Accessible Long Spans:
Pairing Current Analysis Software with Common Resources to Create Monumental Architecture with Developing Communities.

by

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To my wife Robyn
Who supported me and
the pursuit of my dreams

Acknowledgement

I would like to give a special thanks to my professor Scott Shall for encouraging me to pursue this research and supporting me along the way. Secondly I would like to thank my content experts Dan Faoro and Aaron Jones who helped me explore the world of prototyping and structural art forms in the context of my thesis.

Table of Contents

TOP: Image of Velodrome Stadium, a long span representative of the research and technology. https://architizer.com/blog/inspiration/collections/tensile-stadiums/
RIGHT: Fig. 1 Image of a pit house by early civilizations. https://www.thoughtco.com/what-is-a-pit-house-172088

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0.0 ABSTRACT

Historically long spans have been linked to power and wealth. Developing countries, through technologies and research, have had access to larger scale and more complex architecture whereas areas of the world are left to discover through accessible means. Architects throughout history and today dedicate a portion of their services to supporting the needs of the community, but can they bring balance to this separation of resources? The technology to bridge the gap between simple tools, repeated operations, common materials, and complex geometry in the form of long span architecture is at reach. Using local means of construction, the common, accessible material is paper tubes. A form as well as a process of building can be established, repeated, and adapted as a leave behind building strategy. The intent is not to create a new type of form or to discover a new quadratic equation but to better establish the connection between the complex and the simple. The analysis and proof of form comes through advanced computer aided technologies and software. Markets are a critical factor for the economies in developing countries, and from precedent research, will benefit from accessible long spans achieved through this analysis. Several of the countries of Africa have the largest projected population growth in the world with Markets critical to their growth. The architect is not designing the exact form but is more of an influence on how the community can implement their strategies over time with accessible resources. Within the communities the architecture has to be adopted, and then sound structures must be implement with common materials to then be adapted by the people. As the economy grows, so will the implementation strategies. *Using paraboloid geometry, simple tools, repeated operations, and common materials, the architect can create accessible, non-invasive long spans that can be adapted and developed to define current and future trading points in developing communities.*

1.0 HISTORICAL IMBALANCE OF ARCHITECTURE

The historical connection that long span architecture has had to civilizations with power have resulted in areas of the world left behind to discover structural spans through experimentation of common resources. Through obtained and sought out knowledge, these civilizations were able to adapt and achieve various forms of clear span structures through the use of common cylindrical materials, such as “sticks.” The pit house is one example of early complexity in form using common materials and tools (Fig. 1). The developed countries, through technologies and research, have access to the larger scale and more complex architecture of structures for social purposes (Fig.2). These societies and their political agendas have influenced design and pushed for research of structural techniques. Building larger structures for increasing populations for social and commercial uses, increase the support from the population, thus increasing power and further influence. Even when technology was limited, if there were enough resources, it could be obtained. How much did this impact and control the end users of these developed groups? How can architecture be used to solve social and ecological issues? During the expressionist movement of the 1950s in the United States there emerged several architects, Saarinen, Candela,

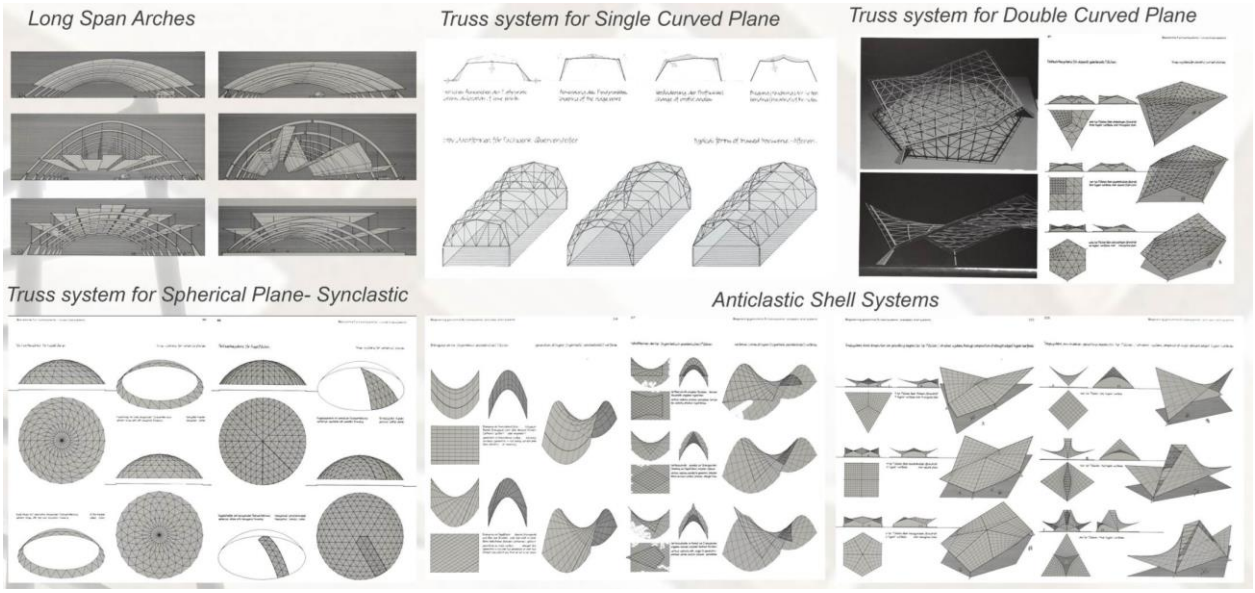
TOP: Fig. 2 Image of Durham Cathedral https://www.durhamworldheritagesite.com

and Nervi, that used complexity to expand limitations of the known materials (Fig.3). It pushed the technology of architecture (Ingersoll, 2019). The idea is that if these efforts could be implemented throughout developing communities, it could have the same impact to the developing world. Architects throughout history and today have dedicated a portion of their services to supporting the needs of the community. The claim is that architects and architecture can be used to bring a balance to power. This balance does not only come from the research and skill set of the architect, but also from making the resources used to build long span structures more financially obtainable than the more common, costly materials used historically. The materials explored in this thesis investigation have emerged and have become more viable in the last several decades and will help bring balance to this historical dilemma.

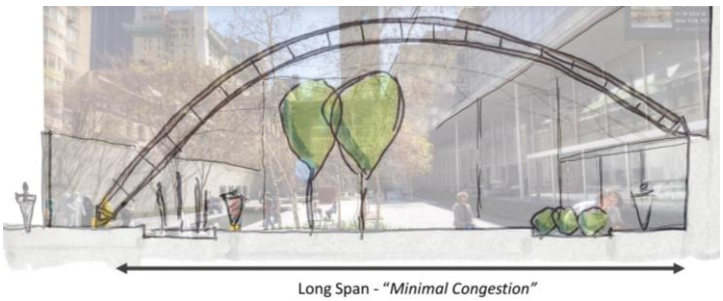
LEFT: Fig. 3. Image of TWA Terminal. Ezra Stoller © Esto. All rights reserved.

2.0 COMMON MEANS AND METHODS

My thesis is a combination of complex parabolic geometry (Fig. 4) with simple operations and materials to make accessible, or obtainable, long spans, which is being defined as a non-invasive structure by containing minimal congestion on the ground (Fig. 5). This lead the research back to the common cylindrical small scale form members such as bamboo, paper tubes, and PVC that could be repeated elements, which simplify the process by reducing the number of unique steps, and can be constructed with simple tools in the resulting architectural form.



TOP: Fig. 4 Images of complex forms. Heino, Engel. Structural Systems. New York Praeger 1968. BOTTOM: Fig. 5 Trace of MOMA Section. RD 2021.

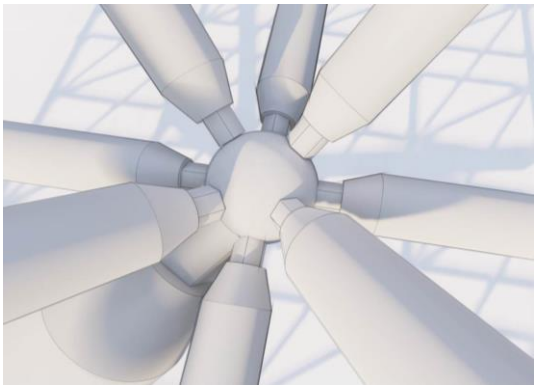


2.1 SIMPLE TOOLS

The tools and technology used by developing communities were limited and oftentimes the tools had to be made first with the resources they had, an example of this being animal

bones used for carving. Knowing the limitations of simple tools will allow an establishment of precedence and goals for the level of difficulty for the type of structures to surpass. This varies by the context. Prototyping will be limited to the use of simple tools and methods. The claim is that longer spans can be achieved from with the same or even simpler methods of construction through analysis software (Mangelsdorf, 2010). There is an argument here that pairing simple tools and modern technologies removes the simplicity for the designer or architect but not to the end user. Much like space frame design, regardless of complexity of form or construction, a lot of time is invested in establishing the detail in order to simplify the construction.

2.2 REPEATED OPERATIONS



TOP: Fig. 6 Space Frame Node. RD 2021

Elaborating on this idea of simplicity for the end user, repeating one complex detail is obviously less complicated than a project with the same number of simple details but that does not repeat a single one. There are obviously many variables in this statement. Space frames (Appendix A) are a cost effective strategy of long spanning that implement many of the strategies for the construction of common materials needed to be successful. The details are minimal but can still be complicated in order to simplify the complexity and flexibility of the install. Companies like IKEA have a connector that is repeated in all of their shelving and cabinetry that is complex in nature yet easily installed by the end user. Likewise, the node (Fig. 6.), or structural connector, in the space frame is repeated as infinitely as needed and becomes the mechanism for small length tubular materials to transfer loads great distances.

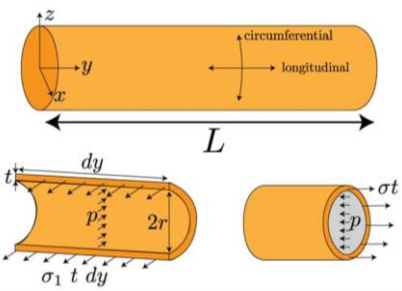
2.3 COMMON MATERIALS – PAPER TUBES

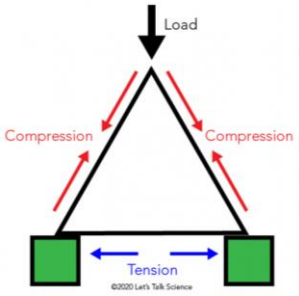
Common materials are being defined as hollow axial tube members that are easily accessible whether reclaimed or in abundance. These are to be used as structural framing members. The linear properties of these tube members are also a common and familiar trait in building materials, a common example being wood studs, “stick framing.” Paper tubes as a reclaimed material will be the tubular material under consideration for analysis because of the context of the site (see 5.0 DESIGN INVESTIGATION) The properties of structural paper tubes can vary by the manufacturer, but are measured for strength using flat and radial crush tests. Paper tubes are recyclable and inexpensive which are additional reasons that make them a “common material.” If this material is to be used in construction the biggest challenge beyond the physical strength is moisture content. Increased moisture exponentially decreases the structural properties of these paper tubes and therefore will need to be waterproofed. Paper tubes in construction is not a new concept. In fact, there are many precedents and evidence that support that the Japanese Architect Shigeru Ban (Appendix A) has made the material more of a competitor. Ban primarily works with paper variety for disaster recovery projects. He also has achieved some of the longest and most complex spans using the extremely modest material, an example being the MoMA with spans that were nearly 90 feet.

