Optimizing Structure

An Investigation into Lightweight Structures

by

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A thesis

presented to the University of Waterloo

in fulfilment of the thesis for the degree of

Master of Architecture

in

Engineering

Waterloo, Ontario, Canada, 2015

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

This thesis investigates how to reduce the raw materials invested in a building, specifically in the structural aspect of its construction, and in so doing decrease the embodied energy required to build a structure. Geometric structures that utilize tensile forces allow for the most efficient, lightweight and economical improvements in building design. This construction method will allow structures to be built in a way that incorporates rapid set up, decreased material transportation costs, and the substitution of local materials. Innovative truss technologies that have the potential to be applied to multiple scales and types of building structures will facilitate the optimization of enclosed spaces.

Architecture typology today is still largely articulated on modernist practices developed nearly a century ago. This research proposes an alternative to the present and future of building technology. The focus is on creating small triangulated units that can be linked together in order to create a grid that makes a stable and supported structure. Unlike space frame construction, this approach reduces the size and volume of materials required by optimizing the use of tension components. Lightweight but strong tensile cable, in combination with small compression struts composed of wood or another renewable material, create a building unit that is extremely strong and utilizes resources to their maximum potential.

Preliminary investigations into tensile structures revealed that the failure in such a system would likely occur in the compression struts rather than in the tension segments themselves. Therefore, the research also focuses on the issue of compression members and how to improve their form. The goal is to achieve a tension structure that resists bending, yet can remain lightweight and can be assembled using humble materials.

The research also addresses ecological and sociological concerns. Technological advancement in an age of consumption has resulted in the creation of extraordinary structures from an architectural standpoint; however, the increased use of materials and the expansion of the human world are taking their toll on the earth's natural systems. The construction method proposed still allows the standard of living that Western society has become accustomed to, but in a way that is much more environmentally responsible. Indeed because of its adaptability and portability, it may afford developing nations a viable building opportunity they could otherwise not have envisaged.

Acknowledgements

The completion of this thesis would not have been possible without the love and support of my family and friends. A special thanks to my wife, Natalie. Her feedback and unwavering ability to ask the hard-to-answer-questions pushed me to contemplate my work from different perspectives. Thank you to my mother in-law, Dr. Maura Dubé, for providing valuable feedback throughout the editing process.

I also wish to thank my thesis supervisor Elizabeth English and the members of my advisory committee, Val Rynnimeri and Lloyd Hunt, for their invaluable knowledge and wisdom. All of these members had their own unique interests in the research and brought with them recommendations and guidance which broadened my outlook on the topics of research.

A special thanks to my external reader, Scott Walbridge, for access to the University testing facilities and for taking the time out of his schedule to offer his knowledge on the engineering principles and questions in relation to materiality and engineering strategies. Thank you to Richard Morrison who assisted with the testing at the engineering structures lab.

Finally, a special note of thanks to William Whitaker, curator of the Robert Le Ricolais archives at the University of Pennsylvania and to Peter McCleary for taking the time to recount his personal experiences as a colleague of Le Ricolais.

I would like to dedicate this thesis to my son, Jack.

I hope the concerns addressed in this work will help lead to change,

if not in my generation, then in his.

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Introduction

NEWS RELEASE: Somewhere in Africa. Date: March 20 2018

The scene at the relief hospital site set up outside the city limits following the country's latest earthquake:

Disaster Relief Hospital Construction:

Hour 1: The container arrives on site. Footing spikes are driven into the ground.

Hour 2: Container is opened and shelter is unfolded.

Hour 3: Tension is set and the 30' x 50' structure is habitable.

The fictitious scenario depicted above illustrates one of the humanitarian applications of the structures researched in this thesis. This structure can remain for a week, a month, or 100 years. It has a temporary quality, in that it is easy to assemble and disassemble, but it is built to stand up against the elements for any time that is required of it. It will not blow away in the wind, fail under heavy snow loads, or fall into disrepair with heavy use. It can be added to so it grows with its occupants, re-tensioned into a different shape, folded down for use elsewhere or completely disassembled for easy recycling. Natural light for occupants is inherent in this structure and its beauty comes from its honesty of construction.

This thesis is a practical investigation of tensile cable structures, specifically the optimal strength-to-weight ratio that can be obtained to economize materials and reduce weight. With a focus on hands-on experiments I venture to answer the question: how can buildings be more efficient while improving quality of life, and without negatively impacting the environment?

In choosing alternative building construction methods, primarily lightweight and structurally efficient buildings, I am expounding on and developing both theoretical and practical concepts put forth by such architects and engineers as Buckminster Fuller, Robert Le Ricolais and Frei Otto. I will use similar structural systems but will focus on greater efficiency through the use of increased tensile cabling as well as by allowing for the integration of local materials into the structural components. In doing so the building will have less embodied energy and be accessible to a greater number of people.

Today's construction methods and codes demonstrate a lack of sensitivity to our sustainable future. As stated by Robert Le Ricolais when comparing our building methods to those of a honey bee:

> "The fact that we rely on a safety coefficient which varies from 2 to 3, sometimes more than that, tells you a great story about our inability to get high precision in the difficult art of building. This makes it very interesting to consider the problem of the beehive, the economy made by the bee with its trihedral lid... And the saving in material is about two percent. Why should the bee do that, working on two percent while we work on two hundred percent? It tells you how far we have to go compared to the way of nature, the puzzling notion of the beehive." [1]

Much thought and effort have been focussed on ensuring our immediate safety from danger, but what about the long term risks associated with consumption with no regard for the preservation of our natural resources? I would like to explore alternative structural methods in order to find a more sustainable answer to our current practices.

