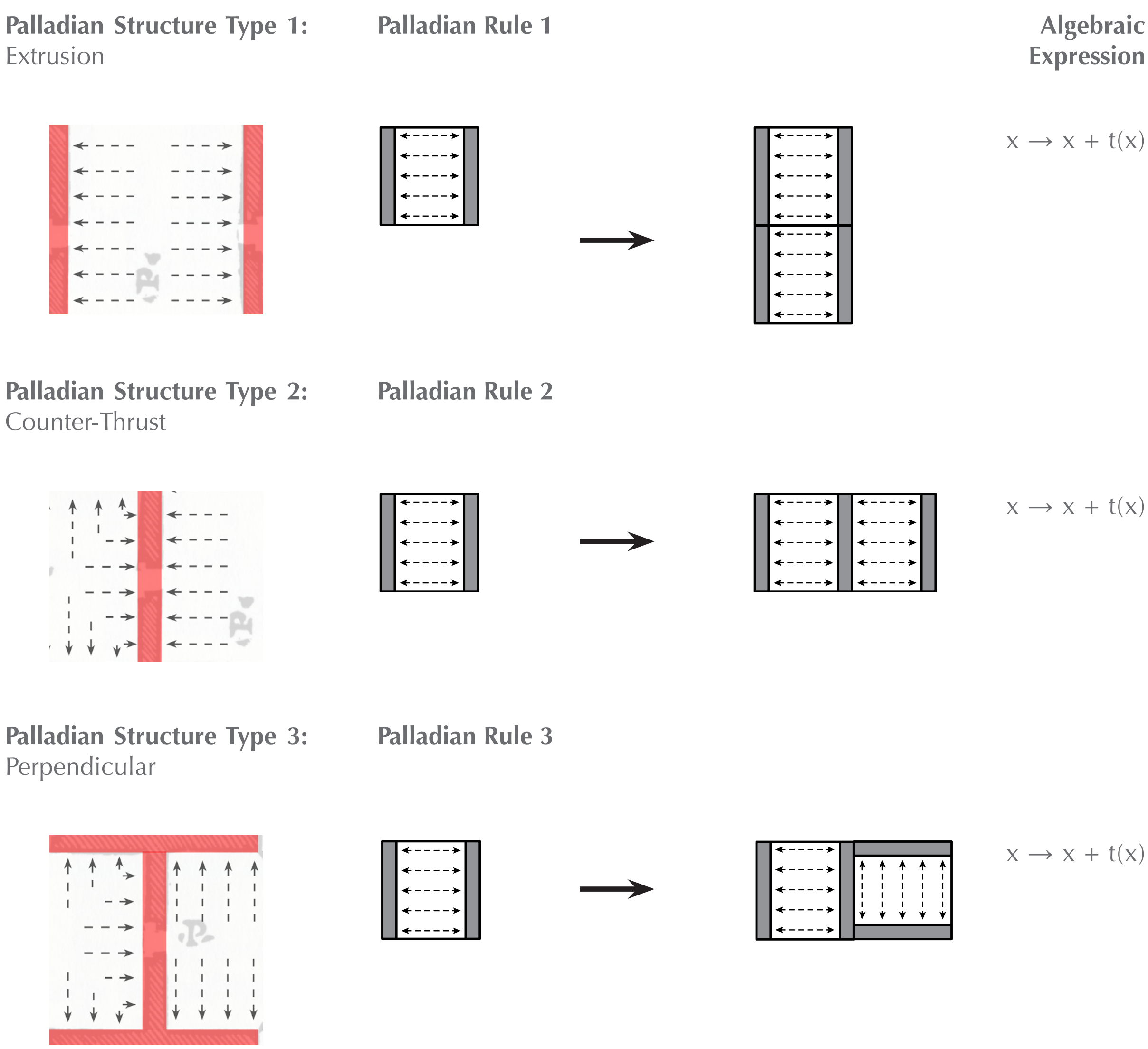


Fig. 3.10. Palladian Barrel Vault Rules

the vault, and should be reinforced; and indeed, reinforced creases confer rigidity on the whole vaulting structure.” Based on Heyman’s description of how a groin is formed, another barrel vault rule can be written [Fig 3.11]. Barrel vault rule 4 is once-again based on **x → x + t(x),** using barrel vaults to make a groin vault by copying and rotating the original shape by 90 degrees. The drawing shows groins that result from the intersection of extruded barrel vaults with green lines. The resulting bay is indeed square as described by Heyman, but is enclosed and keeps both barrel vaults in their entirety. A new schema is introduced to remove **part** of the drawing, and “open up” the vault in the form **x → prt(x)**. The power of using schemas to describe the interactions of vaults is that as new shapes are made by computing with rules, any shape can be used as an assignment in the original rules. For example, the groin vault made by applying rule 5 can be used in the two shape schemas that were extracted from the Palladian grammars and offer a new range of designs using groin vaults [Fig 3.12].

This section has sought to revisit a portion of the shape rules in the *Palladian grammar*, and look at them through the lens of material and structural primacy. First the grid formation

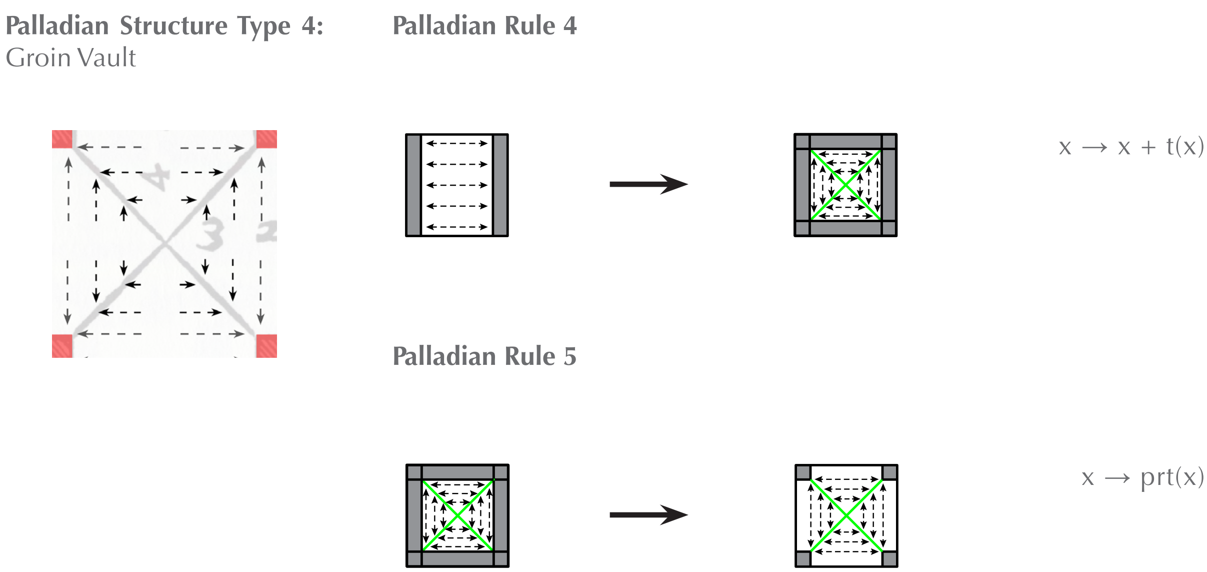


Fig. 3.11. Palladian Barrel Vault Rules for making Groin Vaults.

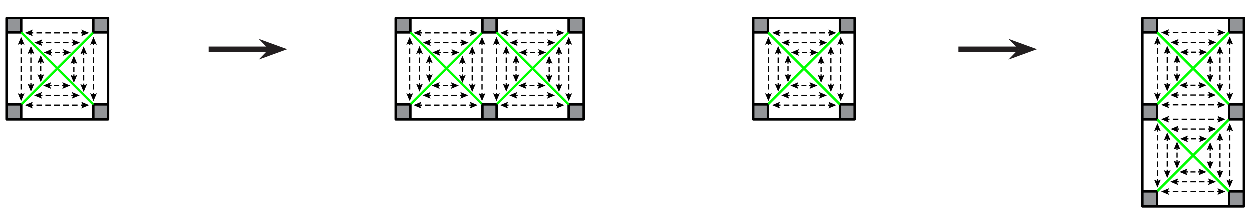


Fig. 3.12. Groin Vault Rules

rules were generalized according to basic schemas to make them more formally flexible and offer the capacity to compute non-tartan grid designs. The schemas offer a means of seeing and talking about a major portion of the history of buildings that use masonry structures. They also suggest other kinds of interactions. In this context, the shape □ needs to be imagined as a vault made of bricks. So an interaction such as □□ has profound structural implications that need to be made explicit. The basic elements of computing, were updated to be more specific to masonry design by using labeled shapes that demonstrate an awareness of the matter and forces at play. Wall thickness is drawn as well as a mapping of the forces in the shape, which provides a visual idea of the curvature of the shape in 3D while working in plan. The different types of structural interactions between barrel vaults found in Palladio's plan of villa Foscari were identified and written as rules, according the basic "copy and move" schema. Eventually, greater material and structural awareness should be incorporated into the system. The red and blue (compression and tension) labels that were used in the analysis of villa Foscari could be integrated into the rules proposed above.
Red indicates conditions of counter thrusting in compression (stable). Blue indicates an edge condition. Depending on the section of the barrel vault, of which any could be assigned to the plan drawings, the edge condition must be treated differently. Palladio's vaults are sitting on top

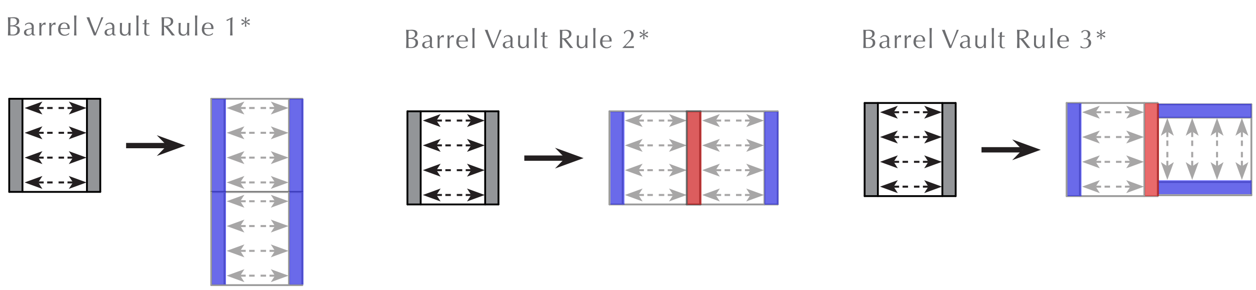


Fig. 3.13. Labeled Barrel Vault Rules.

of tall walls, which means the edges either need to be treated with either a wall above the edge (which is his solution), or to use the Gothic solution - a buttress. Entire grammars could be written for this sectional drawing exercise, but are not being considered at this time. For now, the blue and red labels will not incorporated into the design rules, but it does suggest another means of bringing heightened material and structural awareness - primacy - to the design process. Future work is needed to develop this grammar into a complete compression-only architectural design system. This section shows promise of defining a grammar that could suffice to not only compute the "built form" of Palladian villas, but also any other arrangement of non-gridded designs of masonry structures. The next section will show how this slow computational design methodology lets designers work visually and non-deterministically to produce unexpected results, using simple rules based on the rules that were extracted from Palladio. Furthermore, the computations will show how designing this way can help designers, learn to work creatively with structural principles, and gain an intuition for shapes that can be built with masonry; starting to feel the forces in shapes.

3.4 A Barrel Vault Grammar

Looking at Palladio (again) with slow computing methods has laid the groundwork for a novel structural shape algebra characterized by equilibrium constraints. Five barrel vault rules were extracted from the villa Foscari that describe the allowable kinds of interactions between barrel vaults. “Copy and move” rules, inspired by the generalized grid-formation rules from Stiny & Mitchell (1978a), offer different ways of aggregating vaults with the types of adjacencies found clustered in Palladio buildings. The shape schema **x → x + t(x)** to shed new light on a striking commonality between a majority of buildings made with masonry shapes. Over hundreds of years, and despite different scales, uses, and even material (stone, brick, earth), each design begins with a vault shape and repeats it. Today, vault shape formation is easily accessible to architects and students with fast computation tools. Software such as RhinoVault and Kangaroo offer intuitive ways of generating “compression-only” geometry within the common architectural CAD software (Rhinoceros). However, these plug-ins do not take into account aggregating shapes, or offer feedback about the interactions between shapes. In other words, designing *with* structural shapes is not included in form-finding tools. Though buildings have been designed algebraically with masonry shapes for millennia, why have the rules of aggregation changed so little? The slow computation method being proposed here uses shape grammar rules that promote open-ended formal exploration *within the constraints of compression-only systems and between two traditional architectural media: drawing and masonry construction*.