3.0 PARABOLOID GEOMETRY

Due to the dimensional sizes of these members an efficient form will be vector active structures because of the way that they disperse more complex loads (Heino, 1968). The short linear members (Fig. 7) on their own are only capable of transferring normal stresses. When assembled together in repeated common shapes like triangles (Fig. 8) and hexagons with the appropriate joinery to form space frames, space frame arches, geodesic domes, and grid shells, they can transfer loads in great distances without support. These can contour to and span the existing context with hyperbolic-paraboloid and freeform grid structures. Paraboloid Geometry are a three dimensional parabolic shapes. These shapes will be paired with the complex structural systems listed above to determine the most efficient

forms for the spans and simple methods of construction to be used. Space frames and how there different forms and angles effect the node connections are essential. Machine nodes can be built to a tolerance of 1/100th of a degree but the nodes can withstand a tolerance greater than that depending on the material properties of the members and the node connections. Optimizing geometry and depth of the space frame have a direct correlation to the node connection, the number of node connections, and the different types of node connections. The design and fabrication of a space frame is cumbersome but the spans are efficient and the method of installation can be easy as long as the installer can work with the selected material.

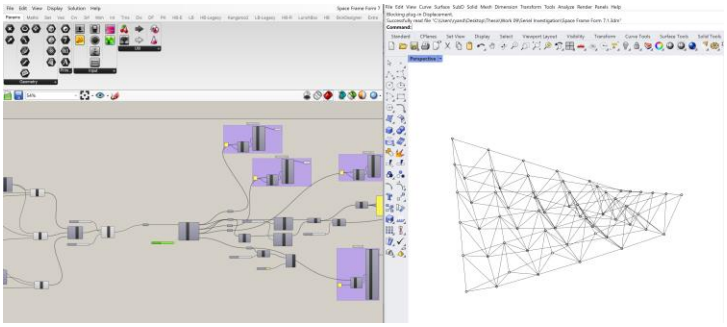




LEFT: Fig. 7 Mechanics of Materials: Combined Loading. https://www.bu.edu RIGHT: Fig. 8 Why is a Triangle a Strong Shape? https://letstalkscience.ca/

3.1 TECHNOLOGY AND ANALYSIS

The power of design software has been growing exponentially since the days when hand drafting was “replaced” by the first CAD software. It has gone from precision line drawing to generating design forms from scripts and data entry. The paper tube members can be analyzed for axial compression, bending and shear stresses. It can analyze variables such as, but not limited to, weather and location when establishing durability and loads on the tubular materials. The information gathered can be used to determine the strengths and weaknesses and will allow the determination of the most efficient methods for modifications in the build, specifically when designing the joinery between members. Paraboloid geometry is complex enough that most architects must rely on scripting software like Grasshopper to adjust the equations that data can be intuitively added in order to create a fluid contouring mass (Fig.9). Past knowledge is paired with current technology. Forms can be generated in computer modeling software for analysis in order to establish design strategies. It needs to be noted that while software can do all of these things, it is also limited by the input and knowledge of the user (Tedeschi, 2014) . Prototyping is a form of proof from the above software analysis. Structure often does not translate when scaled but form can. Prototyping can help in understanding the complexity of the form, the details, the process, and the materials. Can the complexity of the form become more conventional? Are the details easily repeatable? How it is built and how many steps are in the process? How do paper tubes perform in various conditions? These are just some of the questions that will be answered through prototyping. Because of this, modern tools, complex geometry, and implementing state of the art technologies to analyze and improve simple methods of construction can give these civilizations an opportunity to achieve much greater spans and this is what this thesis is investigating.



TOP: Fig. 9 Parabolic Form Generation with Rhinoceros and Grasshopper. RD 2022.

4.0 SOCIOECONOMIC IMPACT

Analysis and prototyping of structure is not architecture unless there is also an analysis on the social opportunities these structures create and how they influence the people using them. It was mentioned briefly in the historical section above, but taking it a step further, is there a limitation to the impact it can have? The structures that are front runners are not being analyzed for thermal envelopes but that is not to say that they cannot be considered sustainable in certain climates as temporary structures made of reclaimed materials that would otherwise end up in a landfill. If these temporary structures are successful they will be rebuilt with more permanent materials as the resources become more available. As the society evolves and becomes more technologically advanced, they can

adapt these structures for other means besides shelter. One example is that components can be applied to generate power and profit. Is it possible for these structures to accelerate the growth of a developing country? To understand this, a target audience and program have to be established.

5.0 DESIGN INVESTIGATION

My thesis outlines a series of variables. These include: the common material of paper tubes, the context as an existing market in Africa, and the structural method and repeated operations of space frames. *Using paraboloid geometry to create accessible long spans* is the focus of my architectural investigation. The means and methods and common materials are all derived from the site and its context. This investigation could be performed in a number of settings but a decision was needed in order to focus on the primary goal.

5.1 DEVELOPING COMMUNITIES

Establishing control, the target audience is areas of increased population and expanding cities in developing communities and countries that have not previously had access to long span architecture. This includes a type of program spaces that is most critical in helping these economies and trade grow markets. The continent projected with the highest population growth is Africa (Koop, 2021), and Gwagwalada holds promise for expanses of new urbanism and previously used common methods of construction to create shelters.

5.2 MARKETS

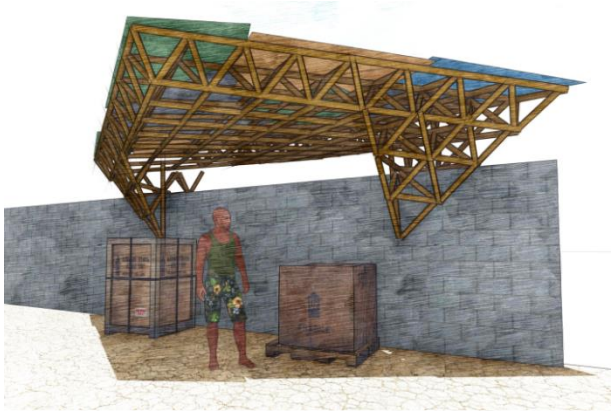
Markets within this target area commonly form sun beaten streets, alleys and plazas due to the geographic location and lack of green space and plantings. The specific site is called the Gwagwalada Main Market in Nigeria (Fig.10, Google 2018) and aside from the sun beaten streets it holds within some of the largest economic exchanges in the area. The negative area between the existing structures within the market lacks “space,” or architecture. In studying the successes and failures of the tactics implemented by other markets to address this, there were instances where the architecture did not consider the human scale and neglected the context (Appendix B). In this instance, the architect does not translate or form the local culture, but rather develops an infrastructure that the culture can express itself through implementation. In order for this proposal to be an architectural entity that can emerge from the people and the community, materials available to the context, such as paper tubes as previously mentioned, will be used. Past structures of paper tubes (Souza 2019) show ways to implement waterproofing and moisture control, but many of these works are an example of a top down approach because of the way they implement themselves, while this proposal is a bottom up because it will emerge from the existing context from simple tools and common materials. Currently, people are convening under the limited shading of umbrellas and overhangs at the individual market stands and buildings of the existing market. The developing community can use this form not just to create shelters from the scorching sun, etc, but also to create hierarchy of space to influence rapid economic growth. As the main market in Gwagwalada is analyzed these areas can be highlighted and focused to influence patrons.

TOP: Fig. 10 Images of the context of Gwagwalada Main Market. https://www.google.com/maps/place/Gwagwalada +Main+Market

5.3 SPECULATION OF FORM

To generate forms for analysis, four different speculation strategies of implementation of architectural forms effective in the context of this market based program were established: “Umbrella”, “Wall Canopy”, “Street”, and “Plaza.” The “Umbrella” is a freestanding element and is in an early phase in the Gwagwalada Main Market Plan (Fig. 11). Its purpose is to give individual vendors without permanent structures a larger alternative to the literal umbrella. This is the only type of the four elements that is independent from the existing context but still relates to it by expanding social spaces where the longer spans do not reach. This also becomes a “filler” option for vendors to expand trade points. These and the following space frame structures will receive

TOP: Fig. 11 Early Speculation of “Umbrella” Form. RD 2021.



TOP: Fig. 12 Early Speculation of “Wall Canopy” Form. RD 2021.

cloth and tarp materials and moisture sealer to complete the shelter. The “Wall Canopy” can take on many anticlastic cantilevering shapes, but it focuses on using the existing perimeter wall as its base that is already being used as a place of refuge from the sun at strategic times of the day (Fig. 12). The structure, secured at grade, latches onto the wall and spans outward to extend the duration and area of the shade. The market is currently surrounded by additional local people exchanging goods and services along the streets. They are currently sheltered by personal umbrellas and tents. The goal is to surround the perimeter wall with sheltered vendor locations. This will define a new space that will attract patrons and allow the market to expand as the surrounding areas continue to develop. The design also incorporates a sheltered defined space within the perimeter wall. The “Street” focuses on defining spaces between the existing structures giving shade to the negative space forming the sun beaten paths (Fig. 13). Depending on the relationship of two adjacent buildings, one example being having the same owner will define the type of structural span used. In both cases the structure will contour, but not connect, to the pitches of

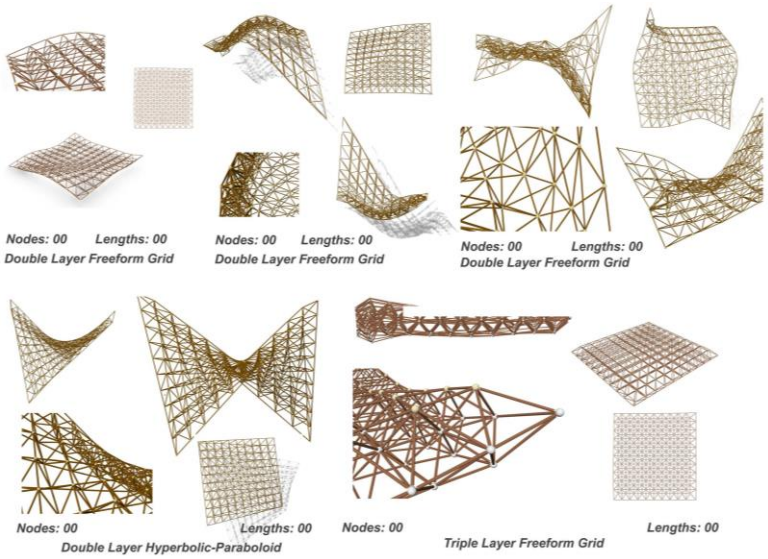
TOP: Fig. 13 Early Speculation of “Street” Form. RD 2021.

TOP: Fig. 11 Early Speculation of Umbrella Form. RD 2021.