Reducing the initial material cost, using materials to their full potential to reduce embodied energy within a building, rapid construction involving minimal labour, creating a building that performs better during the course of its inhabitation and can be recycled after its deconstruction, these are the objectives I hope to achieve by exploring the concept of tensile structures. After analyzing the current global situation and the need for change, my thesis will focus on three main areas of research: the geometry of a structure, energy within a building, and the social implications of design. Finally, I will explain my personal investigations to demonstrate my findings and conclusions.

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[1] LeRicolais, Robert. "Things Themselves are Lying, and So Are Their Images," VIA 2, (University of Pennsylvania: Graduate School of Fine Arts, 1973), p. 9

PART 1

The Problem

Geometry of Structure

Energy Within a Building

Social Implications

The Problem:

Understanding the Need for Change

This investigation's purpose is to understand the use of our natural resources, how humanity is abusing them and how to implement change through advancements in technology. The importance of considering resource management at the global level rather than simply at the national one is vital as we all live on the same earth and all rely on its natural ecosystems to survive. Statistics show habits that one can examine, to judge and understand how to promote a viable building alternative for the future. Instead of limiting people's standard of living, technology can be used to reduce the impact on resources while maintaining a high standard of living for generations to come.

Ecological footprints are one of the best ways to understand an individual's consumption in terms of the environmental systems required to support his way of life. When the national averages of countries are compared, it becomes clear that wealthy nations of the world are using more than their share of the collective global resources available. By comparing ecological footprints to human development and the loss of biological diversity, the devastation caused by our lifestyle choices becomes obvious. By understanding human habits and contributing factors, a solution that will appeal to more of the population can be achieved.

Furthermore, by understanding the shortcomings of global trade, a clear picture of the inequality that plagues nations can be examined. The misfortunes of countries can be better understood by investigating the factors that lead to our have and have not societies. It is crucial to understand the connections between countries and how financial prosperity is contributing to our continued consumption practices, which is accelerating environmental degradation. Big business practices perpetuate the overuse of material and the strain on environmental systems. Since the trend is towards powerful monopolies governing the goods available on the market, less consideration is given to quality, and more towards items that can be manufactured quickly and inexpensively, often leading to the need to replace them frequently.

Finally, by looking at how inefficiently natural resources are being used in manufacturing, change can be stimulated in the field of building technologies. By understanding the effects of embodied energy in materials and how common transportation practices contribute to the continued degradation of ecosystems, better choices can be made in building material selection. Through a systems approach, material selection can be used in the building industry to optimize productivity and therefore reduce waste throughout the entire life cycle of a structure. Technologies that rely less on imported components by being able to incorporate local, sustainable components into advanced building structures are a viable alternative to current, inefficient building practices.

My research focuses on creating lightweight alternative buildings, to reduce the amount of materials required for any structure. Through my designs I promote a new way of thinking, of conservation over consumption, using materials to their fullest potential to save our environment through moderation. This structural method reduces materials by optimizing tension forces to allow for a smaller amount of embodied energy in buildings and the reduction of required components. This type of structure has the potential to be accepted as common practice because affordability is tied to material savings, making it a viable construction solution.

Although humanity's consumption practices are currently leading to environmental and social devastation, positive change through technological advancement is still obtainable. By understanding the problems we have with our current human conditions and why they exist, the creation of alternatives can be implemented to maintain our high standard of living. Technological advancement may be in part responsible for the environmental problems we face now, but technology can also be responsible for the future change needed to end our short-sighted practices. For the sustained existence of our world we need to start making changes now before the environment's degradation surpasses the planet's ability to regenerate, and with it humans' ability to exist.

Buckminster Fuller used mathematical theory to create the Dymaxion Globe, an undistorted visualization of our world, illustrated in Figure 1.1, in order to represent all areas of the globe equally. Although purely geometric, his visualization carries with it a metaphor of the true importance of global equality and the responsibility of the entire population to protect nature's processes in order to maintain life on earth. Like Buckminster Fuller, I am considering the global outlook of our world, as inequality and greed are quickly overextending its natural resources.

Ecological Footprints

Ecological footprints are a straightforward and meaningful way of expressing an individual's consumption habits. The ecological footprint system measures the quantity of natural resources, in global hectares, consumed by an individual in order to understand the number of planet earths that would be required if everyone lived in such a way. Ecological footprint ratings show how lifestyle choices and habits - like transportation methods, diet and living arrangements - are impacting the sustainable aspects of the earth's ecosystems. Figure 1.2, illustrates what nations are using more than their fair share of the global resources in terms of per capita consumption levels. This imbalance will inevitably result in an ecosystem that will be insufficient in sustaining a future in the same manner. If the current state of consumption continues along its ever-increasing trend, the planet's resources will eventually be completely depleted with no chance for renewal. The National Footprint Accounts, a data source of the non-profit organization Global Footprint Network, dedicated to global sustainability, even suggest that the rate at which this happens has already been exponentially accelerated;

> "Humanity demanded the resources and services of 1.51 planets in 2007; such demand has increased 2.5 times since 1961"[1]

[1] Ewing B., A. Reed, A. Galli, J. Kitzes, and M. Wackernagel. 2010. *Calculation Methodology for* the National Footprint Accounts, 2010 Edition. Oakland: Global Footprint Network. for the National Footprint Accounts, 2010 Edition. Oakland: Global Footprint Network.