<u>Overview:</u>
The basic elements of the *barrel vault grammar* are shapes that meet the basic criterion: compressive forces fall within their boundaries. Barrel vaults are simple, and relatively easy to understand structures because they are essentially extruded arches. As long as the stability and safety of an arch are validated, the arch can be extruded into a barrel vault and used for computing. Finding the shape of an arch is a parametric computation [Fig 3.14]. Graphic statics and limit analysis have been shown to be sufficient to bring visual awareness of the matter and forces at play [material and structural primacy]. The barrel vault grammar computes designs in plan, so barrel vaults are drawn as rectangles with fields of *poché* indicating (to scale) the necessary thickness of the abutment to handle the thrust of the vault. (Note: In the previous section, labels were drawn to indicate the direction of the forces in the shape. For now, they

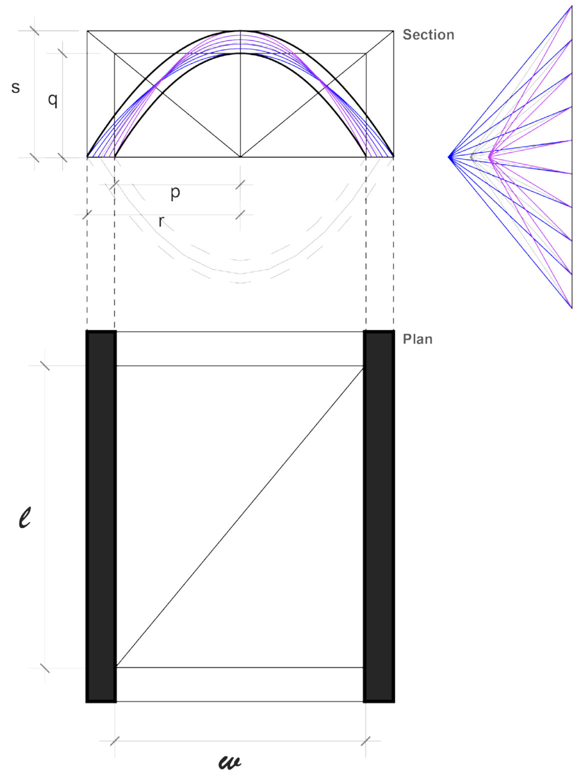


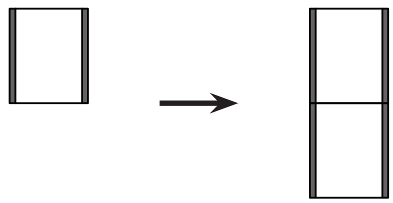
Fig. 3.14. Parametric 2D form-finding of initial arch for computing with barrel vault grammars.

will be left off to keep things clean.) The barrel vault plan drawings are assigned to shape rule schemas identified earlier. The intent of the rules is to generate novel, construct-able forms. They allow a designer to work creatively, and make it so a designer is working only with shapes that are construct-able because the rules only permit computing drawings that represent structures in equilibrium. There are additive rules that take the form **x → x + t(x),** and subtractive rules that take the form **x → prt(x).** Computing starts with a single barrel vault - a rectangle with two thickened sides in plan. Computing is non-deterministic, and can produce different results each time. Computing is finished either when no more rules can be applied or when a designer wants to stop because they like what they see. Early studies of the grammar are included in [Appendix B]. As long as the rules are deployed faithfully, the lines used for designing can be scaled and translated into a design that can be physically constructed. Material thickness (required structural thickness) can be considered based on the maximum compression strength of a material. A wide a range of materials can be used including brick and stone, but also low quality or low-strength materials (such as earth), because in compression-only shapes, stresses are low compared to the compression failure of materials. Since the drawings are structurally informed and the rules only produce shapes that can be constructed, designing with shapes is like designing with the matter and forces at play in masonry vault structures.

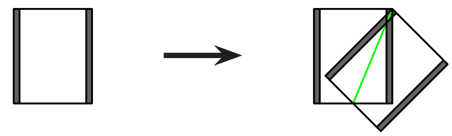
Additive Rules:

These rules take the form **x → x + t(x),** where x is a plan drawing of a barrel vault with thickened edges to show the boundary conditions and t is a transformation. Two additive rules are defined:

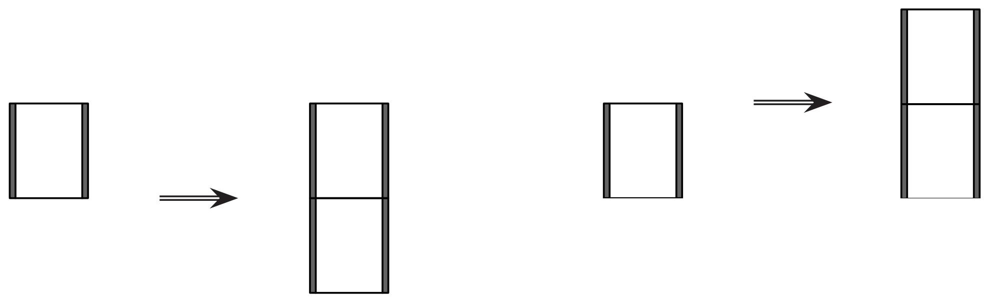
(1)



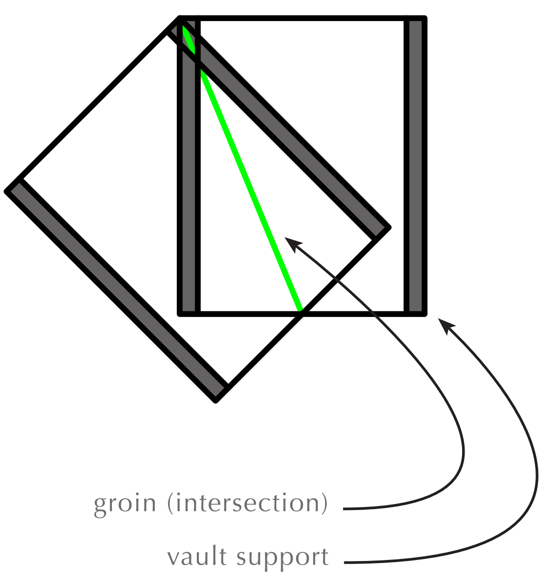
(2)

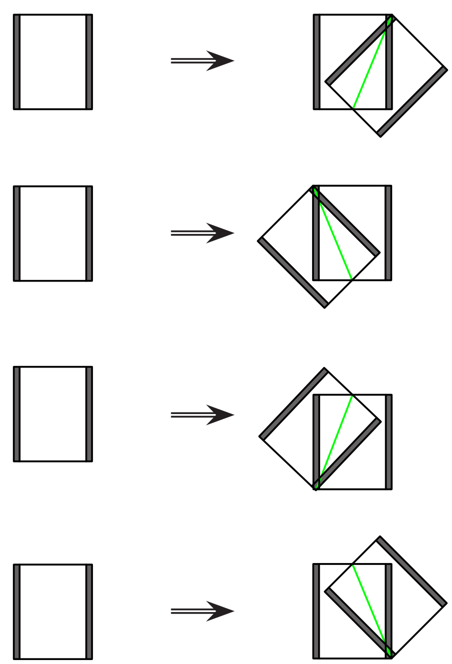


Rule 1 is an extrusion rule extracted from the Palladian rules. The rule gives the designer the option to add a barrel vault above or below any rectangle they see.

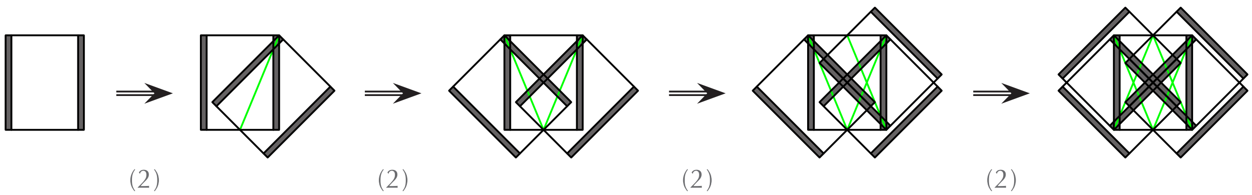


Rule 2 is a "copy and rotate" that causes intersections between shapes, inspired by the basic principles behind how to construct a groin vault discovered by studying Palladio. The rule can be applied in four ways by reflecting the rule both vertically and horizontally.

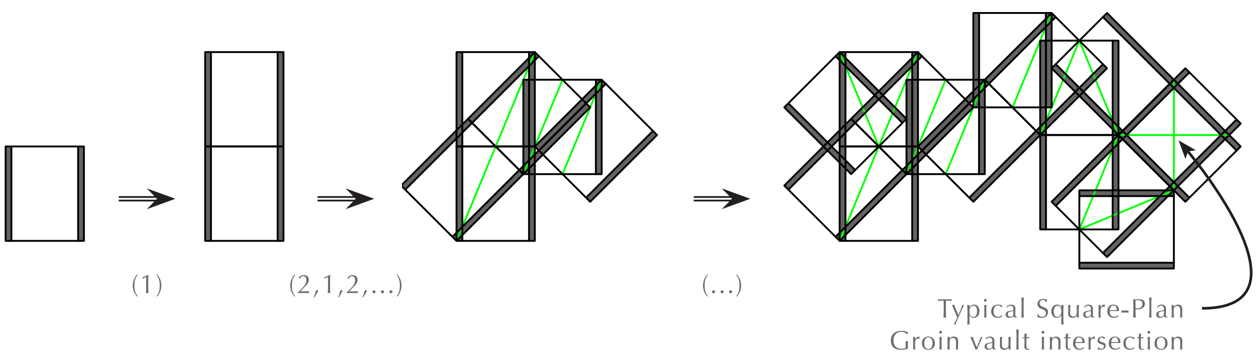




Additive rules count on seeing a rectangle, copying it, and applying a transformation (copy, move, reflect...). The rules add rectangles in a line [Fig. 3.5] or clustered intersections of them together. For example, rule 2 can be applied over and over again to the initial shape to make a tight cluster:

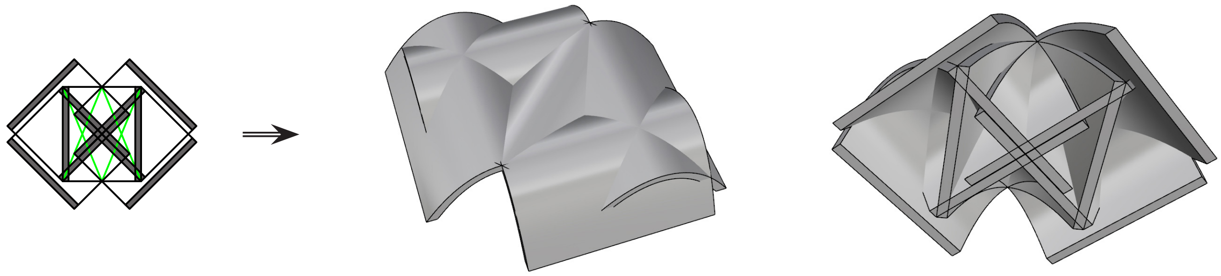


Applying the two rules recursively produces infinite possibilities of clusters of vaults through addition. Each time rule 1 is applied the drawing is lengthened. Each time rule 2 is applied, a new intersection condition is produced. As computing moves forward, new and unexpected conditions can be discovered in the drawing.



Although only the additive rules specified above are being used, the rules made a square-plan groin vault (like the one extracted from Palladio). The condition is produced by surprise, simply by applying rules to the drawing and continuing to calculate. The drawing does not know it has created a square-plan groin vault. Someone has to SEE it in the drawing. George Stiny calls this applying an identity rule of the form **x → x,** which finds shapes embedded in the drawing and picks them out. After an identity is applied, the drawing fuses back and other parts of the drawing can be picked out. Each time another shape is seen, it becomes an assignment for the **x → x** schema. In one moment a rule can be applied to see barrel vault shapes. In the next, another rule to find groin vaults. The key, is to slow down; stop and look around.

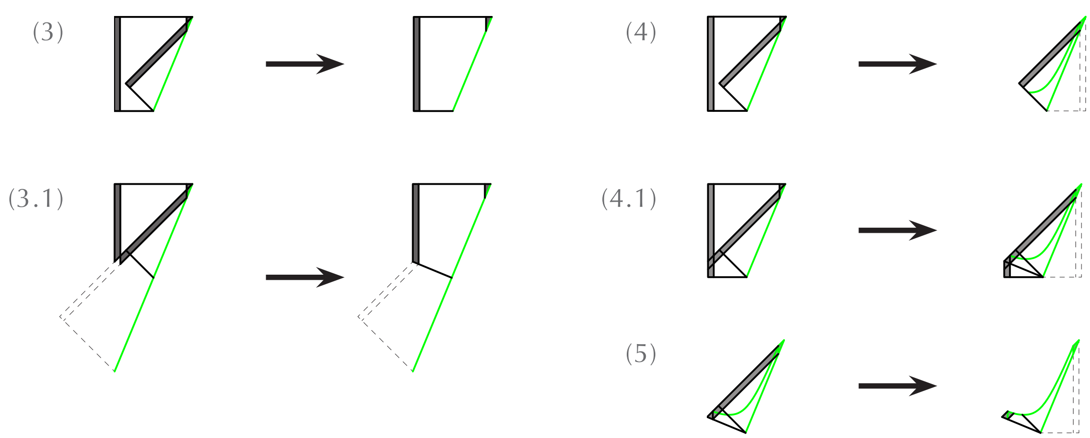
The plan rules can be thought of as a set of commands for 3D formation. As a proof of concept, computations will continue to be shown in 2D drawings and reinforced with images of the corresponding 3D models. The computation from earlier that resulted from applying rule 2 to the initial shape makes a cluster of vaults with a mess in the middle, which is evident from the 3D models. To clear the mess, subtractive rules that remove parts of the barrel vaults to make new shapes from stable intersections will be :