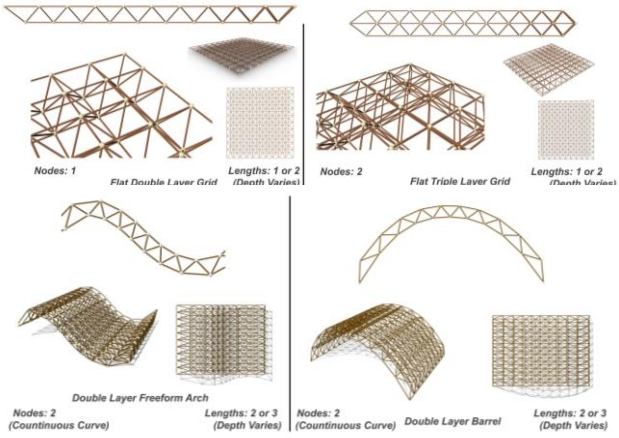
the roofs and can vary to adapt to the existing spans. The “Street” forms, aside from the obvious shelter they provide, can be used to define new circulation paths through the buildings. The “Plaza” is the form with the opportunities for the longest spans and the most impactful from the social gathering aspect (Fig. 14). The plazas of Gwagwalada main market are the locations where there are spaces surrounded on all four sides by existing context/vendors. This can be used as a hierarchal option as well, influencing patrons to spend more time where more of goods are being exchanged. This includes the main entrance to the market as an inviting reference to the entire market. If all four of these elements work together and expand upon each other the entrance will continue to be an important hub to this market.

5.4 ANALYSIS OF FORM AND PROTOTYPING

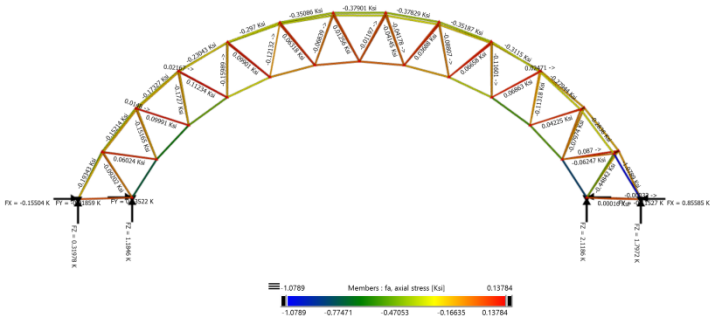
Up until this point the *paraboloid geometry* has been referred to as a 'form' or structurally, a 'space frame'. The context and the intent of the form have been established but the question is what is being constructed? The simple answer is that it varies, but the amount of variation and how it is deployed is a key concern and focus. The form is limited to the complexity of the connector, or joinery. Using the CAD software Rhinoceros 3D with Grasshopper plug-in, a series of hypothetical space frame structures that can be adjust based on analysis were generated. (Fig. 15) These scripts were used to study when a form, or in this instance, the joinery, becomes complex. A continuous flat space frame and a single layer geodesic dome can be constructed of one single unique node (Fig.16) while an arching barrel form space frame, if a continuous curve, can be constructed using two nodes (Fig. 17), one on each top and bottom of arch or inside outside of curve. These forms when limited to just two fixed or adjustable nodes, can only be manipulated two dimensionally. In order for the frame to move in the third dimension, even gradually, the nodes and lengths of members all become unique and the only way to have one universal node would require infinite flexibility. The goal is still to discover a common connector, a structural node that is easily supplied and modified. This could be a "kit of parts" that is 3D printed with varying degrees of angled connections but that is still limiting and takes more finesse in the field. Several existing connections were analyzed, including toys (APPENDIX B). If the connector is constant but adjustable, the assembly will be less complex and becomes a single *repeatable operation.* Once there were a few options they were analyzed structurally using IES Visual Analysis software (Fig. 18). The software allowed for the input of the structural properties of the paper tubes and varying materials for the connectors. There was a focus on the stresses on the connectors and the end of the paper tubes where the two meet. Physical prototyping occurred simultaneously to this analysis. The first prototype (APPENDIX C) looked at infinite flexibility but with some limitations. It is one repeated that can position itself with a range of angles and can be placed on the top and bottom of a space frame. One of the cons of this prototype is that there is still too much flexibility. The joinery still needs to be able to lock into place once an angle is selected or else the structure will simply crumble. Further scripting found that just two settings ten degrees of rotation apart for each of the



TOP: Fig. 15 Hypothetical Space frames generated by scripting software for analysis. RD 2022.



TOP: Fig. 16 Images of a flat space frame. BOTTOM: Fig. 17 Images of an arching barrel form space frame. RD 2022.



TOP: Fig. 18 Image of a structural analysis performed on paper tube space frame arch. RD 2022.

member's connection with the joinery allowed for the creation of varying arching forms that maintained a catenary arch within the structure. The second prototype focused on this idea to limit the degree of angles while still keeping all linear members transferring loads to a central point of the node connector. The challenge is that there are extra insertion points for the framing members and it fails to limit the user to a polyhedron form. The user could build a more conventional frame in a modular cube layout, or string multiple members in a single layer form that would span a fraction of the distance of the desired forms. By the third prototype, paired with further structural analysis, it was visible that the user's construct could be controlled by limiting the depth of the structure and allowing the flexibility to be in rotation of the hemi-octahedron shapes of the space frames. When using the hemi-octahedron forms in the structural analysis, using equilateral triangles as the depth of the space frame produced consistency in span and least failure. This prototype can be made from "scraps" and can be adapted to the user's bulk material's diameter. It has fixed angles to create equilateral triangles for strength in hemi-octahedron modules. It also has built in four adjustable angles to allow the user a controlled complexity for adaptability to the existing context. The fourth angle is the point in which the user has reached complexity. Until that fourth angle of adjustability the user is only able to work in barrel forms. Keeping in mind common materials, the reinforcement is limited. The most effective method would be to leave the paper tubes as a constant in their "natural" state. If the connectors had sleeves, this could solve multiple issues ranging from shear stresses to wetting at joinery. It is common knowledge that paper tubes do not share the same structural qualities as steel or even bamboo (common materials for these types of structures). As the structures evolve, building strategies with rope, fishing line, and/or other materials common to the areas surrounding Gwagwalada will be implemented. In order to complete the analysis, the parabolic space frame structure must stand on its own foundation. It cannot rely on the existing structure for support. This investigation will document ways to implement foundations using tires filled with gravel (Fig. 23). My focus will be on how my connector interacts and fastens to the foundation wall.

TOP: Fig. 23 Image of a foundation constructed from tires filled with gravel. https://mudman.blog/2017/05/10/how-to-cheaply-build-a-foundation-for-your-home

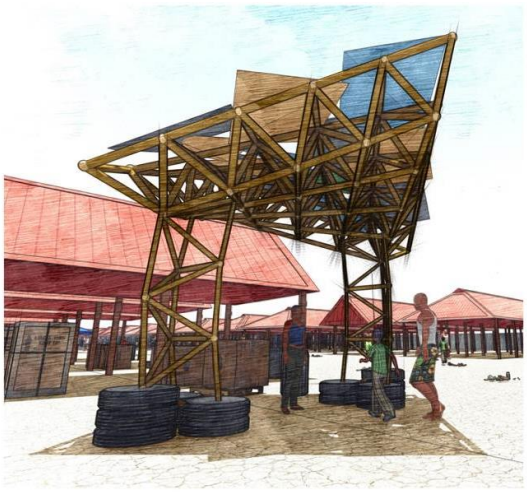
6.0 THE ARCHITECT & THE FUTURE

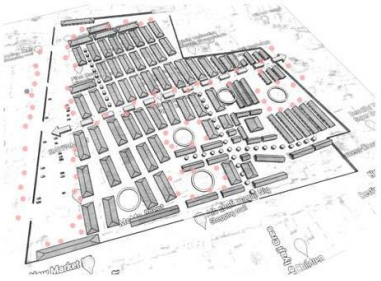
Is there a limitation to the impact it these structures can have on the people using them? As the economy grows and if these common materials, paired with repeated operations and simple tools, the implementation strategies and the potential size and quality of the installation will continue to adapt and improve. The local context allows for the layering of available resources to adjust the supplied infrastructure and will influence the finished appearance of the architecture. If successful the local population will build themselves from wisdom that is obtained, adapted, improved, and taught and given the nature of the resource of paper tubes, these structures will naturally be installed as temporary structures with the intent to be replaced with better as they develop. As the architect the exact form is not being designed, this is just an image to describe how the community may take this and implement it over the next decade. Within the communities the architecture has to be adopted to form sound structures with common materials to then be adapted by the people.

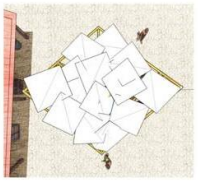
7.0 DESIGN RESULT AND CONCLUSION

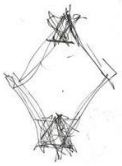
After prototyping further speculation of what could be constructed by the people to form the previously defined forms were generated (Images below) Barrel forms proved optimal in analysis for the self-supporting long spans but other forms can be generated. It can be argued still that perhaps even giving limiting settings in the four directions, the joinery created is too complex, but there is still one way to prove this. The future of this thesis is to have others build with the joinery to prove simplicity and accessibility of structure and long span.

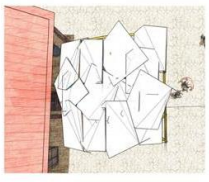
7.1 UMBRELLA

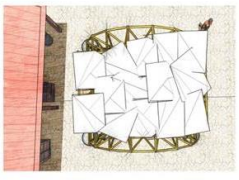




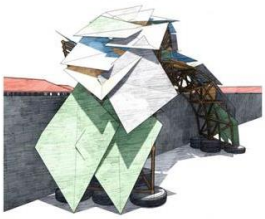


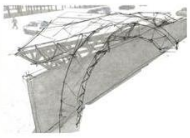


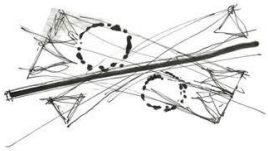


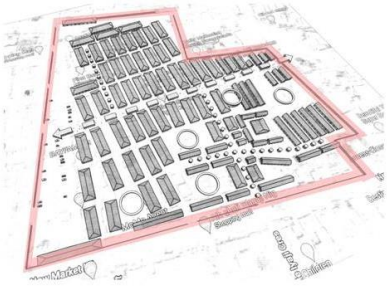


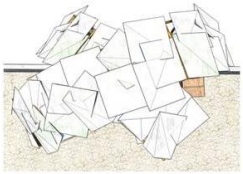
7.2 WALL CANOPY



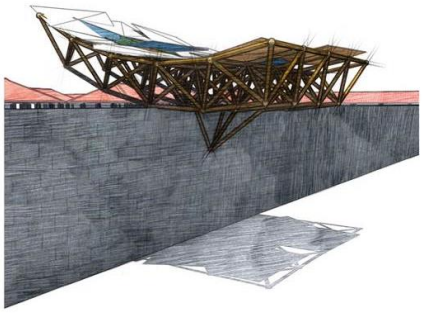




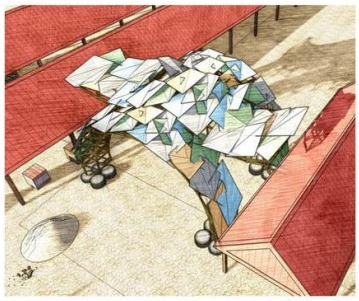


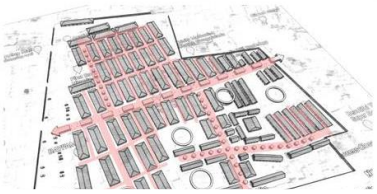


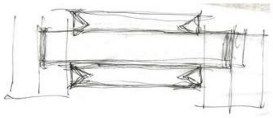
"WALL CANOPY"