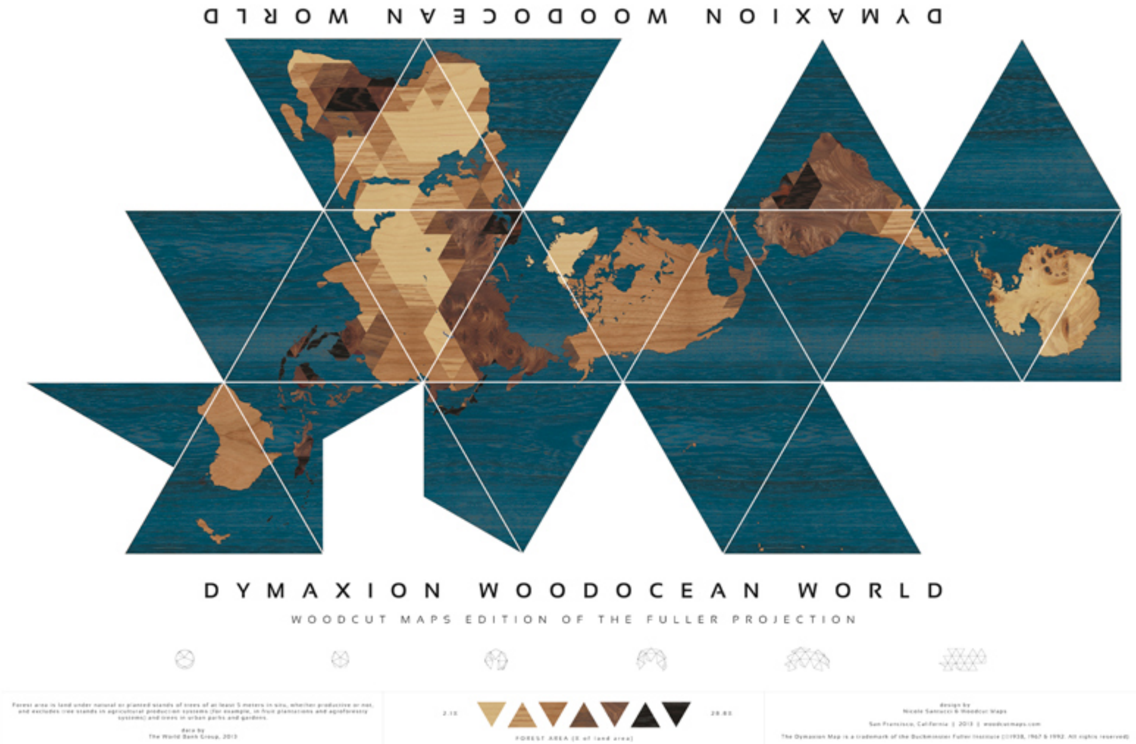

Figure 1.1: Dymaxion Globe

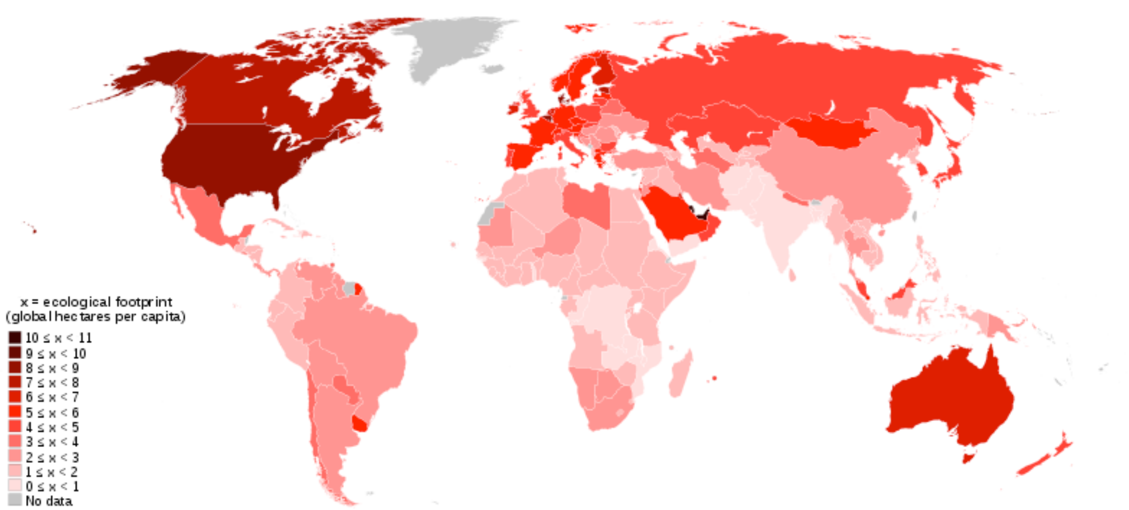

Figure 1.2: Global Ecological Footprint

Biological capacity is the measurement of all land types' ability to meet human demands for life and their ability to absorb toxins through natural processes. As the six land types (crop land, forest land, grazing land, fishing grounds, built up land and the uptake land to offset carbon footprint) are stretched beyond their sustainable levels, they are no longer able to naturally keep up to the demands we are making on them and their biocapacity is said to be reduced. Technological advancements have led to improved extraction of natural resources, along with the rapid production of heavy polluting electrical and transportation technologies, increasing humanity's strain on ecosystems. The largest increases can be seen through the carbon footprint, a staggering 55% from 1961 to 2008[2] as illustrated in Figure 1.3.