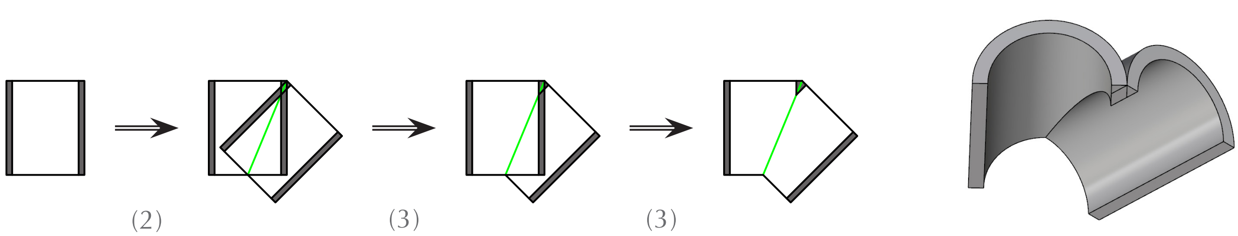
Top View Bottom View

Subtractive Rules:

These rules take the form **x → prt(x),** where x is a plan drawing of a barrel vault with thickened edges. Subtractive rules remove parts of the drawing which signifies “opening up” the space in the design and also limits the where rules can be applied in the future. The two additive rules are retained and five subtractive rules are specified to handle different conditions of aggregated barrel vaults:

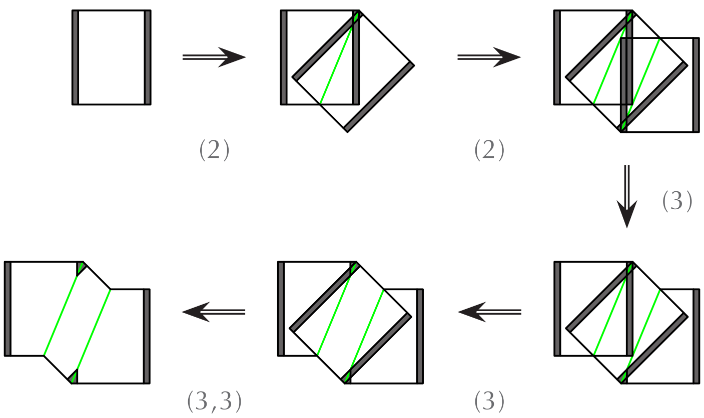


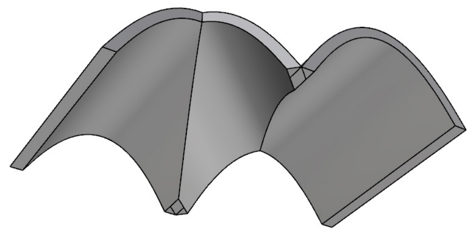
Rule 3 removes an inner triangle made by rule 2 - demonstrated with a simple computation:



Bottom View

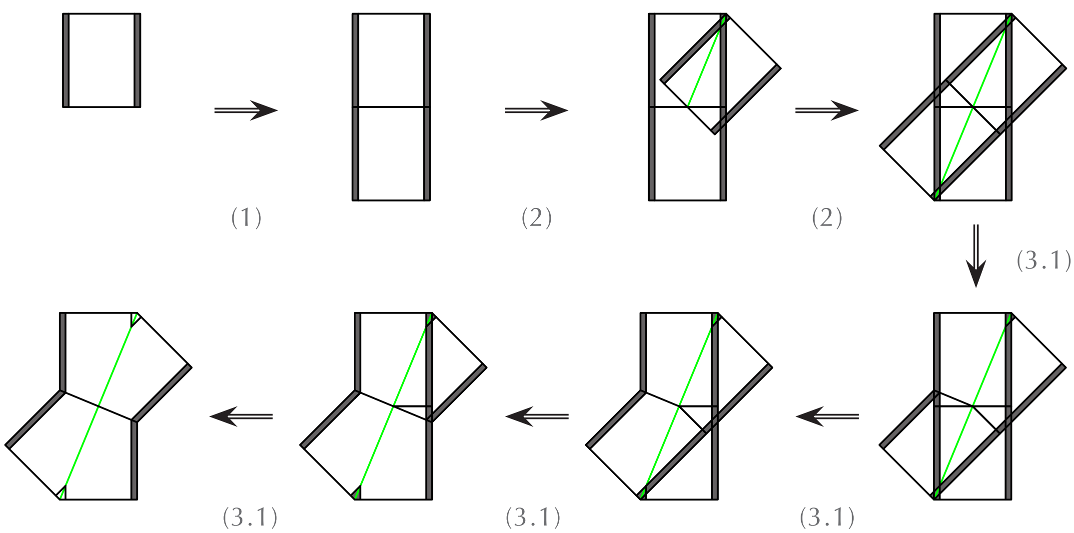
Rule 3 can also handle tight clusters of barrel vaults and safely clear them out to produce new kinds of formal conditions:

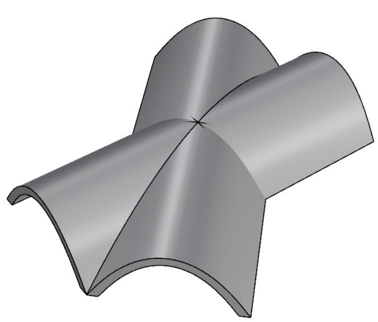




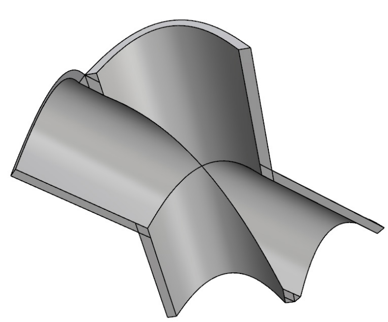
Bottom View

In some cases, rule 3 needs to be applied in more specific conditions. Rule 3.1 handles conditions where an extra triangle needs to be removed from an extruded barrel condition.



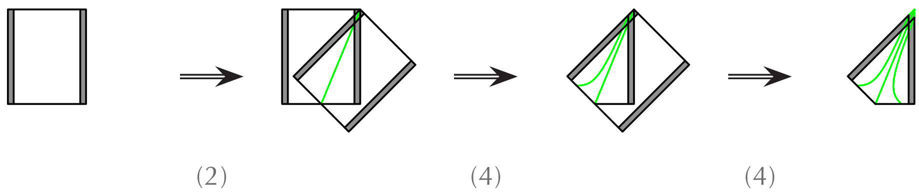


Top View

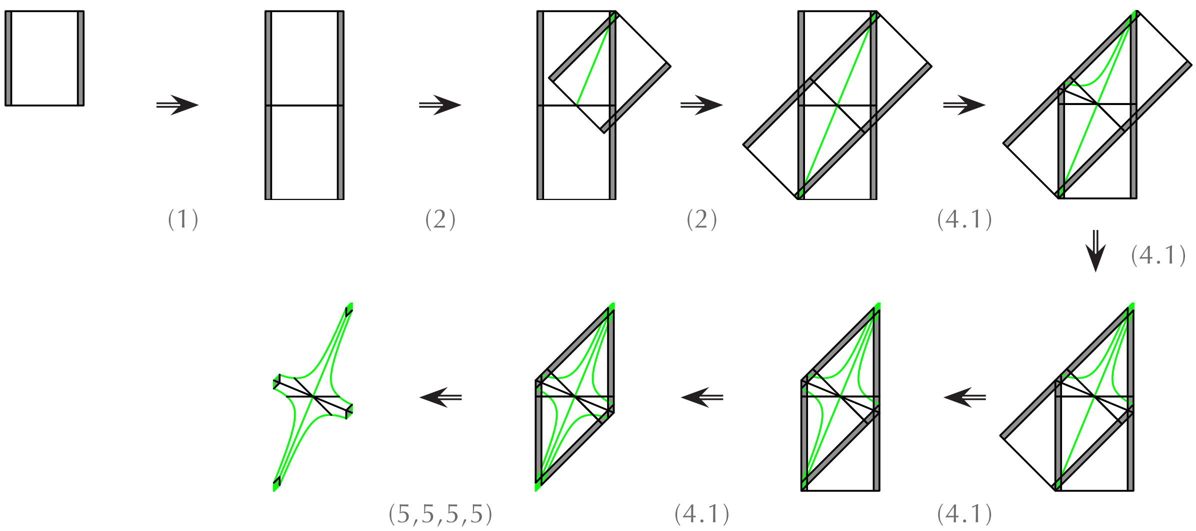


Bottom View

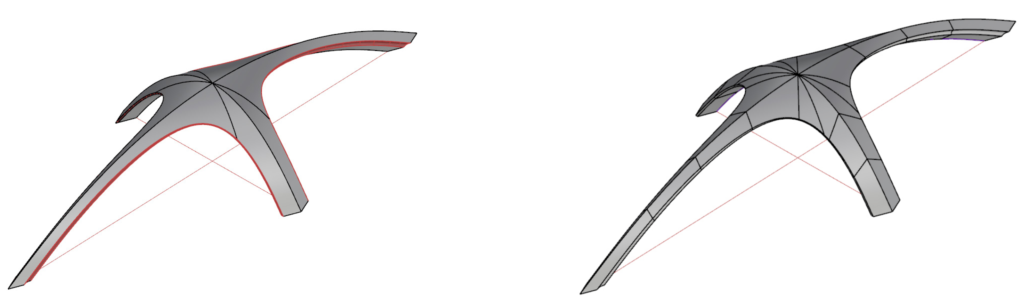
Rule 4 removes the outer shape of an intersection made by rule 2 - leaving the parts removed in rules 3 and 3.1.



Rules 1, 2, 4.1 and 5 together produce a skeletal structure:



The claim is the proposed rules only produce designs that can be built because they work within compression-only constraints. To test this claim, small-scale rapid prototype assembly models are sufficient to demonstrate the capacity to build any design produced because the geometry of stability problems are (nearly) infinitely scalable [Block, 2005]. The two-dimensional computation serves as commands - instructions - to guide 3D modeling. The skeletal 3D shape was refined along its edges and discretized into 14 voussoirs. The pieces were printed solid in a 3D printer and assembled on a cardboard formwork.



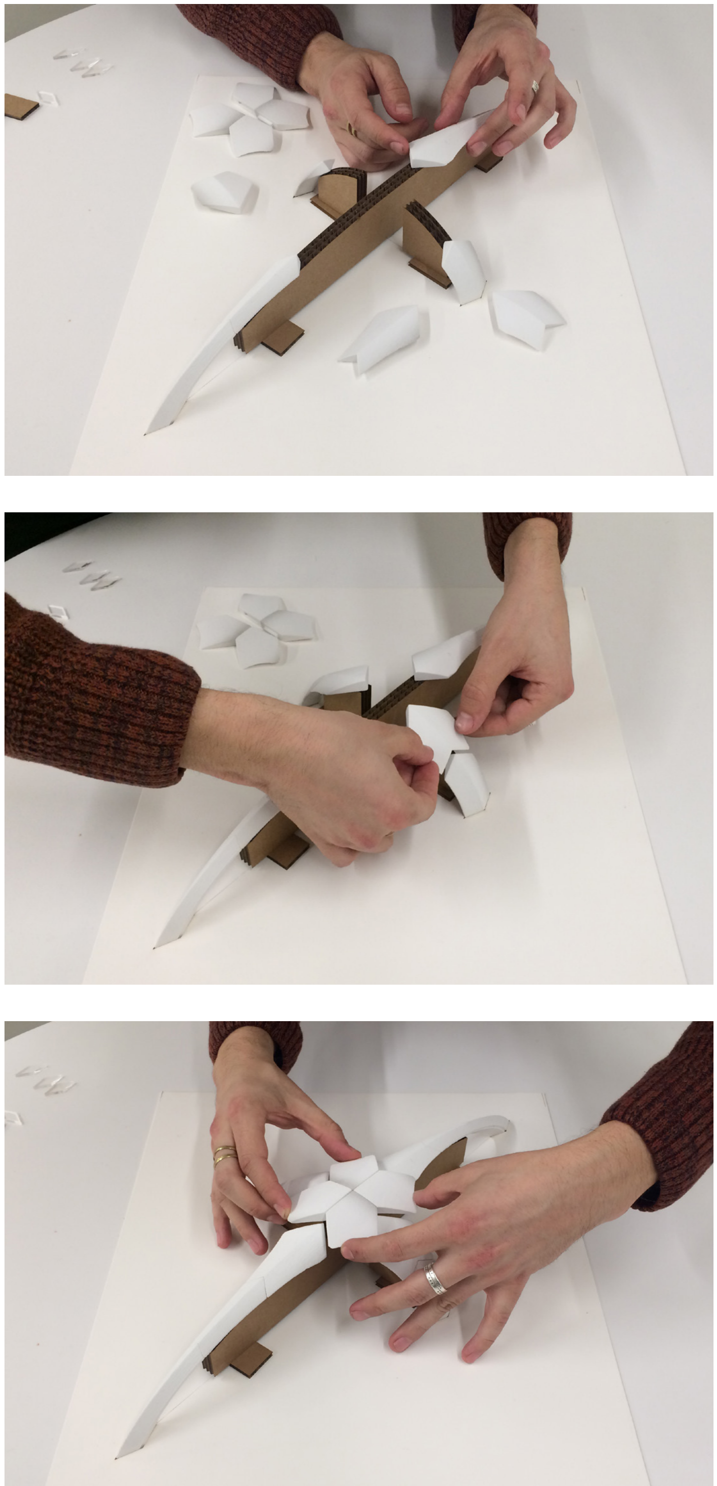


Fig. 3.15. Assembly of scale model on cardboard formwork.