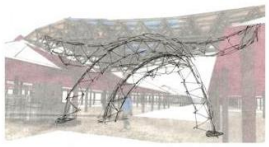


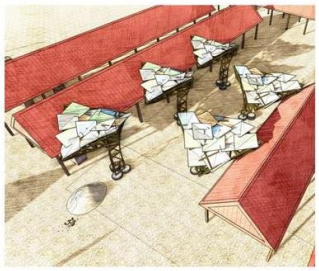
7.3 STREET

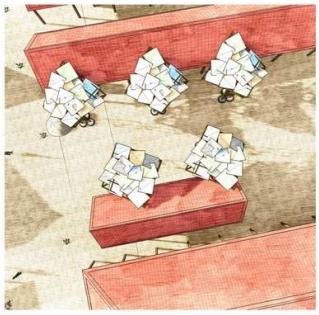




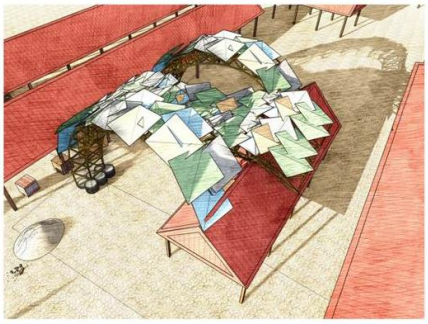


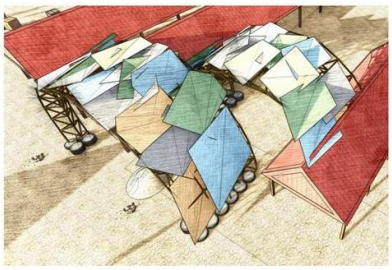


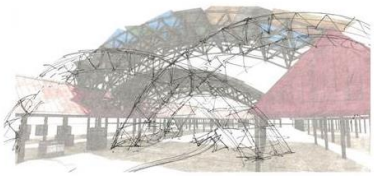


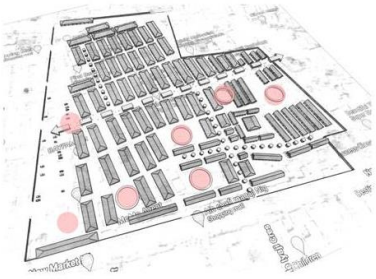


7.4 PLAZA



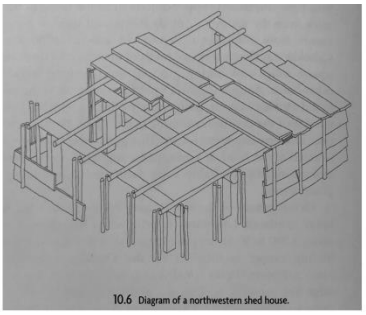




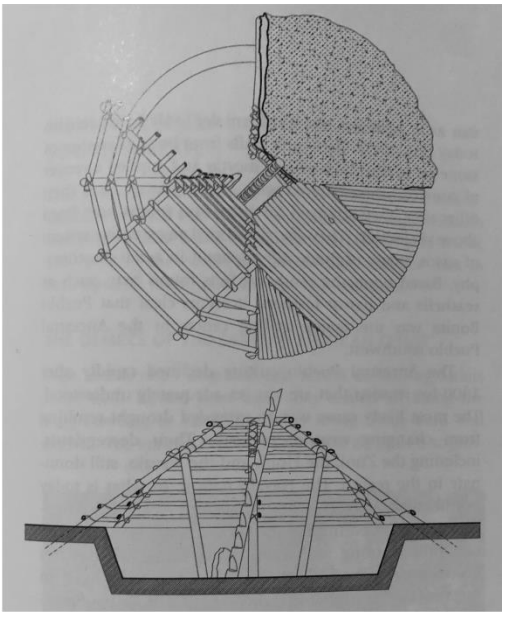


APPENDIX A: LITERATURE REVIEW

Indigenous Architecture in the Pre-Columbian Americas



10.6 Diagram of a northwestern shed house.



This chapter on the history of early human structures in North America because describes how isolated civilizations discovered structural spans using accessible resources and simple tools. This will influence the prototyping of repeatable operations. Early civilizations discovered and built semi-complex structures using found resources and self-built tools. These structures are some of the first to utilize similar tubular members that I am studying to achieve relatively longer spans. This is the start of the historical timeline that lead me to research the evolution of the tubular structure into complex geometric forms.

Moffett, Marian, Fazio, Michael, Wodehouse, Lawrence. “Buildings Across Time: An Introduction to World Architecture, Chapter 10 Indigenous Architecture in the Pre-Columbian Americas” McGraw-Hill 2004.

The Dark Side of Architecture.

"'The structures of political and social, ultimately also cultural power are responsible for how architecture evolves and how it is designed, built, and used." (Barelkowski 37)

"'The basic problem of architecture, especially in the case of public buildings and public spaces, is the recognition of the forces that shape the solution." (Barelkowski 55)

The Power over Space and the Control of Society – CONTEXT I am studying this paper on the link of architecture to power because I want to find out if power can control material selection in order to better understand if paper tubes can offer the same power and control over architecture to civilizations that do not have the same agendas. Advances in architecture and structure historically have come from wealthy civilizations "funding" the discoveries. Long spans and large structures in architecture still remain out of reach to many due to cost of construction and engineering requirements. Paper tubes can potentially allow these elements to be obtainable by all and not just in the form of temporary refugee shelters.

Barelkowski, Robert. (2019). "The Dark Side of Architecture. The Power over Space and the Control of Society. Space & Form.40. 33-74. 10. 21005/pif.2019.40.A-03.

Can Architects be socially responsible?

"...architecture existed as a profession, a credentialed elite legitimized through conventional procedures established by other professions." (Crawford 28)

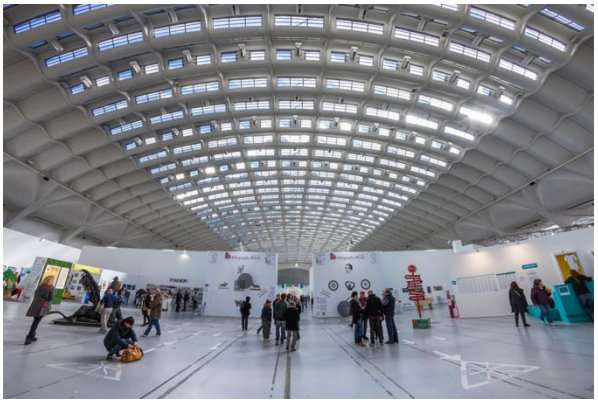
"...architects have almost completely surrendered both the tools and ideological aspirations that might allow them to address the economic, political, and social concerns posed by modern life." (Crawford 43)

"...aesthetics alone cannot solve the difficult problems of current housing and urban conditions." (Crawford 43)

I am studying this critique of the profession of architecture because I want to find out how the profession has changed since it officially became a profession a century and a half ago in order to better understand how architecture can be used to solve social and ecological issues. If architecture is solely based on aesthetics then the profession seems to have missed its masking intent for social justice. The profession is easily influenced by power and creates false identities for itself. Paper tubes can attribute to some of the social issues by bridging the gaps of money and environmental quality.

Crawford, Margaret. "Can Architects be Socially Responsible?" Diane Ghirardo, ed., Out of Site: A Social Criticism of Architecture (Seattle: Bay Press, 1991), pp. 27-45.

Through history and Technique: Pier Luigi Nervi on Architectural Resilience

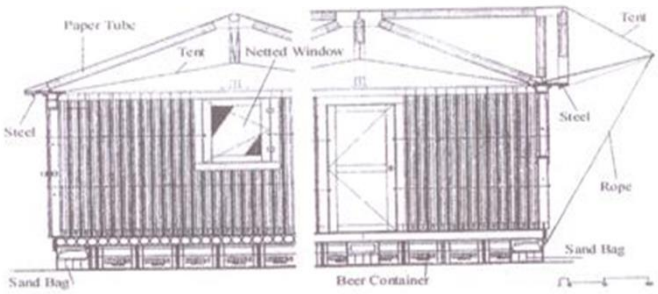


"It was necessary to understand that a 'built work' had to 'obey the objective constraints' linked to materials and building technique." (Antonucci and Nannini 9)"

"He discovered a 'superhistorical lesson, a lesson of [those] constants that lead architecture of all times back to the measure of Man and his relationship with matter" (Antonucci and Nannini 5)"

I am studying this article on Pier Nervi's view of architecture because I want to find out what influenced him to study the relationships between material and form in order to better understand what it means to achieve a "truthful" style. Nervi was fascinated with materials that have existed for thousands of years but was still able to find, study, and create new methods of construction for the material. Bridging the gap between architecture and engineering is what Nervi considered a good architect but can also be an expression of material in design. As young as the idea of paper tube construction is, there is still lessons to be learned from history.

Paper Tube Application (A Paper Tube Shelter)



"Shigeru Ban has developed both a new architectural language and radical engineering technique through his use of large tubes made of recycled paper..." (Wahab 5)

I am studying this analysis and case study of a paper tube shelter because I want to find out the outcome of past applications of paper tubes in order to better understand the known strengths and weaknesses of paper tubes. The article focuses primarily on temporary disaster relief structures and the need for fast, cost effective, and easy to build

structures. Normal construction can be costly with a long duration. These temporary paper tube structures are light weight and easy to handle as well as able to be dismounted and reassembled. When compared to well-known temporary structures such as tents, this case study of the paper tube panel “log house” surpasses it in multiple categories including protection from severe weather conditions.

Abdul-Wahab M. A. El-Kadi. "Paper Tube Application (A Paper Tube Shelter)". The International Conference on Civil and Architecture Engineering, 8, 8th International Conference on Civil and Architecture Engineering, 2010, 1-13. doi: 10.21608/iccae.2010.44436

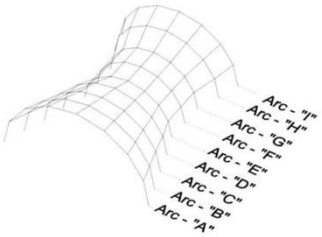
Cardboard: From Industrial Workhouse to Shigeru Ban’s Master Material



I am studying this historical overview and application of paper tubes by Shigeru Ban because I want to find out how Ban was inspired to build with paper tubes in order to better understand what his goals are with his master material to potentially work toward becoming a “master builder,” expert, with the material. Paper tubes were mainly used for piers filled with concrete, but in the last few decades, structural, acoustical, and thermal properties have been analyzed. Ban tested load limitations and for a portion of time only used paper tubes for interior partitions. He since transformed them into fire and water resistant structural elements in a large “temporary” 50 year cathedral.