As our lives become more comfortable and convenience-driven, without regard for how they are getting that way, the environment is paying the ultimate price. For now, this has had no significant effect on the way we live, but at a certain point (its exact time and ramifications are much debated and a topic to discuss elsewhere) the resulting devastation of our environment through our lifestyle will make continuing on the same path impossible.

Living In Canada I am well off in terms of my prosperity and quality of life. I was interested in finding out just how my ecological footprint compared to Canada's 8th place world average of 7.1 earths as seen in the Living Planet Report 2012.[3] According to the online survey, hosted by the Centre for Sustainable Economy, which asks about where you live and your current lifestyle habits, I scored 3.8 earths, well below my country's average. I was happy for a moment until I realized that this means there needs to be nearly four earths if everyone on the planet lived as I do in order to support a renewable and sustainable future! The fact is that globally we are living far outside our means as our planet can no longer maintain its natural processes due to the strains of our consumption.

As discussed, ecological footprint is a useful tool for finding an average impact for a population within a country, but several other factors must

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[2] WWF. 2012. Living Planet Report 2012. WWF International, Gland, Switzerland p. 38

[3] op. cit. p. 43

be considered to understand the country's overall contribution to the global footprint. If a country's collective ecological footprint is below its land's biocapacity, it helps to reduce the world average and vice versa. Biological capacities are a measure of the country's share of the bio regions; however, a country's wealth or deficiency in this area is not a guarantee of its financial wealth, as exports of valuable goods are a large part of economic prosperity.[4] A country that has goods for trade, even if these are not environmental assets such as oil, is able to import resources to create a thriving, wealthy nation, despite its lack of environmentally viable land. The commodity may fluctuate in value and therefore generate enormous fluctuations in a country's income, which also increases greed for merchandise. Overall, a high availability of environmental commodities leads to more trade, which results in more financial wealth, perpetuating a cycle of exploiting resources for economic gain. With this comes an unnecessarily high ecological footprint.

The Ecological Wealth of Nations, as seen in Figure 1.4, demonstrates to what degree countries are using their own resources to support their ecological footprint. It separates nations into two categories, 'debtors' and 'creditors', (with a further breakdown of how severe in either direction) depending on whether they can sustain their current lifestyle or not. If the country is incapable of producing sufficient ecological wealth within its borders, the country is termed a debtor and it must rely on other countries to make up for its consumption. Canadians are fortunate, as Canada is a large land mass with a high biological capacity but a comparatively small population. As a country, it is helping the global carrying capacity despite a high ecological footprint.

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[4] Living Planat Report. op cit. p. 47