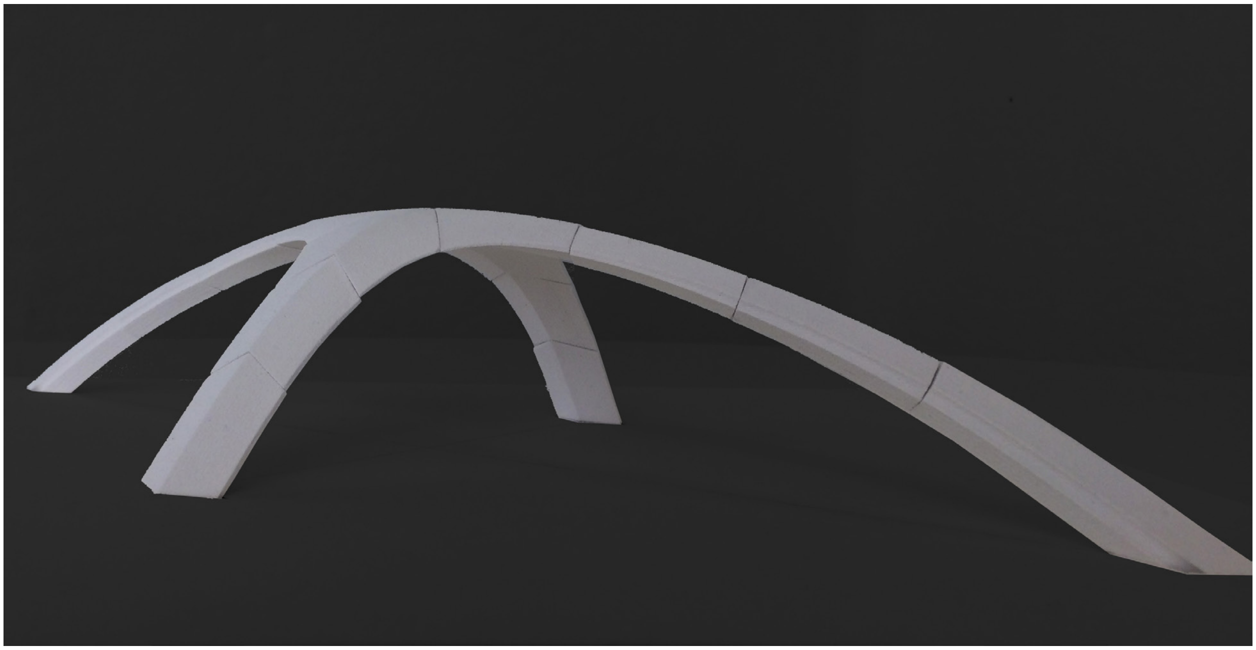


Fig. 3.16. Assembly of scale model. Pieces fit together dry - no glue was used.

The contention is this slow computation methodology promotes creative production through an open-ended, non-deterministic process with material and structural primacy. The input for barrel vault grammars are parametric: any arch shape that is stable in compression can be extruded and used for computing. Graphic statics and limit analysis are effective slow computing methods that are effective for visually validating the stability and safety of shapes. Mechanical formation of structural shapes is not the focus of this project - rather, a means of designing *with* structural shapes. The shape rules offer unlimited possibility to compute new spatial arrangements of structural shapes, but are hard to ***see*** in three-dimensions. The abstract though simple nature of the line/plane drawings make certain that when rules are applied, the material and structural implications that result from adding and subtracting to drawings are respected. The rapid-prototype assembly model proves the two-dimensional slow computing process offered by barrel vault grammars makes designs of things that can be built - and scaled. Further exploration is undoubtedly needed to better understand the capacity of the system to generate surprising and novel forms and aggregations of the shapes. The rules themselves need refinement to ensure only stable shapes are made as rules are deployed. The hope, is with practice working in 2D, it is possible to gain an intuition for seeing the structural rules in 3D. Major development is also needed to begin transferring designs to large-scale constructions. While the schemas should be defined that handle transferring the designs from 2D drawing to 3D model. Making grammars [Knight & Stiny, 2015] need to be developed to extend computing from drawings to construction including material selection, construction method, discretization of voussoirs (if applicable), formwork structures, and assembly sequences.

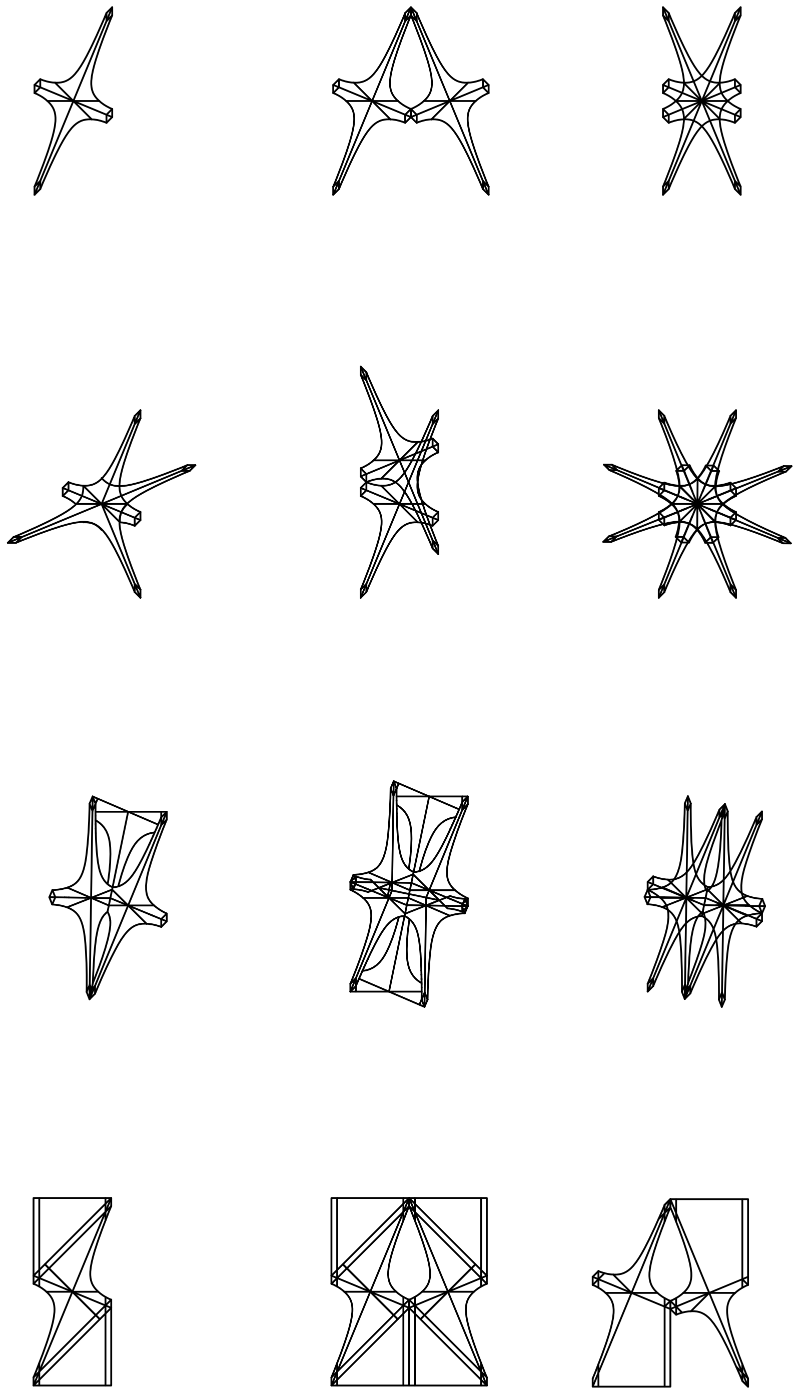


Fig. 4.1. Design Possibilities from the barrel vault grammar.

4. Conclusion

4.1 Summary

The objective of this project has been to demonstrate a way of working that promotes a greater understanding of the matter, shapes, and forces at play when designing architecture. The previous chapters have defined the notion of material and structural primacy in response to observed shortcomings of fast computation to provide relevant feedback for translating digital work into assembled material. The value of working within equilibrium constraints was established the as a means of designing with material and structural primacy. Slow computing techniques were implemented as a means of making material, structural and constructive concerns explicit and visual for analysis and for suggesting new ways of designing creatively based on knowledge developed through historic inquiry.

4.2 Primacy, Equilibrium, and Slow Computation (reprise)

The personal motivation for the project came from my own interest in addressing contemporary issues in architecture and design through historic inquiry. A major portion of the world's building heritage is made with unreinforced masonry and history is rich with remarkable examples of invention and creativity building with stone and brick despite strict material and structural constraints: the materials work only in **compression**. Before engineers had a means of calculating the stresses in structures, medieval builders used an intuitive understanding of materials and their relationship to shapes that make structures stand up. A brick likes an arch. The medieval builder's tactile experience working with materials gave way to a visual understanding of the relationship between form and forces and an ability to work creatively within the rules set by their material worlds. The open-ended and action-oriented nature of building design was lost to a disciplinary approach in the Renaissance, based on the Albertian notion that design and creativity are matters of the mind - not material and hand.

Material and structural primacy has been defined as *promoting a way of designing architecture that uses a greater understanding of the matter and forces at play to catalyze creative production of designs that can be built.* A perceptual understanding of *what* materials to use and *how* to put them together in space is at the heart expanding the creative capacity of contemporary designers. *Primacy* was inherent to builders' process but replaced by the idea that buildings could be produced entirely in advance by any educated person who could represent buildings in abstract form with the homogenized material medium: the lineaments. The *architect* left aside questions of *what* and *how* in favor of producing building forms from pure geometric exploration. This led to a trend of buildings that are conceived of entirely without consideration for material and structure during the design process - recently facilitated and popularized by fast computing tools. The current lack of integration of material and constructive intelligence in contemporary design methods has resulted in buildings that are overly structured and wasteful. Many contemporary architects have contributed to a body of built work made from overly heavy structures that waste material and not only cost more financially but are also more environmentally harmful.

Working in the context of masonry has provided a unique opportunity to both learn from history and leverage analysis techniques and (where appropriate) computing technologies for the sake of building material knowledge and making advancements to contemporary design methodologies and construction practices. The behavior of unreinforced masonry - *why* brick likes an arch - can be described visually by the reciprocal relationship between a chain hanging in tension under self-weight and an arch standing in compression, brought to light in Robert Hooke's anagram (1675). The principles of **equilibrium** have brought to light simple yet powerful concepts and offered profound visual feedback on the behavior of historic buildings. They serve as a learning tool for developing a heightened understanding of the relationship between form and forces. Past research efforts confirmed the value of implementing graphic statics with fast computation because of the interactive engagement with drawings that enhance a user's awareness of the relationship between form and forces, and generating content that is formed with *primacy*. Computational graphic statics suffer one major drawback common to all fast computing tools: *they alone are not sufficient to produce creative work*. Whether simulated (Kangaroo) or geometrically formed (RhinoVault, eQuilibrium, etc.) form-finding is based on parametric variables, goals, and constraints - the range of possible shapes are known from the start. Finding form is an active though mechanical enterprise that generates design content only and therefore has little creative value on its own. Even shapes made with material and structural *primacy* are still routine design possibilities within preconceived boundary conditions. Following forces to make forms is evidence of material knowledge, but not necessarily evidence of a creative capacity.

This thesis has taken a critical approach toward technology in the context of doing creative design and has proposed a methodology that leverages an awareness of the matter, shapes, and forces at play in masonry structures. A focus on enumeration using fast computation has drawn architects' attention toward programming tools to make families of design possibilities. Architects need to leave aside obsessions with catalogs, SLOW DOWN, and look for ways of working with technical knowledge to *catalyze creative production*. **Slow computation** offers new ways of looking at historical content and a theoretical context for design and research. Slow methods include all forms of visual or haptic computing that promote creativity through open-ended exploration. This project has promoted the use of slow computing methods to gain new forms of material and structural knowledge from history and apply that knowledge toward the definition of a new generative design system that works between traditional architectural media: drawing and masonry construction. Inspired by the theories and mechanics of shape grammars and graphic statics the contention was working this way offers a method of designing masonry structures that bares on contemporary disciplinary concerns by showing how designing within the constraints of a masonry arch does not have to be mechanical or deterministic, but rather is open-ended, imaginative and creative. At the scale of architecture, structure is unavoidable. Having the capacity to intuit structure would make it possible to improvise; to design directly with the "stuff" of architecture. Constraining design to compression-only in the context of an academic project offers some exciting design implications too. Masonry structures are nearly infinitely scalable which means rapid prototype assembly models can be used as a reliable design feedback mechanism. Today it is ethical and essential to work toward designing more efficient buildings and constructing them with sustainable materials. Due to the low stresses involved compared to the strength of materials, compression-only structures can be built with materials that are low-strength and have low embodied energy.

4.3 List of Contributions

This project has worked across to three broad disciplinary areas: history, construction and computation. The objective has been to demonstrate a way of working that promotes a greater understanding of the matter, shapes, and forces at play when designing architecture. A new structural algebra - characterized by equilibrium constraints - was defined that lets designers work visually and non-deterministically with material and structural primacy; to feel the forces in shapes. Structural rules were extracted from history to inspire a slow computation methodology for an open-ended generative process that only produces results that can be constructed and be stable in compression.

- A case was built for using slow computation methods as means of designing with material and structural primacy.

- A definition of material and structural primacy was given within the context of creative production - making the distinction between active mechanical formation, and open-ended formal exploration. Primacy promotes a way of designing that uses a greater awareness of matter, shapes and forces to catalyze creative production of designs that can be built.
- Slow computation was generalized to include all forms of visual or haptic computing that promote creativity through open-ended exploration.