Souza, Eduardo. “Cardboard: From Industrial Workhouse to Shigeru Ban’s Master Material” (2019) https://www.archdaily.com/913567/cardboard-from-industrial-workhouse-to-shigeru-bans-master-material

Design and Failure Study of a Papertube Structure



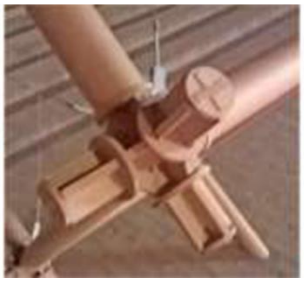
“..conventional and strong materials are used to make weak material like papertube strong and fit for building a structure.” (Shah 6)

I am studying this case student case study of a paper tube structure because I want to find out techniques of analysis in order to better understand opportunities for prototyping my own long spans and structure types. In physically building varying lengths and shapes of arches, the group was able to subject the individual members

and joints to different bending moments and compression forces to pinpoint locations and reasons for structural failure. It is no secret that paper tubes are inferior structurally to wood, steel, and other building materials as well as require more analysis of the geometry but this has great insight into continuing this analysis to potentially make this an official construction classification.

Shah, Anand. (2017). “Design and Failure Study of a Papertube Structure.” 10.5176/2301-394X_ACE17.18.

Paper-tubes as a building material

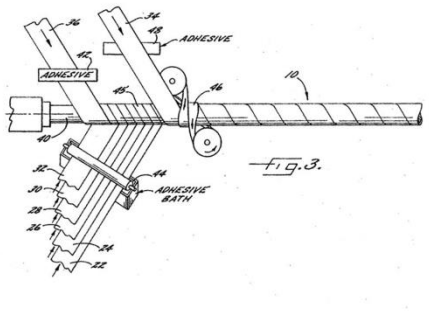




“..The main aim was to understand material properties of paper-tube by constructing something which is aesthetically pleasant as well as structurally sound.” (Shah 4)

I am studying this case study of a paper tube space frame because I want to find out past methods of experimentation with paper tubes in order to better understand techniques for testing and understanding the material. This case study introduces methods/materials for joinery and bracing that can be easily demounted. It offers insight to techniques for producing these joinery pieces. It notes some of the major reasons that paper tubes are not main stream in construction which is a direct relation to my thesis and underlying goal. It strives to achieve aesthetics while understanding the limitations of the material.

Shah, Anand & Hirpara, Sapan. (2017). “Paper-tubes as a building material.”

Paperboard Tubes in Architecture and Structural Engineering: A Review



"Paper strength is significantly reduced when it is exposed to elevated humidity environments, so the use of large paperboard tubes in load–bearing architectural structures is uncommon." (Bank and Gerhardt 4)

I am studying this review of paper tubes because I want to find out how paper tubes are manufactured in order to better understand the variables that the manufacturing process has on the structural integrity of the paper tubes. The government does not directly regulate the use of structural paper tubes meaning the designer and structural engineer must exercise caution in the selection of paper tubes. Understanding what makes paper tubes potentially stronger, will give me a baseline as to where the paper tubes I acquire for prototyping compare. This will ultimately help with achieving the spans and appropriate joinery to avoid premature material failure.

Bank, Lawrence, Gerhardt, Terry. "PAPERBOARD TUBES IN ARCHITECTURE AND STRUCTURAL ENGINEERING : A REVIEW" Conference: NOCMAT 16 At: Winnipeg, Manitoba, CANADA Volume: 1 Published 2015 https://www.researchgate. net/publication/298064617_PAPERBOARD_TUBES_ IN_ARCHITECTURE_ AND_STRUCTURAL_ENGINEERING_A_REVIEW

Ecological Design Strategy of High-Tech Architecture

"Environmental resources increasingly strained, in this background, high-tech building onto the road of sustainable development is a historical necessity." (Hou and Yao 4)

I am studying this work on the future of high-tech architecture because I want to find out sustainable strategies of the structural elements in order to better understand how paper tubes can play a pivotal role in the future of sustainable architecture. The life-cycle cost is a big factor in sustainable design and paper tubes excel in that. This may be too advanced for the paper tubes at this point in terms of integrating technology like artificial intelligence but it can be an integration into the future of high-tech architecture in order to fulfill the ecological problem of non-renewable resources.

Hou, Zhaoming, Yao, Jiawei. "Ecological Design strategy of High-Tech Architecture" Applied Mechanics and Materials Vols. 174-177 (2012) pp 3186-3189

Paper Palaces

I am studying this article about Shigeru Ban at the time he was honored for the Pritzker Prize because I want to find out his view of what architecture is in order to better understand why he is one of the few that has been pursuant of paper tubes a large portion of his career. He is very humble and still sees architecture in its simplest form. It is ironic that his initial interest and pursuit of paper tube construction was not for the primary reasons we research it today. He is an example architect that is working to allow the less fortunate access to architectural services.

Goodyear, Dana. "Paper Palaces: The architect of the dispossessed meets the one per cent." The New Yorker. (2014)

High Tech Architecture

"..in architecture it now means a particular style of building." (Davies 1)

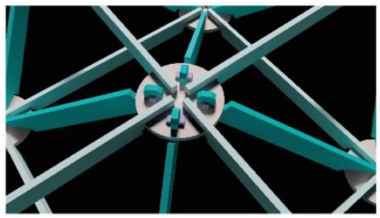
"..the muscular steel structure, the smooth, impervious skin, the deliberately exposed pipes and air ducts - are often powerfully expressive of their technical function..." (Davies 13)

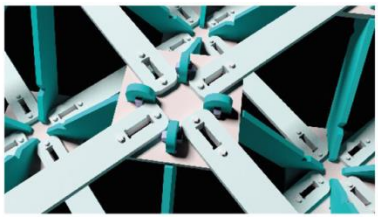
I am studying this interpretation of High tech Architecture because I want to find out how structure has influenced the architecture in order to better understand structural expressionism. When the architecture is designed on function and structure is the dominate feature, it develops its own machine like style. This can result in the ease of construction when the structure is also the aesthetic. In the case of my approach to paper tubes, I will consider the approach of how the paper tubes can influence the design. The limitations of size to span in comparison to other building materials will likely exaggerate the traits of this style.

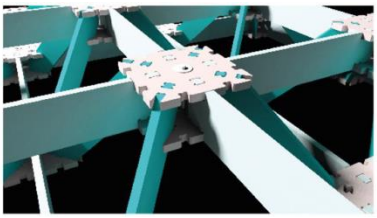
Davies, Colin. "High Tech Architecture" https://www.academia.edu/27323968/High_Tech_Architecture

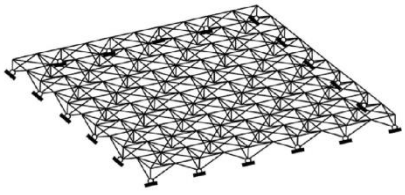
Photo: https://www.archdaily.com/405538/happy-birthday-richard-rogers

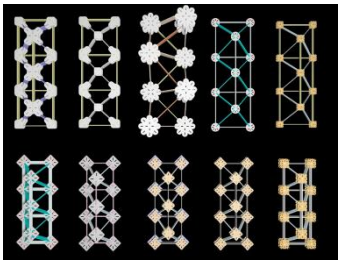
Experiments in Timber Space Frame Design: Fabrication, Construction and Structural Performance









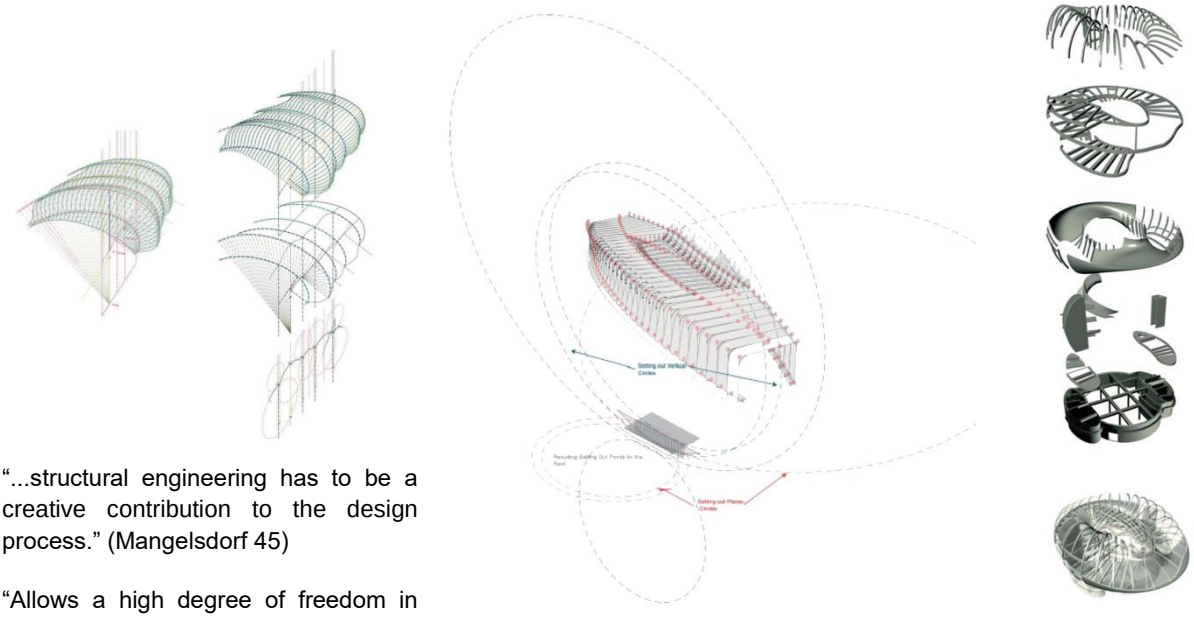


I am studying this case study of an experimental wood space frame structure because I want to find out how they used computer aided manufacturing in order to better understand how these simulations helped achieve the long horizontal spans. The aim of the study was to utilize CNC routing technologies to create joinery that would allow the wood to be assembled into a 3D structural matrix that will ultimately be lighter and more economical than equivalent

spans with comparable conventional materials. Over complexity can be an issue for real world implementation but it is a step in the right direction for structural long span research.

Finch, Gerard, Gjerde, Morten, Marriage, Guy, Pelosi, Anthony. Experiments in Timber Space Frame Design: Fabrication, Construction and Structural Performance, 2019. https://www.researchgate.net/publication/332567655.