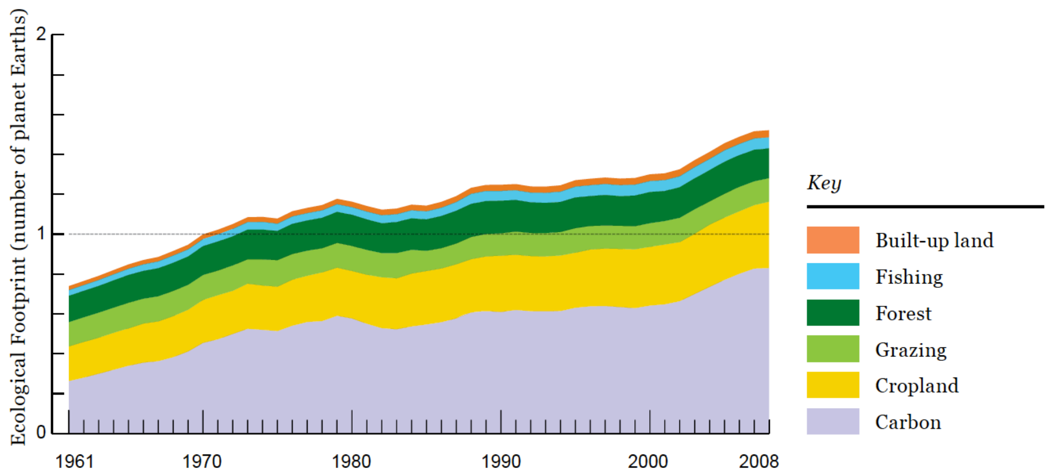


Figure 1.3: Global Ecological Footprint by Component, 1961-2008

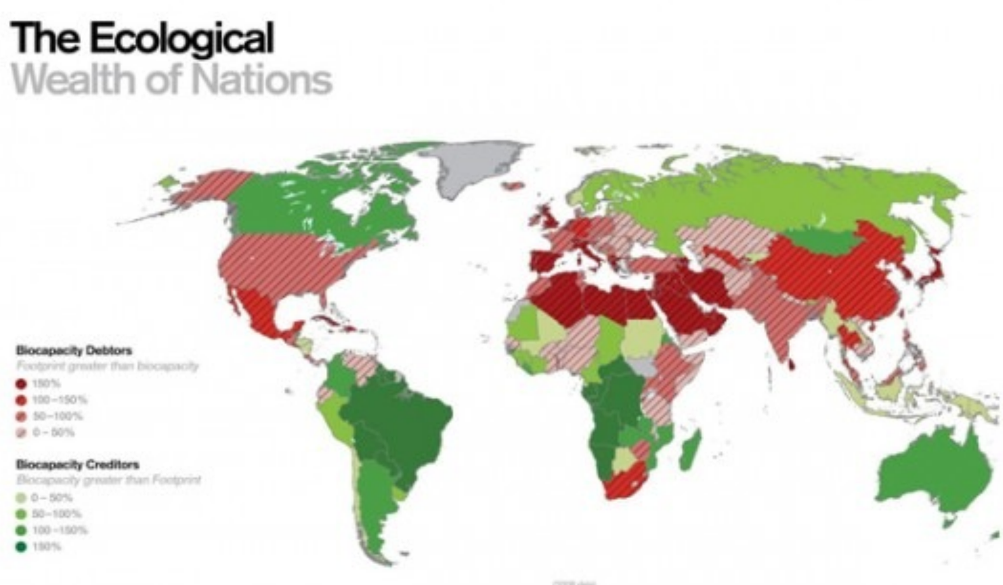


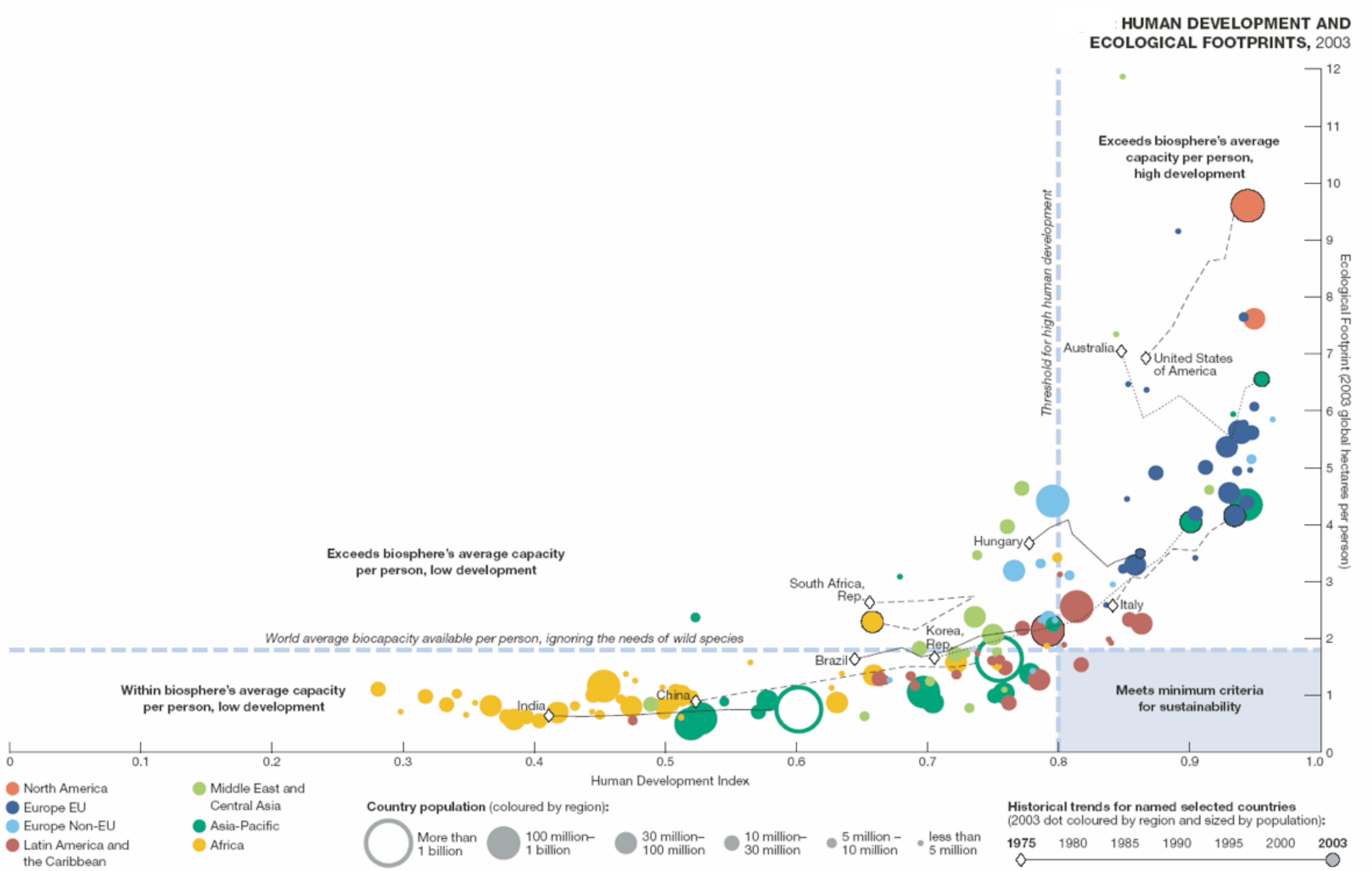
Figure 1.4: The Ecological Wealth of Nations

Another indication of a country's ecological footprint can be found in the human development index (HDI)[5], which gauges the quality of life that is expected for a country's population. In order to indicate how any country compares to the next, the HDI is made up of a series of factors: life expectancy, education and income. Although this number is not a guarantee, it is a good indication of the overall state of its citizens and therefore a fair indication of human living conditions in comparison to others around the world at any given time.