Chapter 2: *An Inquiry into Palladian-ism* presented a new way of looking at a historical body of work. From a scholarly perspective, very little work has been done in terms of looking at the safety and stability of Palladio's buildings as unreinforced masonry structures - and yet, the Villas in particular were made primarily out of brick. An theoretical inquiry into the Villa Foscari, "La Malcontenta" as it was drawn in the Quattro Libri and by Scamozzi sought to extract structural design and construction knowledge.

- A rationalist way of looking at Palladio's buildings was presented that engaged questions about the forms of vaults the in villas and the forces in them in response to a lack of scholarly work on Palladio's masonry structures.
- Methods and theories (shape grammars and graphic statics) were used to demonstrate a new way of looking at historical buildings for the purposes of extracting generative material, structural and construction knowledge.
- A systematic and repeatable method of analysis was proposed based on O'Dwyer's method of mapping potential force paths in shapes. The mapping in plan reveals a certain level of structural/constructive literacy in Palladio's design system - smaller vaults were distributed symmetrically around a central core vault and oriented so they counter-thrust and buttress each other.
- An observation was made about Palladio's use of masonry vaults in his architecture without external buttressing.
- A hypothesis was proposed about the Palladio's system for buttress free construction. The height of the exterior walls above the first floor should be looked at closer as a solution to weigh down the perimeter condition to account for the outward thrust of the vaults in the smaller rooms surround the central space.

Chapter 3: *A New Structural Algebra* presented a series of designer rules based in part on shape rules in the Palladian grammar by Stiny and Mitchell (1978a) and in part from the material and structural knowledge about Palladian villa design developed in chapter 2.

- Though structural grammars have been explored for many decades now, this project proposes the first shape grammar formalism for compression-only masonry shapes.
- The Palladian grammar rules were revisited, described in terms of general parametric schemas and simplified to two rules of formation that account for non-tartan grid spatial organizations.
- A slow computation methodology - barrel vault grammars - inspired by the theories and mechanics of shape grammars and graphic statics, was proposed and tested. The method promotes doing non-deterministic, visual, and algebraic design using structural shapes that bare the necessary information to produce results that are formally novel and build-able.
- Demonstrated a means of working between two traditional architectural media (drawing and masonry), that was neither mechanical nor deterministic. Rather, open-ended, imaginative and creative. The rapid-prototype assembly model served as a proof of concept that unpredictable forms can emerge from the rule-based design process that are still structural shapes that are stable in compression and therefore scalable to any scale of construction.

4.4 Future Work

The work done for this thesis has only brought to light nearly limitless future pursuits. The background to and definitions of material and structural primacy and slow computation should be revisited and refined. The terms have so far been effective in describing the spirit of my work and the attitudes it takes toward design, creativity, technology and construction. The historical work should also be continued. The analysis of villa Foscari should be completed - each vault type at the perimeter should be looked at carefully - and the entire analysis can serve as a theoretical model for looking at other villas, should also be used to look at the actual buildings more carefully. These same methods could be used to analyze 3D building scans and provide a systematic way of determining the stability and safety of Palladio's remaining architectural heritage. The slow computation methods for analysis should be extended to a wider range of masonry buildings throughout history. Design rules could be extracted out of any building that has vaults working in compression only. An unique would be to look at the aggregations of vaults at the Cuban Art Schools and develop a grammar based on those. As it was stated early in this document. This project did not seek to produce designs. A design studio curriculum based on extracting simple rules from historic buildings and material systems should be developed and deployed to better understand the design implications of method and the extent to which it works for making creative, new, evocative, materially and structurally conscious design.

5. References

5.1 Bibliography

Ackerman, J. S. (1966). Palladio. Harmondsworth: Penguin.

Alberti, L. B. (1988). *On the Art of Building in Ten Books*, trans. J. Rykwert, Leach N., Tavernor R., Cambridge, MA: MIT Press.

Allen, E., & Zalewski, W. (2009). Form and Forces: Designing efficient, expressive structures. 1st edition. Hoboken, NJ: John Wiley and Sons.

Anderson, S., and E. Dieste. (2004). *Eladio Dieste : innovation in structural art.* New York : Princeton Architectural Press.

Beltramini, G., & Burns, H. (2008). *Palladio.* London : Royal Academy of Arts, c2008.

Blanciak, F. (2008). *Siteless: 1001 Building Forms*. Cambridge, MA: MIT Press.

Block, P. (2005). Equilibrium Systems: Studies in masonry structure. SMArchS thesis, Massachusetts Institute of Technology, Cambridge, MA.

Block, P. (2009). Thrust Network Analysis: Exploring Three-Dimensional Equilibrium. PhD Thesis. MIT PhD Dissertation.

Block, P., M. DeJong, and J. Ochsendorf. (2006). "As hangs the flexible line: Equilibrium of masonry arches." *The Nexus Network Journal* 8 (2):13-24.

Block, P., T. Ciblac, and J. Ochsendorf. (2006). "Real-time limit analysis of vaulted masonry buildings." *Computers and Structures 84* (29-30): 1841-1852.

Burns, H., et al. (1975). *Andrea Palladio, 1508-1580 : the portico and the farmyard* : catalogue. [London] : Arts Council of Great Britain.

Culmann, C. (1864/1866). *Die graphische Statik*. Zürich: Verlag von Meyer & Zeller.

Davis, L., et al. (2011) "Efficient and Expressive Thin-tile Vaulting using Cardboard Formwork." Proceedings of the IABSE-IASS Symposium 2011. London, UK,2011 (September).

Dessi-Olive, J. (2010). "Studies of XVI C. Masonry Structures in Oaxaca, Mexico". In proceedings of The National Conference On Undergraduate Research (NCUR) 2010, University of Montana, Missoula, MT. April 2010.

Dessi-Olive, J. (2014). Computation to Construction (and back again). MArch thesis, University of Pennsylvania School of Design, Philadelphia, PA.

Di Mari, A., and N. Yoo. (2012). *Operative Design: A catalogue of spatial verbs.* Amsterdam: BIS Publishers

Di Mari, A. (2014). Conditional Design: An introduction to elemental architecture. Amsterdam: BIS Publishers

Downing, F. and U. Flemming. (1981) The bungalows of Buffalo Environment and Planning B: Planning and Design 8: 269-294.

Duarte, J. P. (2005). "Towards mass customization of housing: the grammar of Siza's houses at Malagueira." *Environment and Planning B: Planning and Design*, 32: 347-380.

Foster+Partners. (2015/2016) Droneport Project page. Accessed May 24, 2017. <http://www.fosterandpartners.com/projects/droneport/> and <http://www.fosterandpartners.com/news/archive/2016/05/norman-foster-s-droneport-prototype-goes-on-show-at-the-venice-biennale-2016/>

Greenwold, S., and E. Allen. (2003). Active Statics. Last update in 2003. Accessed May 24, 2017. <http://acg.media.mit.edu/people/simong/statics/data/index.html>

Harvey, J. (1958). Medieval Designs. Transactions of the Ancient Monument Society. New series, 6:55-72.

Heyman, J. (1995). *The Stone Skeleton: Structural engineering of masonry architecture.* Cambridge: Cambridge University Press.

Huerta, S. (2004). *Arcos bovedas y cupulas: Geometra y equilibrio en el calculo tradicional de estructuras de fabrica.* Madrid: Instituto Juan de Herrera.

Ingold, T. (2007). “Comment” in Jorge, V. O. and Thomas, J. (eds), *Overcoming the Modern Invention of Material Culture, special issue of the Journal of Iberian Archaeology.* Vol. 9/10: 313-317.

Ingold, T. (2010). “The textility of making.” *Cambridge Journal of Economics*, 34:91-102.

Kahn, L. (1971). Quote transcribed from the 2003 documentary ‘My Architect: A Son’s Journey by Nathaniel Kahn’. Master class at Penn, 1971.

Knight, T. (1989). “Color grammars: designing with lines and colors.” *Environment and Planning B: Planning and Design* 16: 417-449.

Knight, T. (1999). “Shape grammars: six types.” *Environment and Planning B: Planning and Design* 26: 15-32.

Knight, T. (2012) “Slow Computing: Teaching Generative Design with Shape Grammars” in Wan, X, Gu, N. (eds), *Computational Design Methods and Technologies : Applications in CAD, CAM, and CAE Education* (pp. 34-55). Hershey, PA: Information Science Reference.

Knight, T. and G. Stiny. (2015). “Making grammars: From computing with shapes to computing with things”. Design Studies 41(A): 8-28.

Koning, H. and J. Eizenberg. 1981. “The language of the prairie: Frank Lloyd Wright’s prairie houses.” *Environment and Planning B: Planning and Design* 8: 295-324.

Lee, J. (2015) Grammatical Design with Graphic Statics: Rule-based Generation of Diverse Equilibrium Structures. MEng thesis, Massachusetts Institute of Technology, Cambridge, MA.

López López D., et al. (2016). “Tile vaulting in the 21st century.” Informes de la Construcción,68(544): 33-41,2016 (October-December).Special issue “Nuevos avances de la cerámica en la construcción”.

March, L. (1998). *Architectonics of humanism : essays on number in architecture.* Chichester ; New York : Academy Editions.

Mitchell, W. J. (1991). “Functional Grammars: An Introduction. Reality and Virtual Reality“ (ACADIA 1991) (pp. 167-176). Troy, NY: ACADIA.

Mitrovic, B. (2004). *Learning from Palladio.* New York : W.W. Norton.

Moussavi, F. (2009). *The Function of Form.* Cambridge, MA: Harvard GSD.

Mueller, C. (2014) Computational Exploration of the Structural Design Space. PhD Thesis. MIT PhD Dissertation.

Muslimin, R. (2010). “Interweaving grammar: reconfiguring vernacular structure through parametric shape grammar.” *International Journal of Architectural Computing*, 8(2): 93-110.

Nagakura, T. Tsai, D., and Choi, J. (2015). “Capturing History Bit by Bit”, eCAADe 33.

O’Dwyer, D. W. (1999). “Funicular analysis of masonry vaults”. *Computers and Structures 73* (1-5): 187-197.

Palladio, A. (1997). *The four books on architecture*. Cambridge, Mass. : MIT Press.

Puppi, L. (1975). *Andrea Palladio*. Boston : New York Graphic Society, 1975, c1973.

Ramage M., et al. (2009) “New African vaults built with soil-cement tiles” in Proceedings of the International Association for Shell Spatial Structures Symposium 2009, Valencia.

Scamozzi, O.B., et al. (2014). The buildings and designs of Andrea Palladio. New York : Princeton Architectural Press.

Shea, K., and J. Cagan. (1999). Languages and semantics of grammatical discrete structures. Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 13, 241-251.

Stevin, S. (1586). *De Beghinselen der Weeghconst.* (In The Principal Works of Simon Stevin, vol. 1, Leyden.)

Stiny. G., (1977). “Ice Rays: a note on the generation of Chinese lattice designs”. *Environment and Planning B: Planning and Design* 4: 89-98.

Stiny. G., (1980a). “Introduction to shape and Shape Grammars.” *Environment and Planning B: Planning and Design* 7: 343-351.

Stiny. G., (1980b). “Kindergarten grammars: designing with Froebel’s building gifts.” *Environment and Planning B: Planning and Design* 7: 409-462.

Stiny. G., (1985). “Computing with form and meaning in architecture”. *Journal of Architectural Education* 39(1):7-19

Stiny. G., (1989). “What is a design?”. *Environment and Planning B: Planning and Design 1*7: 97-103.

Stiny, G. (2006). *Shape: Talking about Seeing and Doing.* Cambridge, MA: MIT Press.

Stiny, G. and J. Gips. (1972). “Shape Grammars and the generative specification of painting and sculpture.” *Information Processing*, 71: 1460-1465.

Stiny. G., and W.J. Mitchell (1978a). “The Palladian grammar”. *Environment and Planning B: Planning and Design 5*: 5-18.

Stiny. G., and W.J. Mitchell (1978b). “Counting Palladian plans”. *Environment and Planning B: Planning and Design 5*: 189-198.

Strauss, C., & Fuad-Luke, A. (2008). “The slow design principles: A new interrogative and reflexive tool for design research and practice”. In C. Cipolla & P. P. Peruccio (Eds.), *Changing the change* (pp.1440-1454). Allemande Conference Press.

Van Mele, et al. (2016). “Form finding and structural analysis of a freeform stone vault.” Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2016,K. Kawaguchi, M. Ohsaki, T. Takeuchi (editors),Tokyo, Japan,2016 (September).

Wittkower, R. (1988). *Architectural principles in the age of humanism*. London : Academy ; New York : St. Martin’s Press, 1988.

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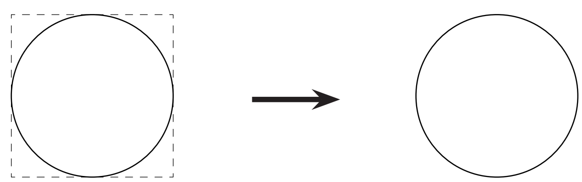
6. Appendices

6.A Appendix A: Palladio’s Proportions

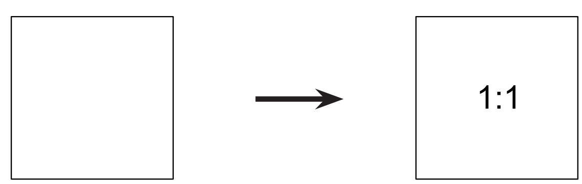
Palladio’s Plan Ratios
[Book I, XXI, On Loggias, Entrances, Halls, and Rooms and their Shapes]

Palladio lists seven room ratios. I’ve drawn them all below, showing how each is constructed from a square, with the ratio width to length, or w : l, where the width w is equivalent to the span of a vault overhead.