Structural Strategies For Complex Geometries



"...structural engineering has to be a creative contribution to the design process." (Mangelsdorf 45)

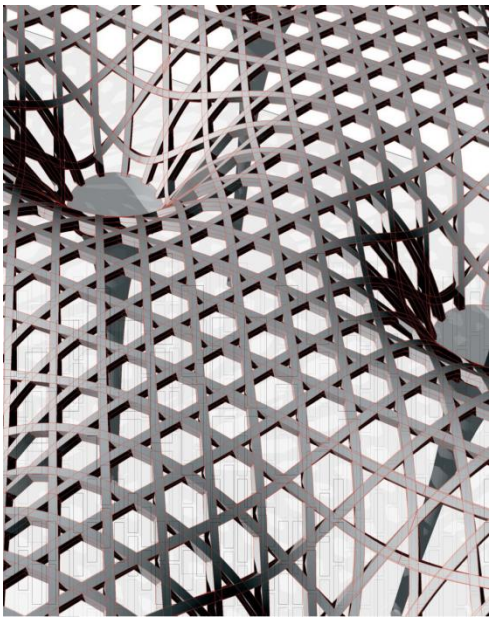
"Allows a high degree of freedom in the development of the form, but integrates concepts based on physics, form description and fabrication. (Mangelsdorf 41)"

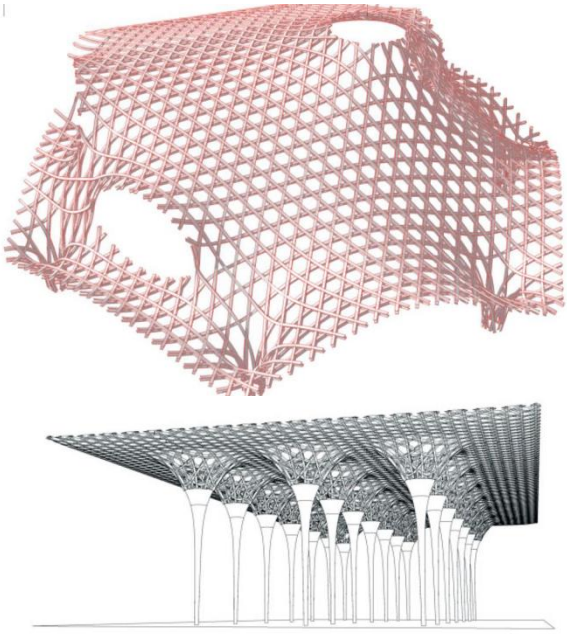
"...a parametric modelling approach integrated with the structural analysis of the strips, allowing he aesthetics and the engineering of the surface to be investigated in an iterative development. (Mangelsdorf 44)

I am studying this article outlining methods of approach for designing complex structures because I want to find out these forms have been used in large scale architecture to better understand how to design and implement similar approaches with reclaimed modest materials. The article gives case studies that implemented physical prototyping to help determine initial geometry and behavior of the material. The initial shapes were then further simulated and developed using computer models. Another case study was able to reach long spans column-free by designing a series of interlocking ridges and valleys. These methods are a good starting point for research development.

Mangelsdorf, Wolf. "Structuring Strategies for Complex Geometries." Architectural Design July/August Vol 80, No 4, pp. 40-45.

Materializing Complexity



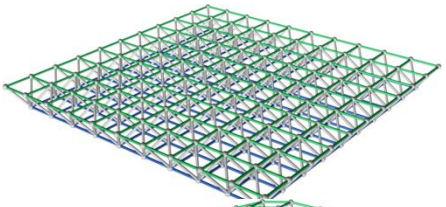


I am studying this article on the emergence of complex forms over the past few decades because I want to find out how they were generated to better understand how to document, simulate, and analyze complex geometric forms. The document notes the transitional period in which architecture when from regular to irregular and references Zaha Hadid for her famous complex geometric shapes and their expensive price tag. Software has made these shapes more feasible but still not readily obtainable by all because of the cost for certain building materials to take on these complex geometries can still be costly even with less material.

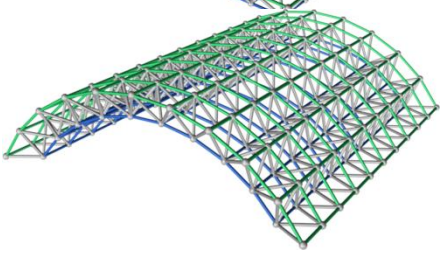
Scheurer, Fabian. Materialising Complexity. Architectural Design July/August Vol 80, No 4, pp. 86-93.

Space Frame Structures

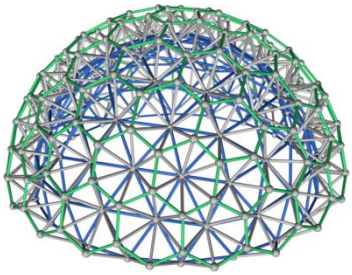
Flat Double Layer Grids Square on Square Offset



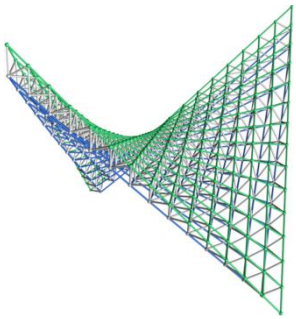
Double Layer Braced Barrel Vault



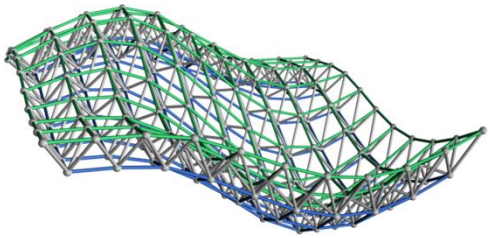
Double Layer Braced Dome



Double Layer Hyperbolic-Paraboloid



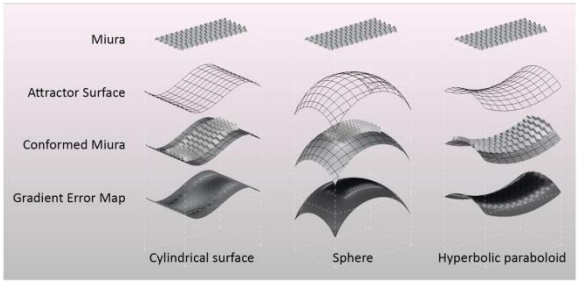
Double Layer Freeform Grid

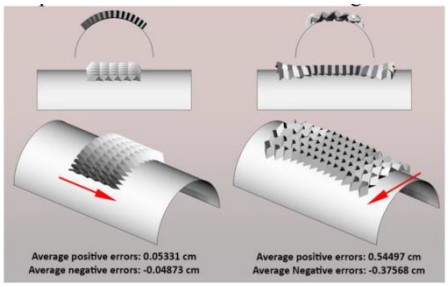


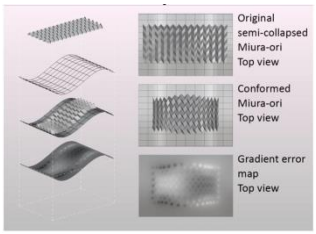
I am studying this article on the concepts of space frame structures because I want to find out advantages of space frames to better understand the strategies and implemented when designing a space frame structure. This article simplifies the approach to establishing a geometric form and then breaks the space frame structures into modules. These details can be applied to different tubular materials and analyzed specifically based on the weight of the material to establish the appropriate geometry and layers. It continues with a more complex analysis of structure, but lists and explains several types of tubular structural space frame typologies, including possibly the most complex yet most versatile, the hyperbolic paraboloid.

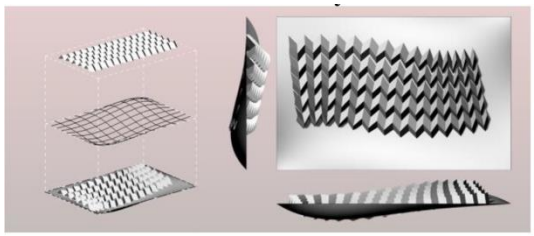
“Spatial (space) Structures” Structure and Form Analysis System (SAFAS) https://www.setareh.arch.vt.edu/safas/009 _ introduction_01_ss.html

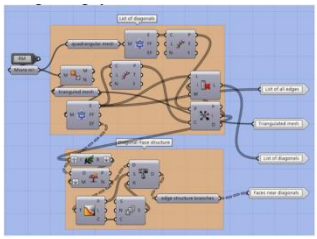
Conformation of a flexible Miura Pattern on a double Curvature Surface









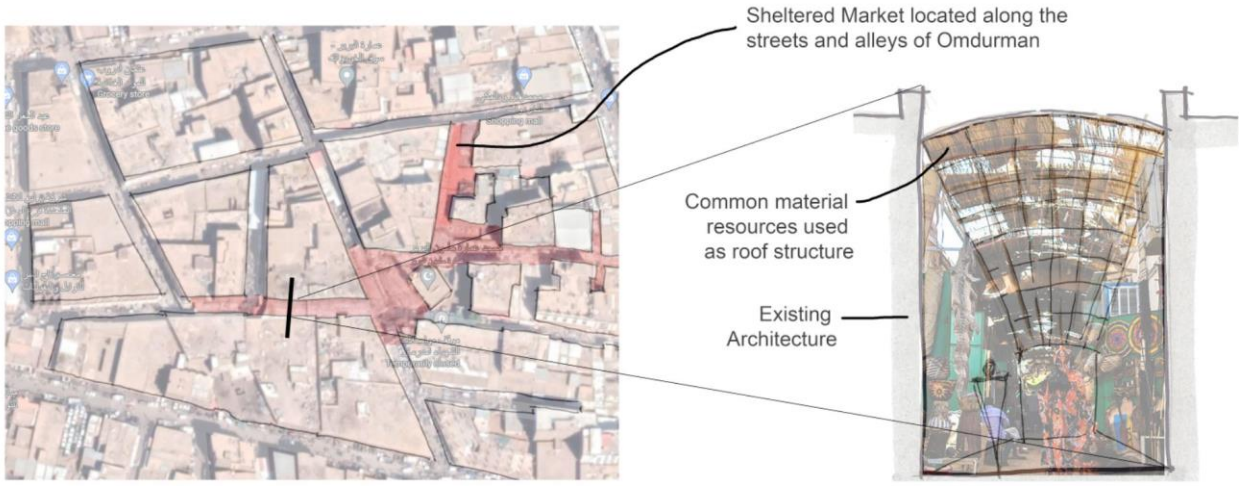


I am studying this article about a case study and analysis of a parametric double curvature surface because I need to know the tools in order to better understand how to generate these parametric models. Designing with complex curved surfaces have become much more common in recent years, but a lot of the industry software hinder and limit these designs. In order to create and analyze space frames in anticlastic forms that can vary based on the existing context, mathematical algorithms will be required and grasshopper will perform. No two forms will necessarily be the same but the process is streamlined with math and the planning becomes less complex and adaptable, which is one of the primary goals of this thesis. It is noted that this not an analysis of tubular materials but the principal findings of the article are still very relevant.