As can be imagined, nations with a higher HDI tend to use more of the earth's resources, resulting in a larger ecological footprint. Figure 1.5 illustrates these coinciding relationships. A clear curve appears: as standard of living increases, the cost on world resources is reflected in the increased ecological footprint. Nations with larger populations, specifically India and China, carry with them a huge resource requirement, and since a steady incline in the human development index is the trend, an even bigger strain on global resources can be expected in the future. Improvements in medical care and education continue to aid in the development of third world nations, increasing human comfort and creating better lives. At the same time, wealthy nations of the world continue their irresponsible consumption of resources at a quickening pace, as modern culture dictates that in order to be considered 'successful' you need progressively more material goods and financial wealth. A constant drive for the newest gadget or bigger house keeps global trade alive as we are willing to sacrifice local, possibly more costly products in favour of less expensive alternatives. Unfortunately, this constant drive for the cutting edge leads to environmental devastation that affects less fortunate nations of the world more than the developed ones. Marketing of products has created a class that uses more than it needs, a fortunate few that hoard the resources of the world from others, creating have and have not conditions.

[5] Living Planet Report. op. cit. p. 60

Figure 1.5: Human Development and Ecological Footprint, 2003

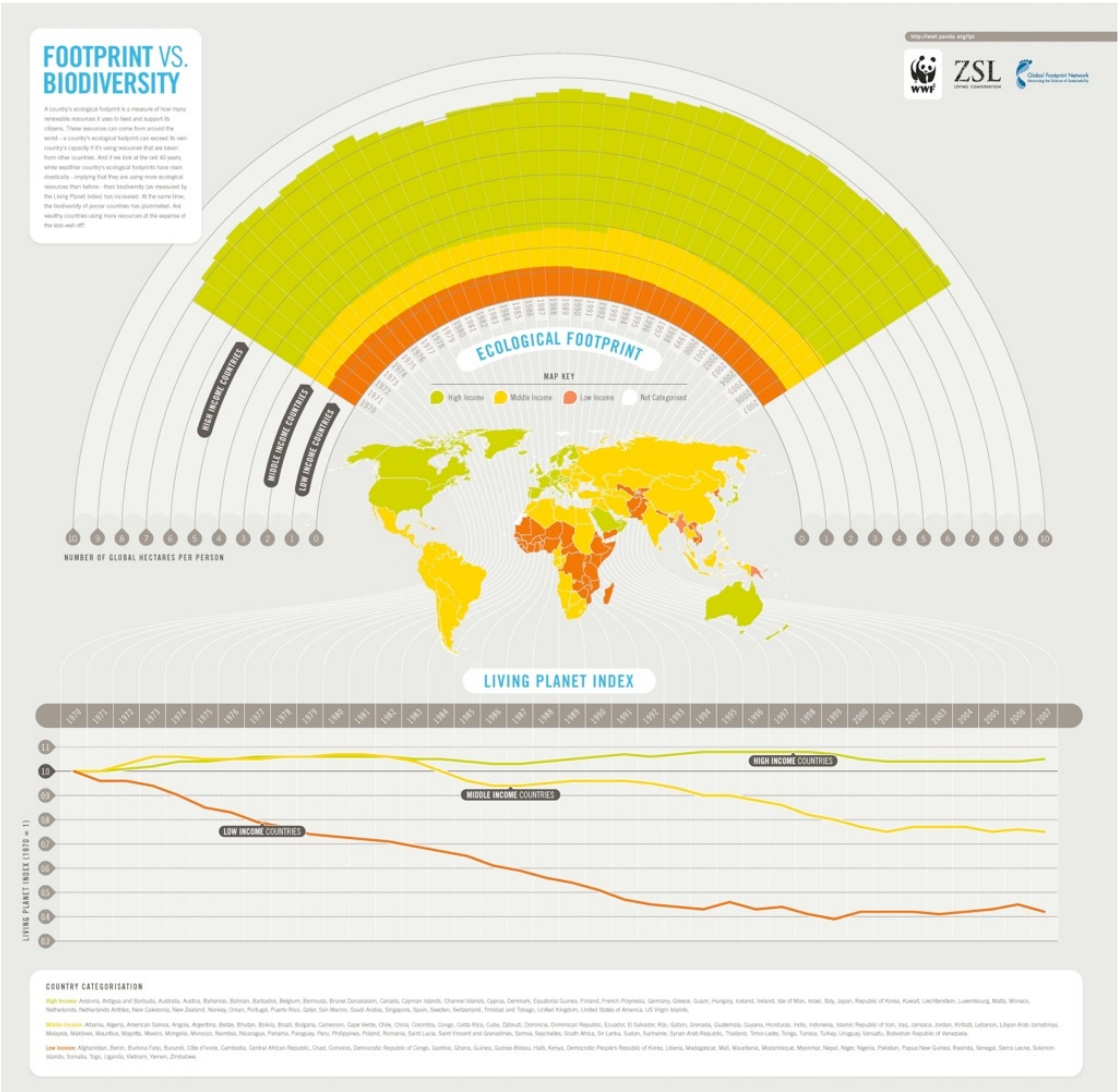


The first signs of trouble are already present, as in the world today a loss in biodiversity can be traced to human beings' overuse of global resources. As mentioned earlier, countries that use most of the world's bioregion resources do not always have these present in their own countries, so the debt is passed to the less well off nations of the world. Loss of biodiversity works in much the same way. High income countries are using the resources and the poorer nations of the world are paying for their over-consumption through the loss of biodiversity.[6] The chart in Figure 1.6 shows the designation of high, middle and low income countries, and the number of global hectares consumed by individuals. Continued growth of over a hectare per person for wealthy nations in a mere 37 years (1970-2007) is seen; this tread is significant as it shows that even the most well off people in the world are still demanding more. Continuing the analysis of the data in this illustration, the living planet index of high income nations has actually increased where both middle and low class countries have seen a decline, making a large imbalance even more substantial.