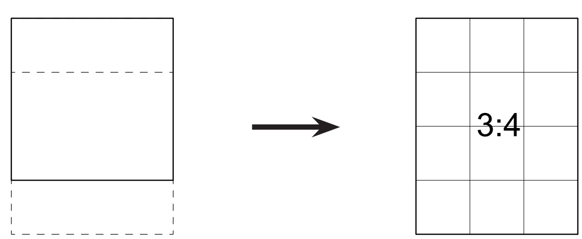
(i) circular



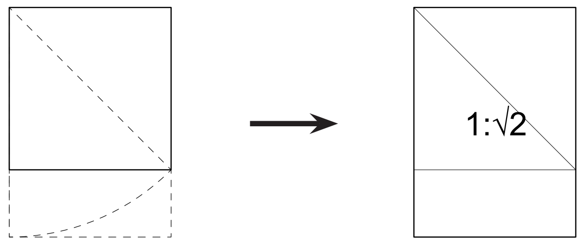
(ii) quadrato [square]



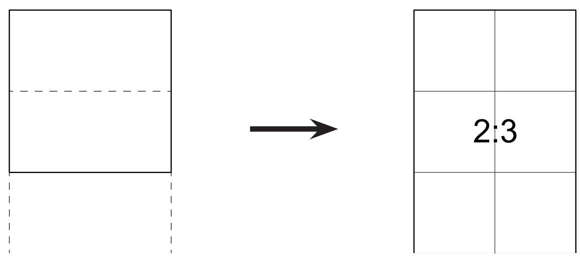
(iii) quadrato and 1/3



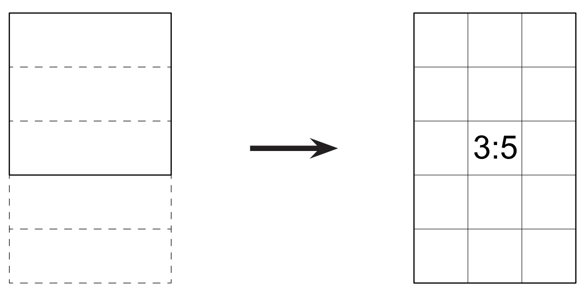
(iv) length equal to the diagonal of a square



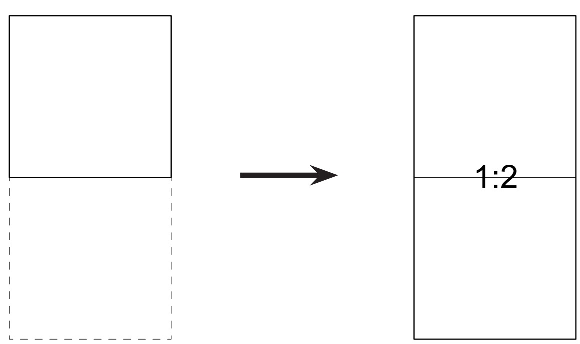
(v) quadrato and 1/2

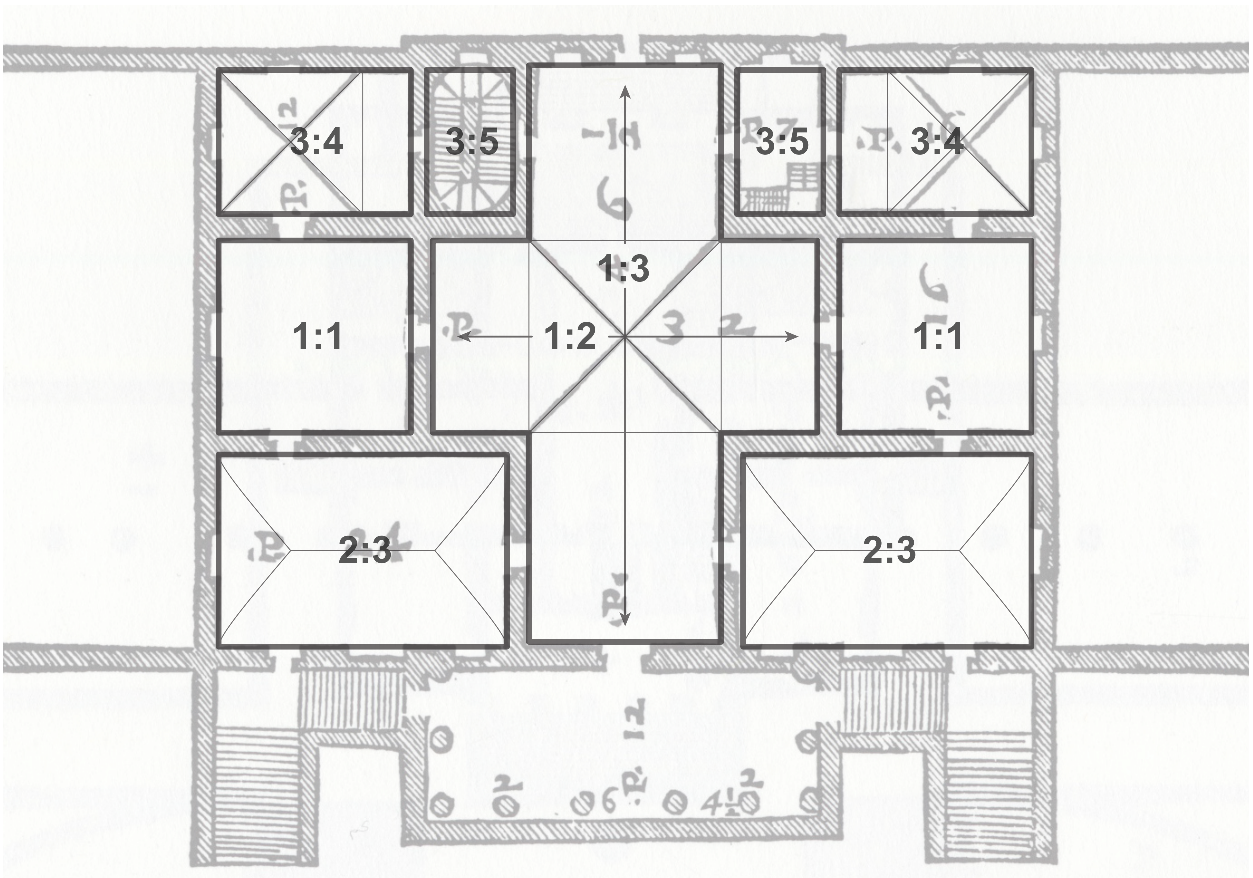


(vi) quadrato and 2/3



(vii) two squares



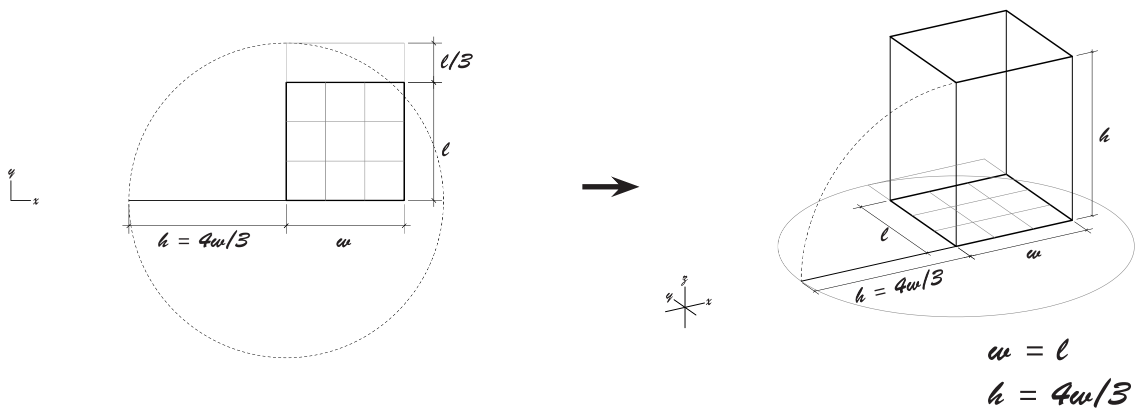


Plan of Villa Foscari, "La Malcontenta" overlaid by room proportion approximations.

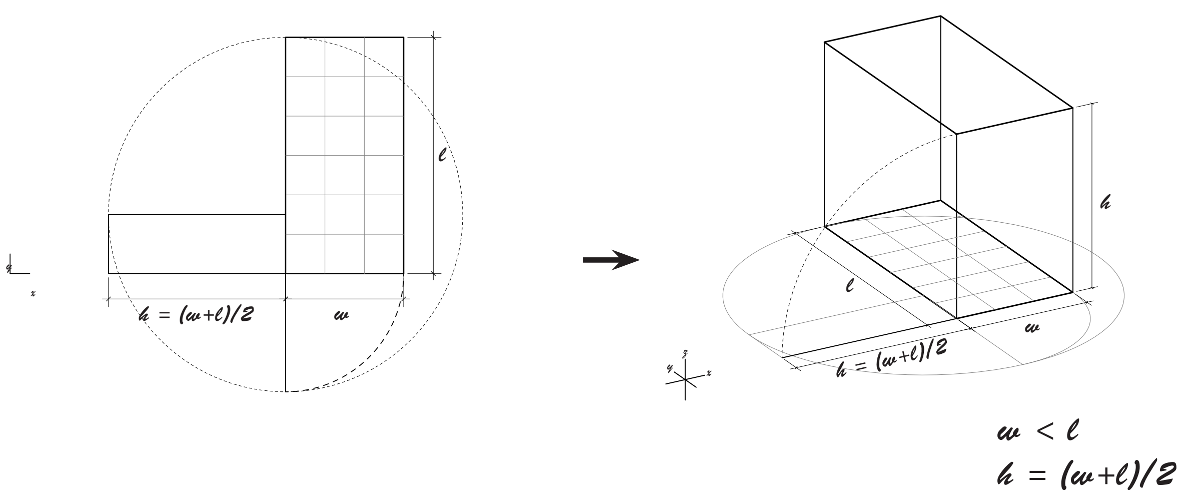
Palladio's Methods for setting the heights of rooms
[Book I, XXIII, On The Heights of Rooms]

Palladio offers a number of methods for determining the heights of rooms - more specifically, the heights of the vaults, which is being interpreted as the distance from the floor to the highest portion of the vault [the crowd]. Although he does offer rules for ceilings that made of wood joists or beams, only those which apply to the heights of vaults will be considered for now. The goal here is to clarify and visualize the rules and derive simple equations to solve for h in terms of w and l for each method.

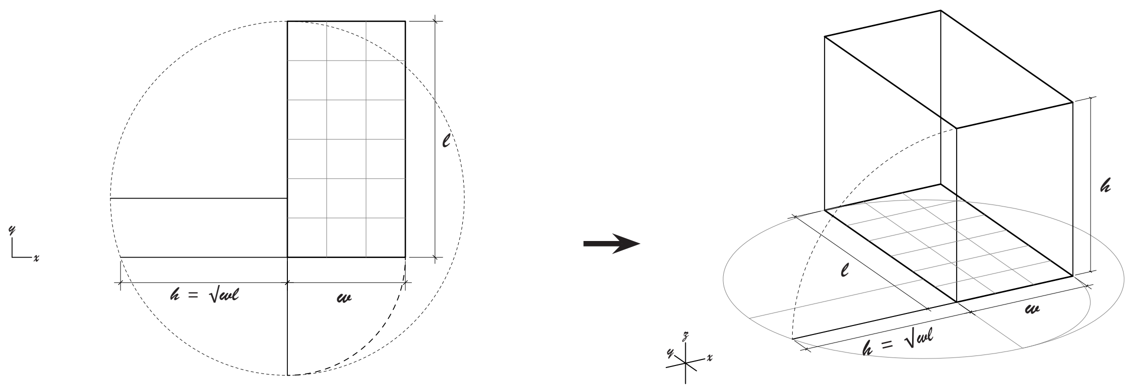
Method 1:



Method 2:



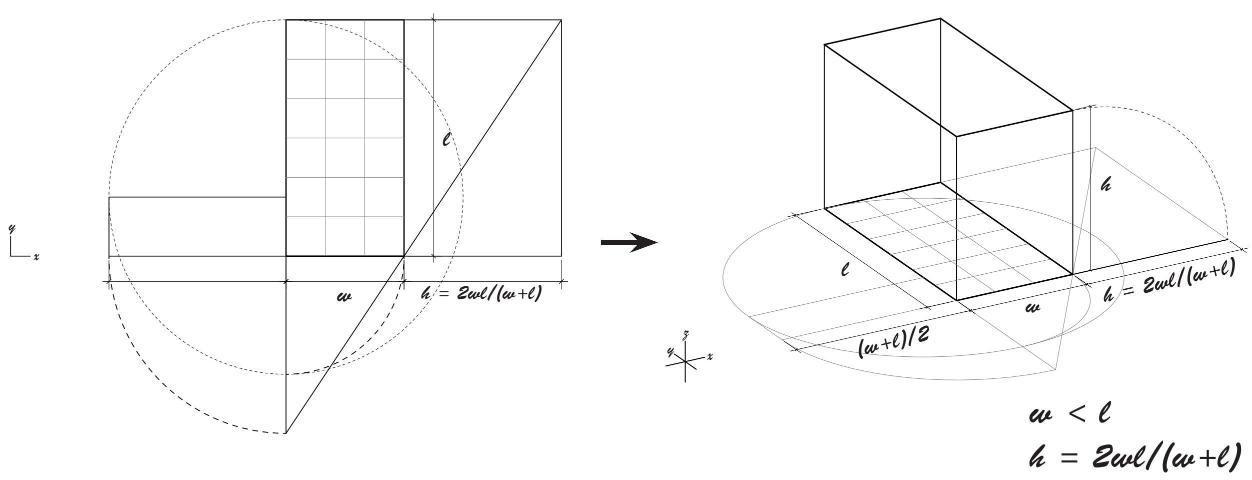
Method 3:



$w < l$

$h = \sqrt{wl}$

Method 4:

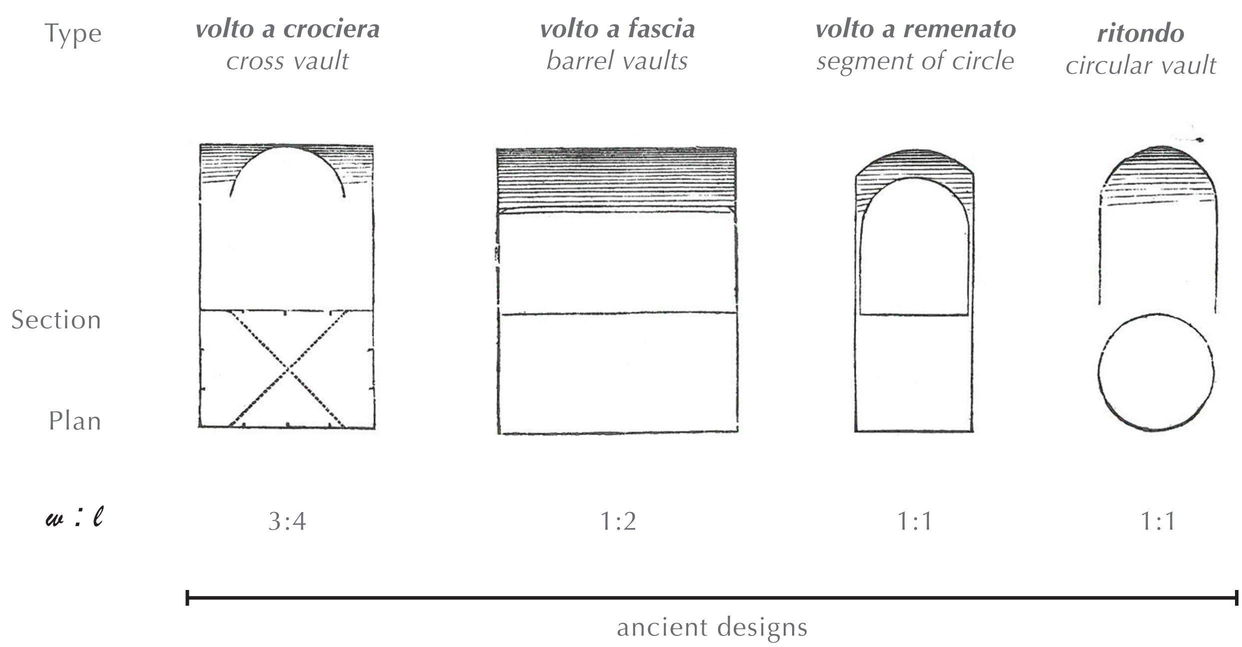


$w < l$

$h = 2wl/(w+l)$

Palladio’s Vaults
[Book I, XXIV, On *The Types of Vaults*

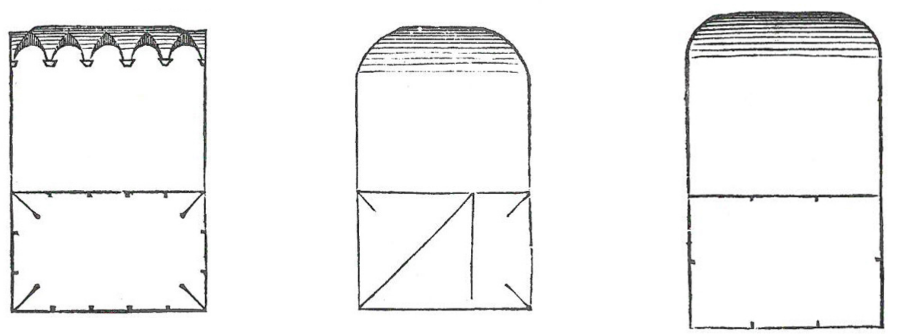
Palladio says he uses 6 types of vaults and draws examples of each on different room ratios. As mentioned before, the height is proportional to the width and length of the room. An assumption being made here is that the height, h coincides with the crown of the intrados of the vault. This assumption is based manner Palladio draws his vault sections:



Type	***volto a lunette*** *lunette vault*	***volto a conca/*** ***volto a cadino*** *cove vault*	***volto a schiffo*** *depressed* *cove vault*

Section

Plan

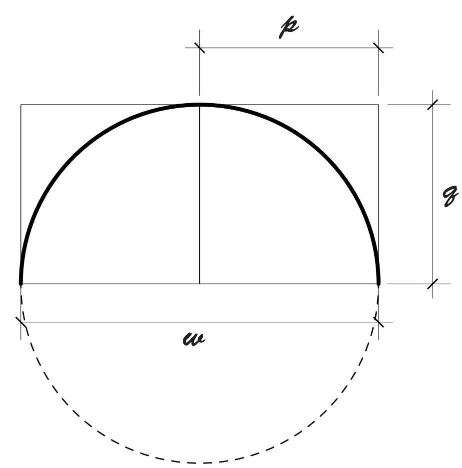


w : l	3:5	$1:\sqrt{2}$	2:3

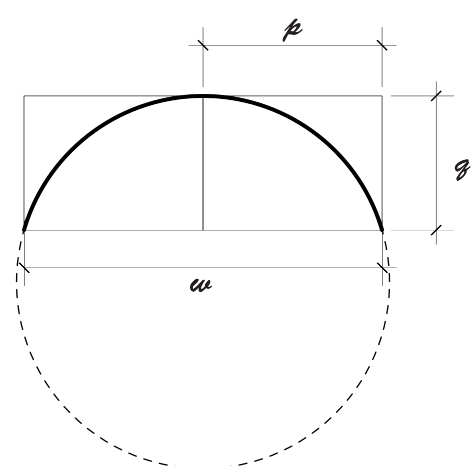
"modern" designs

Palladio, Book 1, Ch. XXIV, Types of Vaults

This exercise is looking at a sample of these drawings - analyzing them to determine their underlying geometry and demonstrate Palladio's general rules for the shapes of vaults. For this analysis, the ratio of the vault intrados will be described in terms of a half-span p and the rise of the vault q. Two examples are shown below. On the left is a vault ratio $p : q$, where $p = q$ making a semi-circular section. On the right is a vault ratio $p : q$, where $p \geq q$, which is the general case, making a segment of circle section for any $p \neq q$.

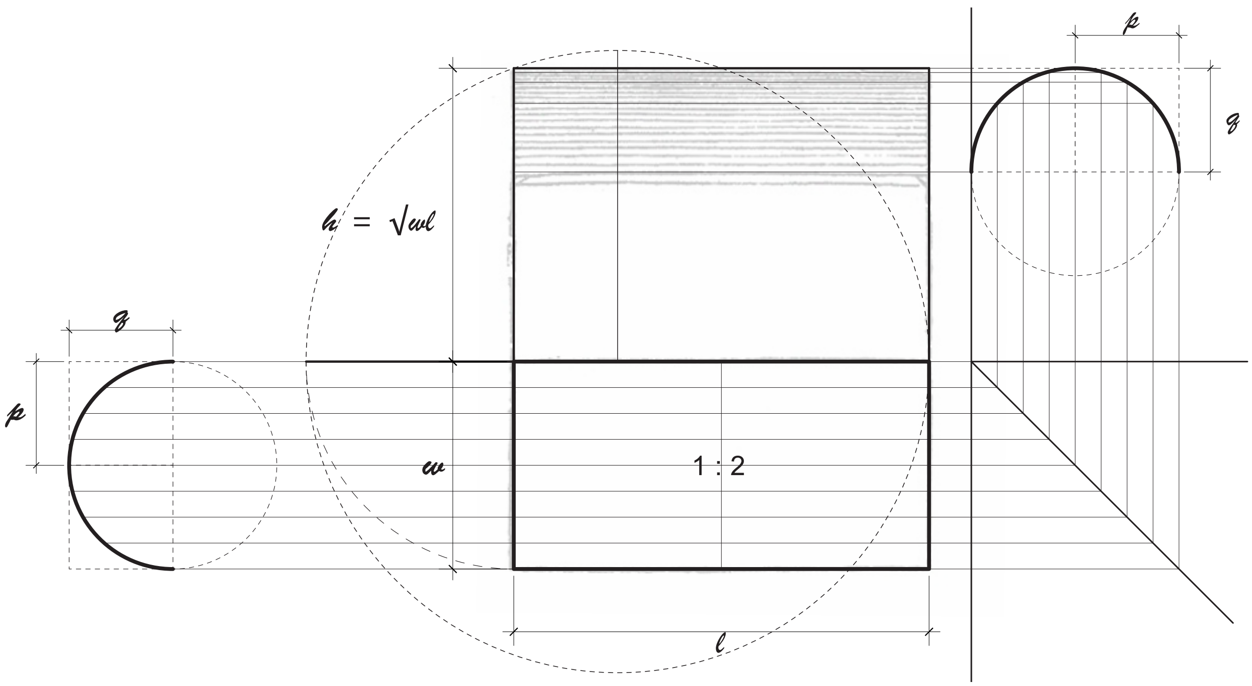


$p : q$, where $p = q$

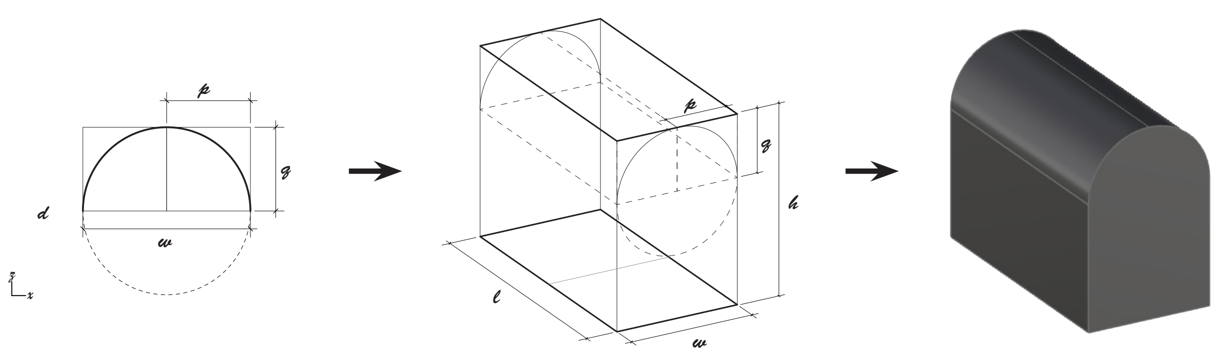


$p : q$, where $p \geq q$

We now have a catalog of Palladio's room ratios, room height rules, types of vaults, and a means of categorizing the vault shapes in terms of a ratio. For each of these, a method of visualizing the geometrical relationships has been defined. Now it's a simple matter of overlaying the drawings from the visual proportion catalog on any drawing to determine its underlying proportions. All of variables discussed until this point can be visualized all at once in a single drawing:



Palladio's depiction of a barrel vault, is a particularly good example because it's easy to see how the rules are deployed by overlaying the ratios and rules onto the drawing. The design of the volume begins with a 1:2 plan ratio. Applying the height rules, shows Palladio used method 3 to determine the height. Finally, a descriptive geometry technique can be used to set the span [$w = 2p$] and next find the height of the vault from spring to crown and set the vault ratio $p : q$. With these values, its possible to reconstruct the volume:

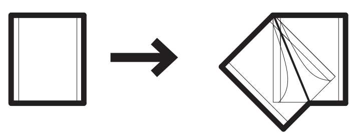


6.B Barrel Vault Grammar [Extras]

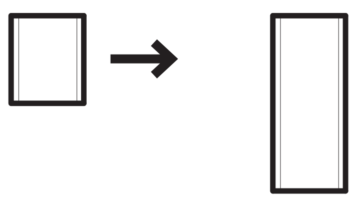
Early Barrel Vault Grammar Development

Though less rigorous in the rule applications, the barrel vault grammar rules are founded on intense geometrical studies of shapes.