Foschi, Riccardo. “Conformation of a Flexible Miura Pattern on a Double Curvature Surface” University of Bologna 2017

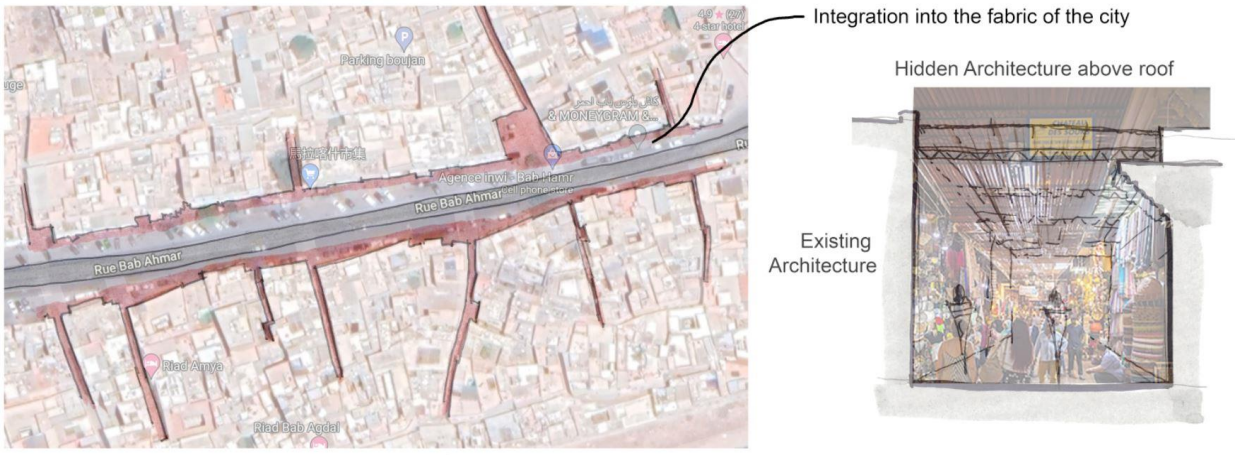
APPENDIX B: PRECEDENT ANALYSIS

Omdurman Market, Sudan



Omdurman Market is a large local market in one of the most populated cities in Sudan. The Market spans through the streets and alleys and is full of the culture of the local population. It utilizes existing architecture to support sheltering system to maintain the pedestrian scale at the market spaces. The sheltering system is constructed of common materials and resources. The structure is very contextual and maintains the cultural values of Omdurman and does not impose itself. The structure is at times too simple and not maintained, but it still offers shelter from the sun.:
The spans are not overbearing but are utilizing more complex forms to span over the top of the structure and will offer more opportunity to expose more of the architecture that is hidden by the spanning shelter without sacrificing the pedestrian scale. This will also allow greater uses for available resources.

Souks of Marrakech



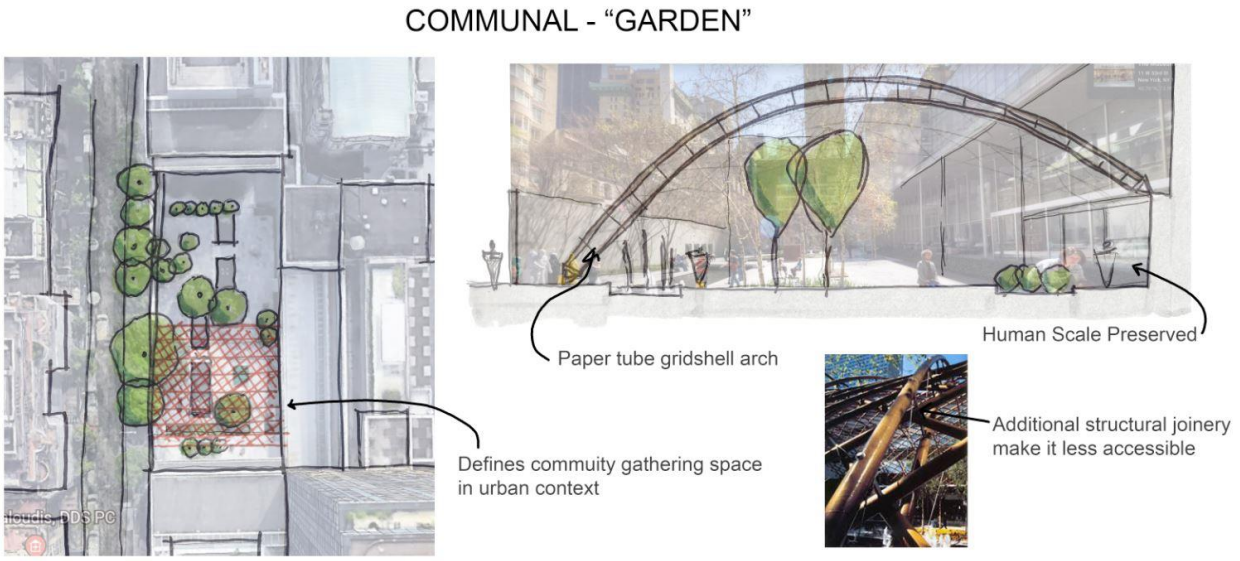
The Souks of Marrakech are a series of winding streets and alleys that house many shops and have have been the center of trading for the area for many centuries. It utilizes existing architecture to support a sheltering system that creates a more interior space experience for pedestrians. It uses less common materials and resources to create a

more permanent roof over its alleys. The structure is integrated well and does not impose itself preserving the pedestrian scale. The structure itself is simple and completely shelters the occupants in some areas taking away from the open air cultural market experience. Integrating some common materials helps preserve the context.

Kejetia Market Kumasi, Ghana

Kejetia is one of the largest markets in Africa consisting of over 10,000 stores. In 2015 it was impacted by the construction of a nearly 2 million square foot shopping structure. It utilizes large scale structure to reconfigure market and city function. It uses large open spaces to create a grand communal shopping experience that redirects traffic to separate pedestrian and vehicular traffic entirely. The structure completely imposes itself and steals from surrounding and removed cultural context. It treats the pedestrian as "flow" vs the "individual experience" and Itemizes infrastructure, destroying the human scale. The design does not take into account the people. Scale of the architecture is critical in underdeveloped areas to avoid isolating or separating surrounding communities from one another.

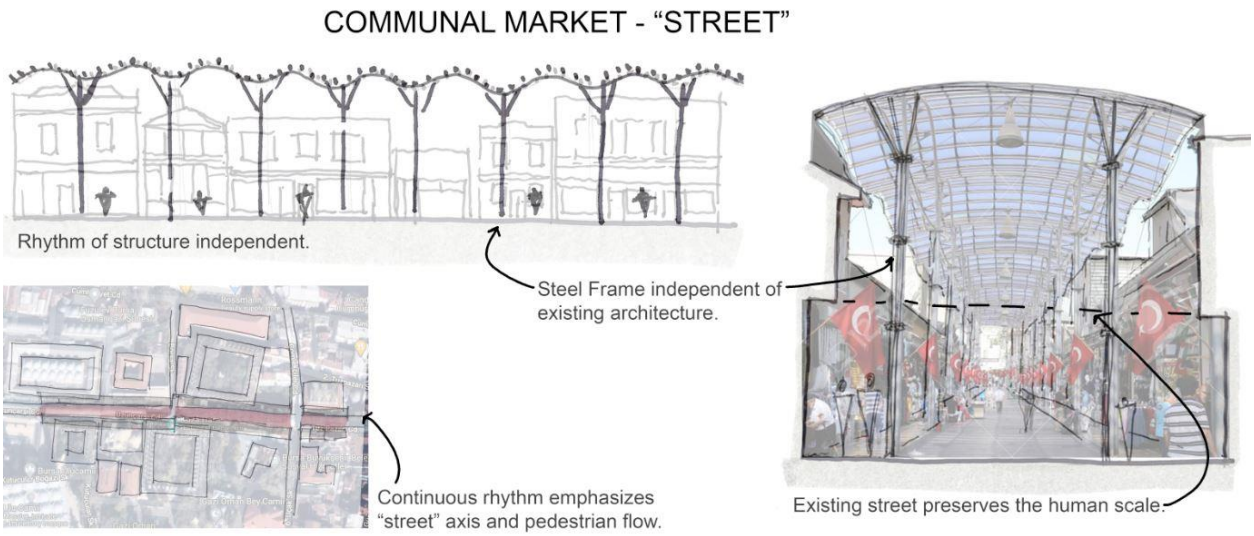
MOMAPaperArch,NewYork



The Paper Arch was a temporary exhibit piece by Shigeru Ban for the Museum of Modern Art in New York. It was made out of paper tubes and it spanned over 80 feet. It uses simple materials in a more complex grid structure to

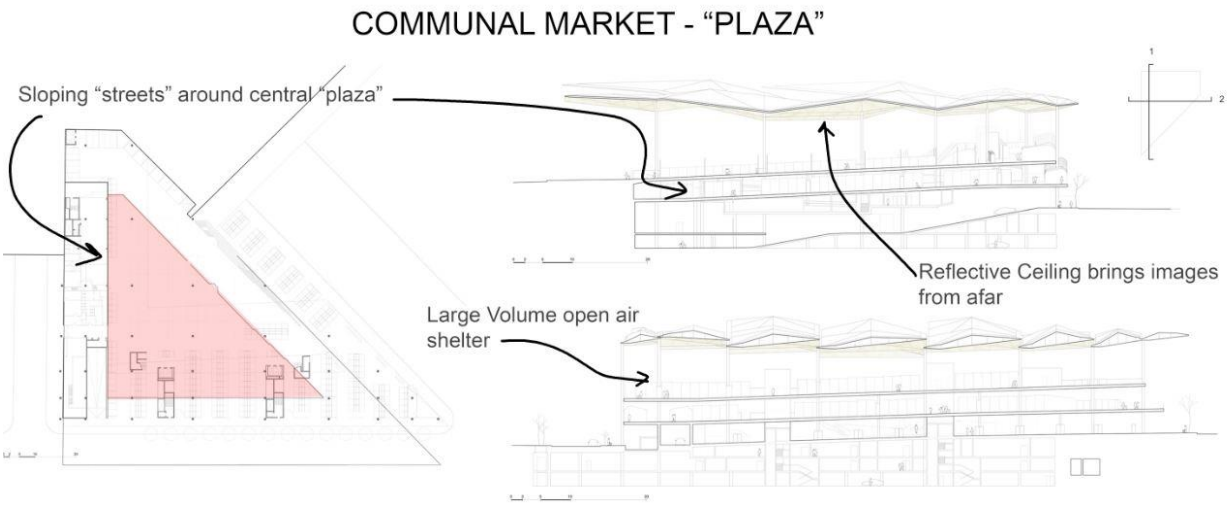
define outdoor space. It adds a human scale to an open air recreational urban green space as well as common materials and resources. It feels light and does not steal from the experience of the outdoor environment.
It doesn't provide shelter, but is more of a sculptural definition of space. It is an exhibit of long span using a "common" material. Depending on the program of space, a sheathing material can add function and opportunity to the communal space below.

UzunCarsi,Turkey



The Uzun Carsi is a traditional Bazaar that is located on the streets of Bursa, Turkey. The open air street is sheltered by a free standing steel and glass structure. The structure functions entirely independent of the existing architecture and ignores the cultural style. It uses transparency to express and preserve the feel of an open air street. It uses a more complex form to limit the invasive columns in a congested area. The contemporary form still integrates by not screening or stealing features from the existing architecture, and the structure defines the street as a pedestrian street. The structure integrates well and has minimal impact on the existing architecture. The sheltering form can integrate more with the existing architecture. The rhythm of the columns seem to ignore the street facade below.
The shelter could extend over the roofs below to shelter individual shop fronts from the elements.