The conclusion is that wealthy nations do not need to demolish ecosystems to continue existing, but they have the financial means and a mentality leading them to continue consuming the resources of others. Until some solution is reached that reduces consumption and optimizes the resources we already have, the land and its species will continue to pay the ultimate price, starting with the poorest nations. The dangerous side of this is that technology, however powerful, cannot replace an extinct species, and as we continue our exploitation we are losing the very systems that allow our world to function.

[6] Secretariat of the Convention on Biological Diversity (2014), Global Biodiversity Outlook 4. Montréal, pp. 19-23 (Target dashboard, in a summary of components)

Figure 1.6: Footprint vs. Biodiversity



Global Trade

Crop land makes up one of the six bioregions used to calculate ecological footprint and the carrying capacity of a nation. As food is a crucial component of any ecosystem, examining where the largest amounts of grain crops are located helps in determining a nation's ability to feed itself. Figure 1.7 shows where grain is being grown in the world, and the import and export of this valuable commodity.[7] North America, the largest producer of grain, is also the world's largest exporter of it at 130.2 million metric tons. North America has more than enough to feed itself. Only a small percentage of the total production is traded, possibly explaining why North Americans are one of the most obese nations in the world as well.[8]

This seems to be another example of undervaluing resources as we are able, with our abundant reserve of food, to pay less for the amount of food we eat. 10-20% of consumer spending in industrialized nations is on food, compared with upwards of 60-80% in developing nations. This leaves the populations of these nations with very little money for other living necessities. The cost of importing grain far outweighs the cost to produce it locally, another way developed nations are able to take advantage of the shortcomings of the less fortunate nations of the world. This can especially be observed in Africa where unsuitable conditions make it difficult to cultivate soil and therefore create a reliance on grain imports, driving up the cost of food. The U.N. states that 21 out of the 37 countries in food crisis are located in Africa, showing the harsh living conditions present in the continent.[9]

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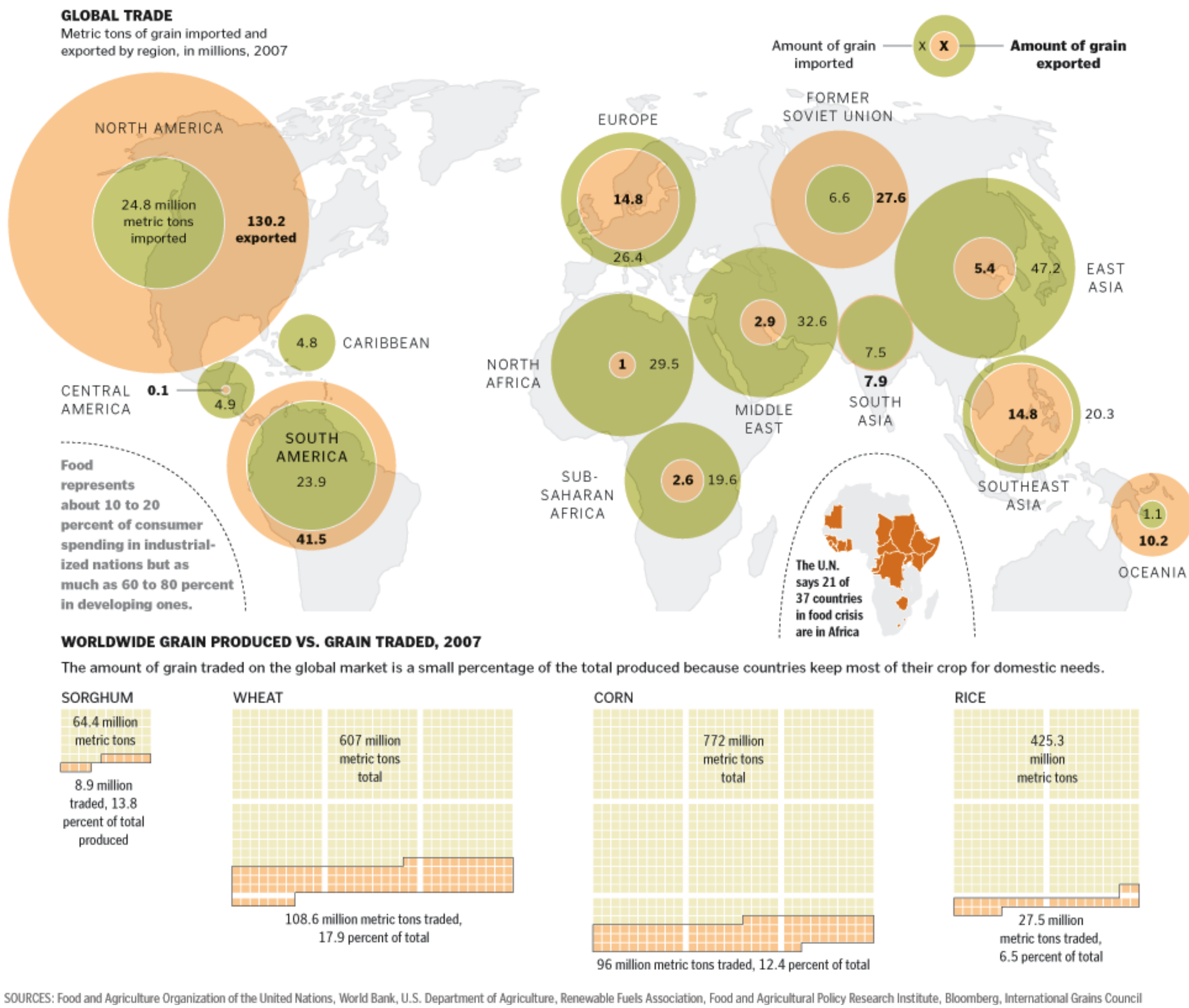
[7] Yourish, Karen and Todd Lindenman. "The Global Grain Trade: The Haves and Have-nots" map graph, April 27, 2008. The Washington Post. Web. November. 2013. http://www.washingtonpost.com/wp-dyn/content/graphic/2008/04/26/GR2008042602472.html