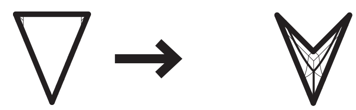
(1)

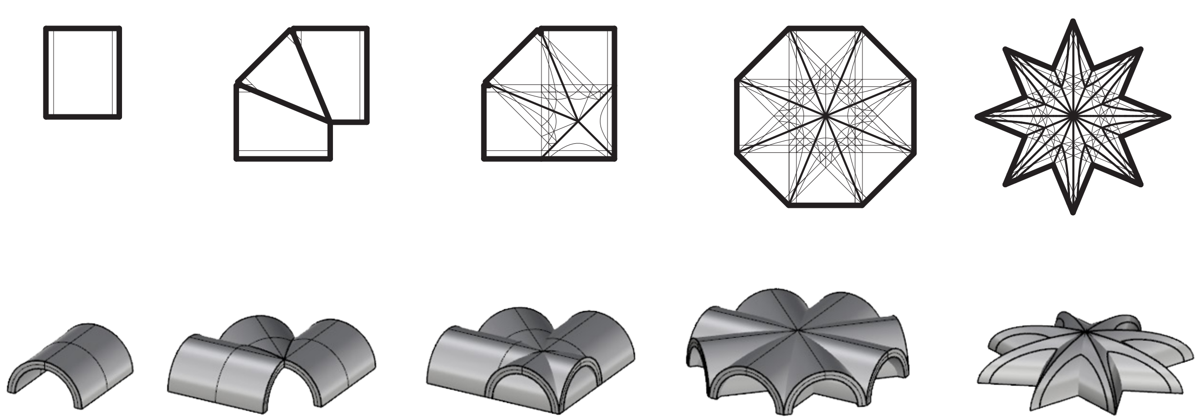


(2)

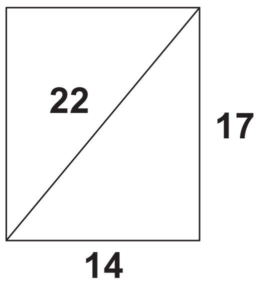


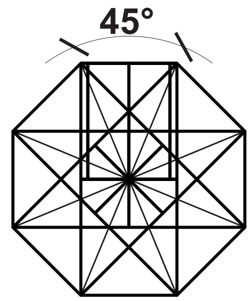
(3)

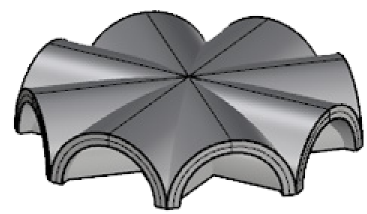


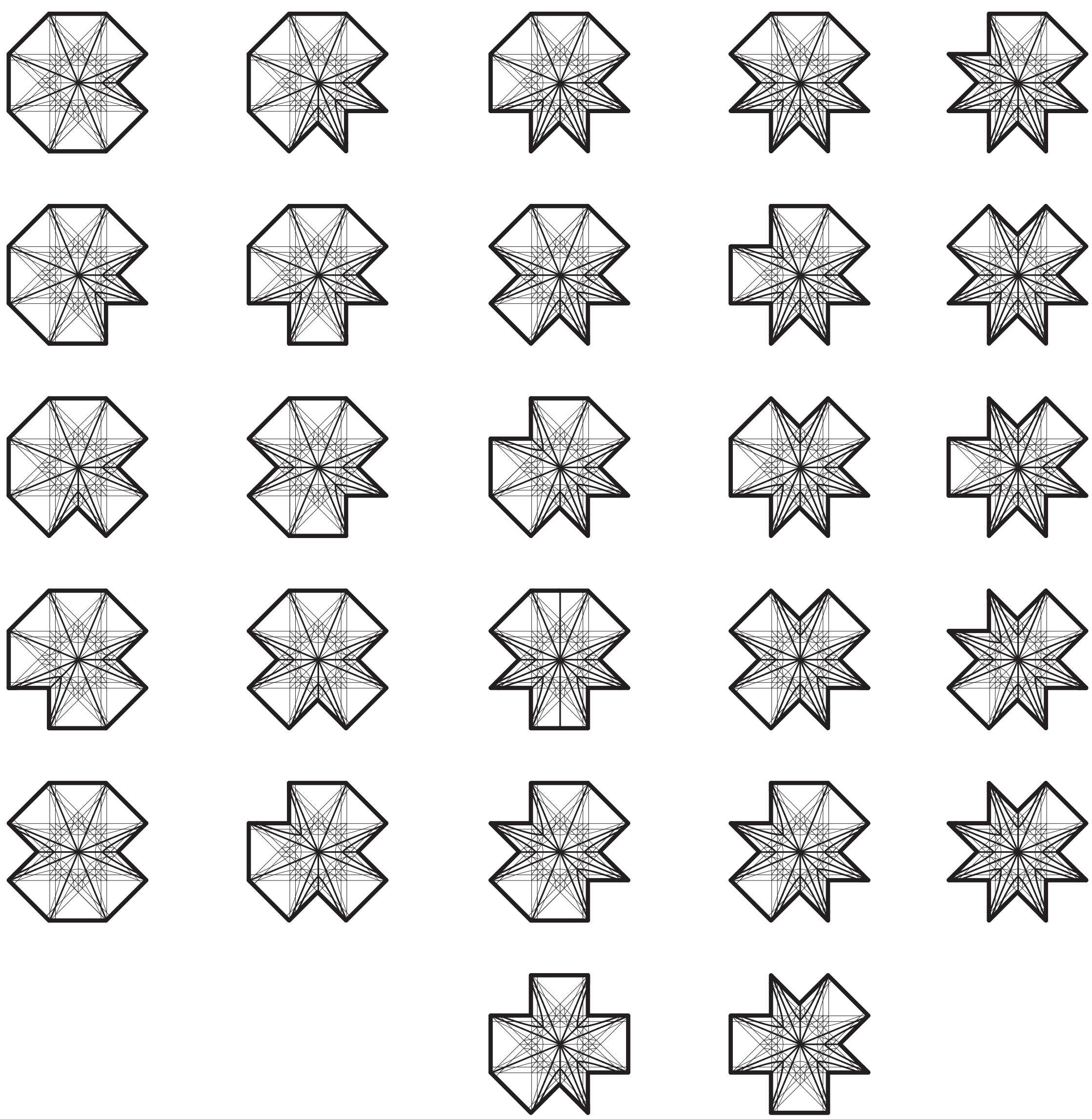


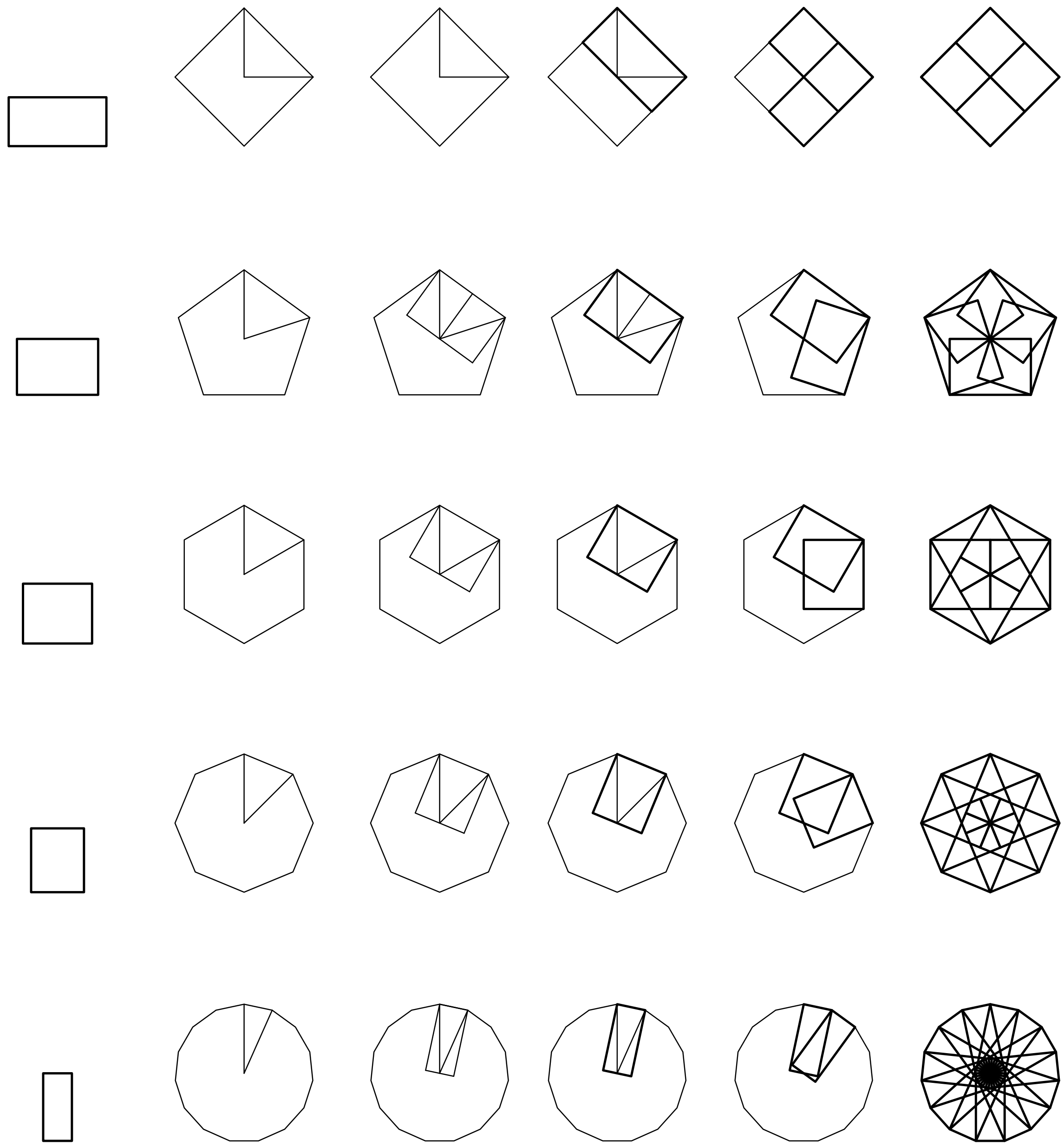
visual barrel transformation rules: basics

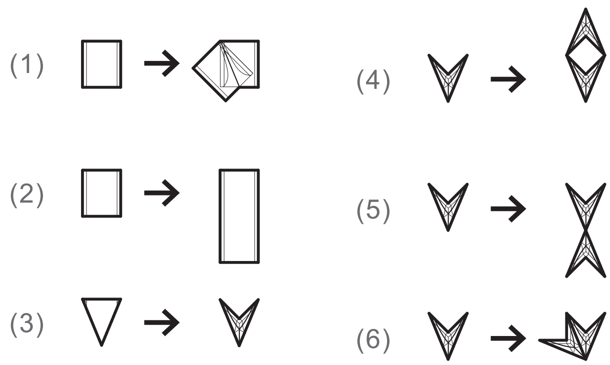

22
17
14

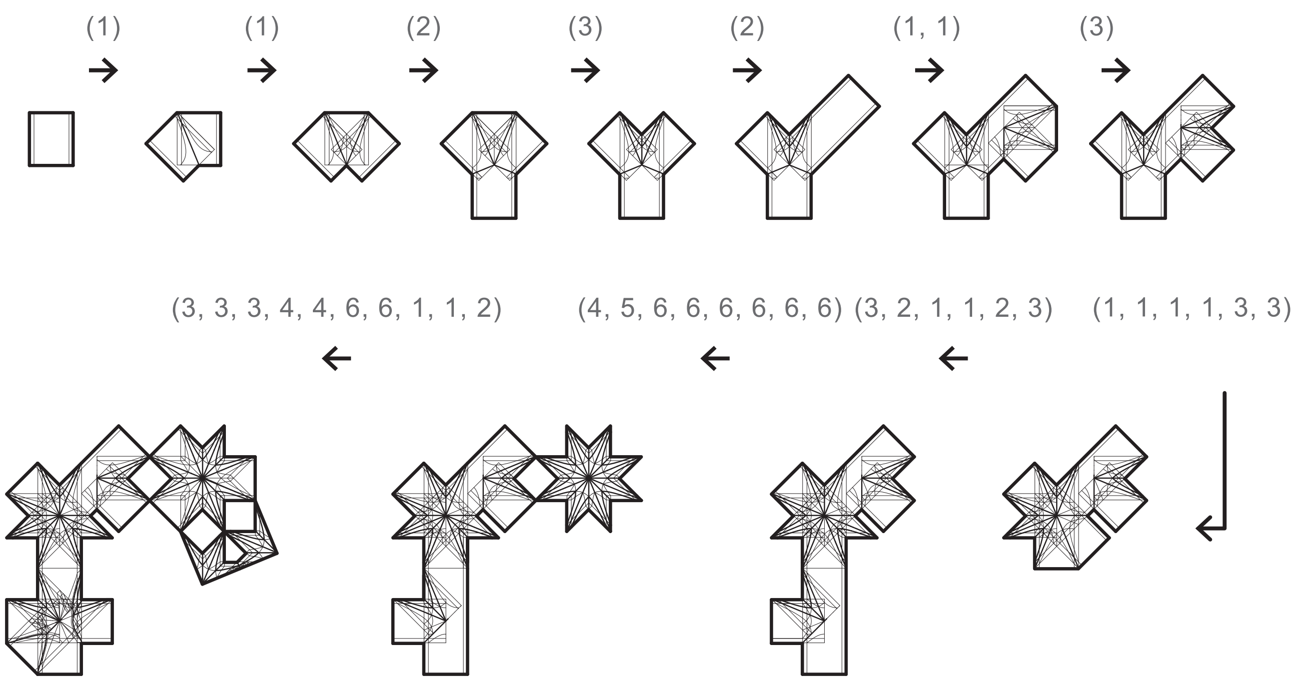

45°








(1)
(2)
(3)
(4)
(5)
(6)


(1)
(1)
(2)
(3)
(2)
(1, 1)
(3)
(3, 3, 3, 4, 4, 6, 6, 1, 1, 2)
(4, 5, 6, 6, 6, 6, 6)
(3, 2, 1, 1, 2, 3)
(1, 1, 1, 1, 3, 3)