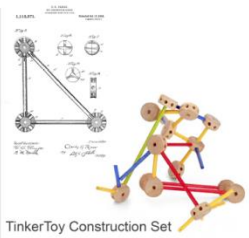
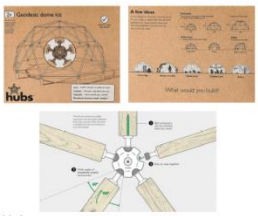
Mercat Encants, Barcelona Spain



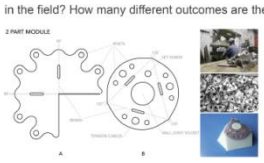
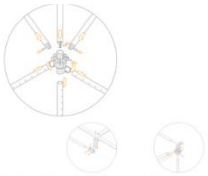
The Mercat Encants was built over an existing site that is the home a famous annual market that has been reoccurring for over a century. It uses large scale space and open air volume to emphasize exterior space.
It uses winding sloped planes to give the feel of pedestrian roadways around the central plaza. The reflective materials bring images of the city into the market space. It feels like an outdoor space with a new structure, but preserves the ideals of a traditional market. The modern materials help preserve the history of the annual market.
The large scale roof canopies steal from the pedestrian scale of the market. Additional lower canopies can help preserve the pedestrian scale, and using architectural elements from the surrounding context can help connect historical context.

PRECEDENT CONNECTOR COMPARISON

"Comparison of Parts" Connection Precedent Matrix

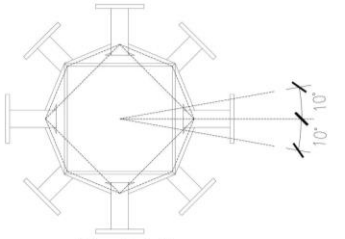
Connection	 K'nex	 TinkerToy Construction Set	 Toobalink	 Hubs
Number of Parts	9	1 Main	5	1
Type of Connection	Triodetic	Triodetic	Tuball Node	Hemispherical Dome
Number of Angles	7 (Plus 360 Rotation)	5 (Plus 360 Rotation)	4 (Plus 360 Rotation and double nodes)	4 (With 180 tolerance)
Adaptable (Flexible)	Limited	Limited	Yes	No
Tools Required (Ease of Install)	N/A (toy)	N/A (toy)	N/A (toy)	No
Summary and Observation	The user is limited to a set of pieces and angles but the range of the build is vast. Because of the limits it is harder to veer from the intended use. The flexibility is in the rotation. The human error is minimal.	The user is limited to one piece with set angles but the rotation is where the flexibility and potential human error comes from. The human error is still minimal and hard to veer from the intended use.	The ability to connect joinery adds a level of versatility, but this may have structural set backs when transferring loads in a real application. This product also has several parts just for connections to be installed.	Even with the flexibility during construction, it is still limited to a dome. It is only scalable based on size of members not flexibility in the connection.

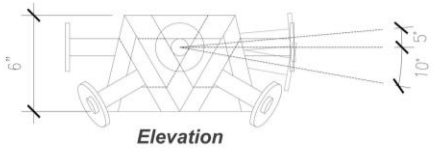
"Comparison of Parts" Connection Precedent Matrix

Connection	 Joint for Complex Structures	 Pipe Connectors	 ACSA Steel Design Competition	 Straws and Connectors by PlayLearn
Number of Parts	1	25+	4	2 Main
Type of Connection	Tuball Node	Varies	Hemisphere Dome	Tuball Node
Number of Angles	Varies	Varies	5 (With pivot)	4 (With 360 Rotation)
Adaptable (Flexible)	Yes	Limited	Yes	No
Tools Required (Ease of Install)	In Fabrication	Yes	Wrench	No
Summary and Observation	This joint is designed to be made by the end user. Once past that the ball joints allow for a great level of flexibility. One joint can create complex space frame geometry. There is a great deal of human error without any limit of angles.	There are many connection types but the user is still limited to the catalog of connectors. The available ones are not modifiable the flexibility comes from the vast number of connection types.	This connection gives great flexibilty but there is a great level for human error because of the infinite set of angles allowed. This will have an impact on load transfer.	Very limited angles do not allow for much flexibility. Everything is done on the x,y,z, axis plus a 45 degree angle. Any flexibility is in the members.

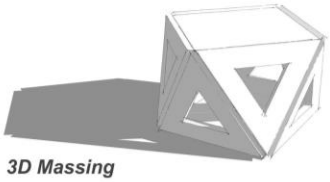
APPENDIX C: PROTOTYPES

PROTOTYPE 1:

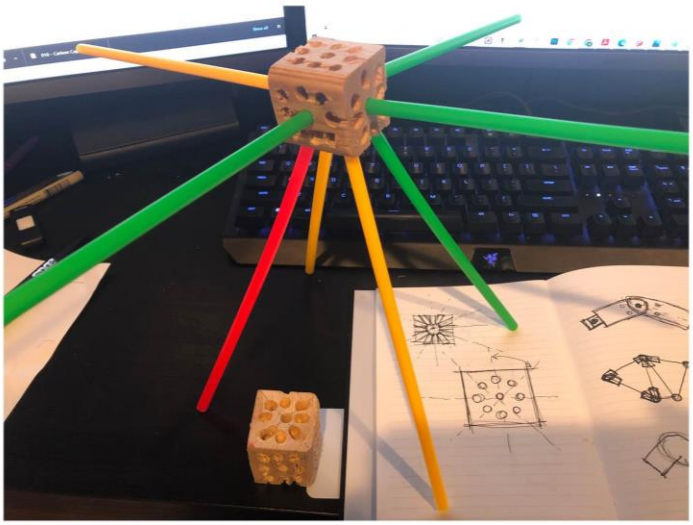


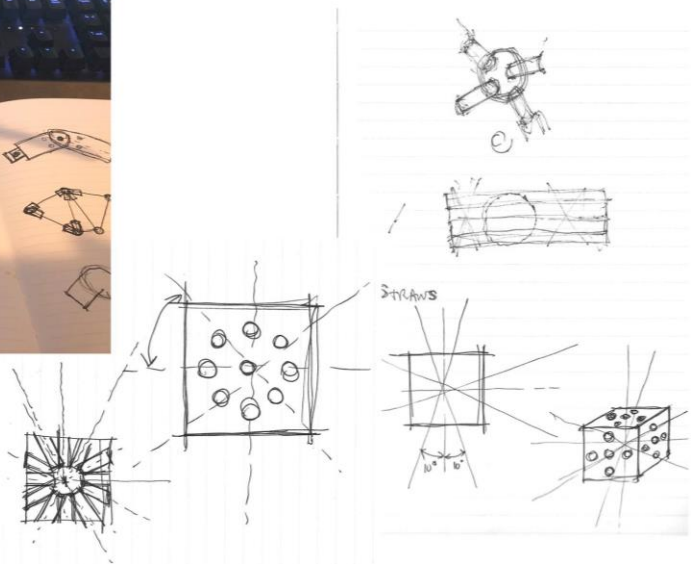



Node Prototype 1


3D Massing

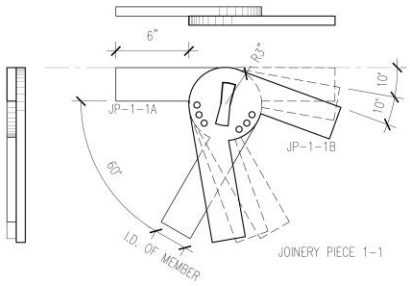
PROTOTYPE 2:

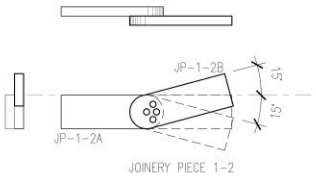


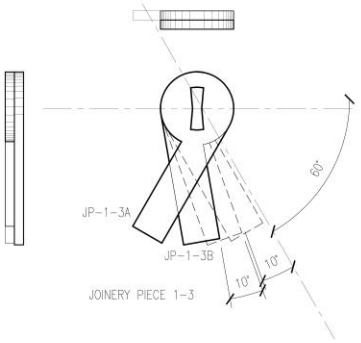


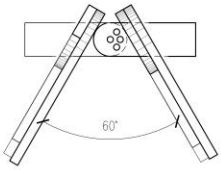
PROTOTYPE 3:

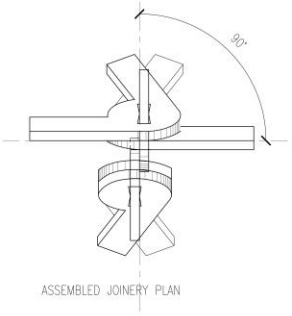
JOINERY PIECE 1

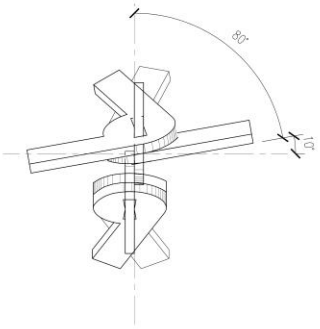


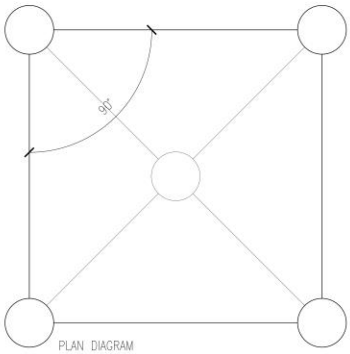


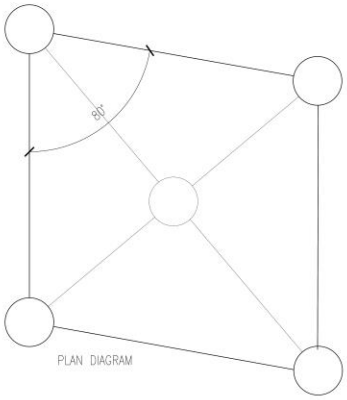




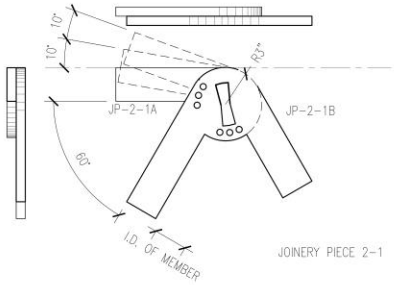


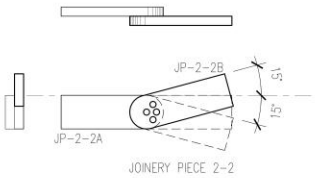


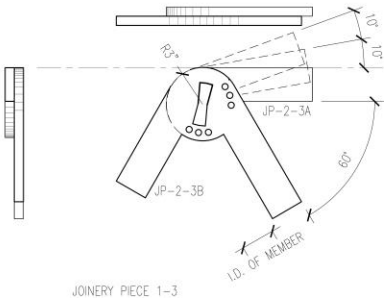




JOINERY PIECE 2







PROTOTYPE 3:

PROTOTYPE 3:

Straight - "Flat"

10 Degree - "Arch"

20 Degree - "Arch"

Paraboloid

Bamboo sleeves

TOP:These images show two built modular hemi-octahedrons formed from the joinery. The joinery forms fixed equilateral triangles to control structural spans.

LEFT: To avoid crushing and axial stresses on the paper tubes the true joinery will have the option for oversized bamboo sleeves that will receive the paper tubes. The prototype is simply showing paper tubes to represent this.

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