[8] Diamond, Jared. "Guns, Germs, and Steel: The Fates of Human Societies." W. W. Norton, New York, N.Y., 1999. Print.

[9] Yourish. op cit. # 7.

Figure 1.7: Global Grain Trade



In recent centuries the human population has skyrocketed, mainly due to medicine and advancement in agricultural productivity. The global population hit 1 billion in the year 1800 A.D. and by the year 2011 had reached 7 billion.[10] This is truly astounding when one considers that over hundreds of years previous to that period we historically maintained a relatively consistent population with only small fluctuations in growth. This huge amount of population increase is also a factor in our global resource struggle as despite the rise in numbers, the carrying capacity of the earth has remained the same. Figure 1.8 clearly shows the uneven distribution of human populations.

Global population has been stabilizing since 1962, when the birth rate peeked. Today, a more stable population regeneration can be seen throughout most of the world. Africa continues to have a higher than average birth rate, as seen in Figure 1.9, making it more difficult to feed its population as continuing growth only strains the resources available. Education and safer living environments are key to reducing population growth to a manageable state. Continued growth is expected but thankfully the rate is drastically decreased in comparison to our last century, yet the imbalance among nations' ability to feed their populations remains.

Disparities in global trade are also affected by other factors. Fortune 500 companies are among the most powerful forces in affecting the goods consumers purchase. The significant power of corporate companies can be seen throughout the world as local business is bought out or forced into bankruptcy by mega enterprises. Large corporations are successful because they can buy bulk quantities of goods, allowing them to sell their products at rock bottom prices, reducing the competitive edge of smaller companies and independent local businesses. Most consumers are strangely unaware of the fact that these companies control the goods and services available to them. Naturally, the incentive is the price of goods, and the volume of goods is so high that corporations are able to drive down the cost of the product for the consumer. Again, naturally, the average person feels the need to get the best value for his money and

[10] Meadows, H. Donella, Dennis L. Meadows, Jørgen Randers. " Limits to Growth" Chelsea Green Publishing Company, 2004. Print

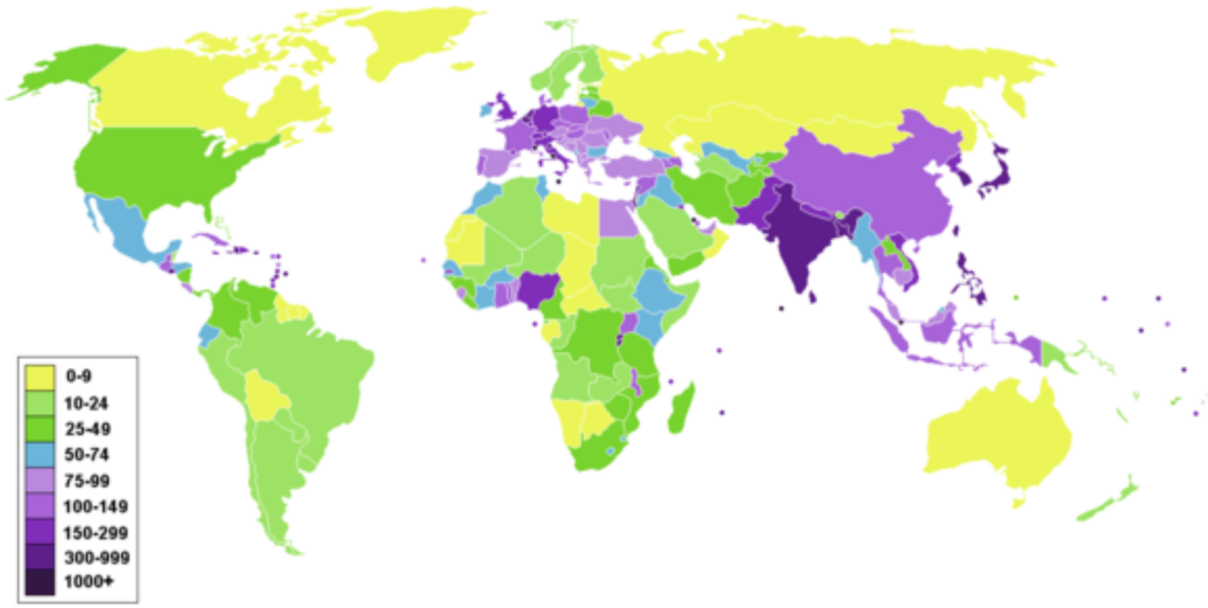


Figure 1.8: Global Population Density (Indicating number of people per square kilometre)

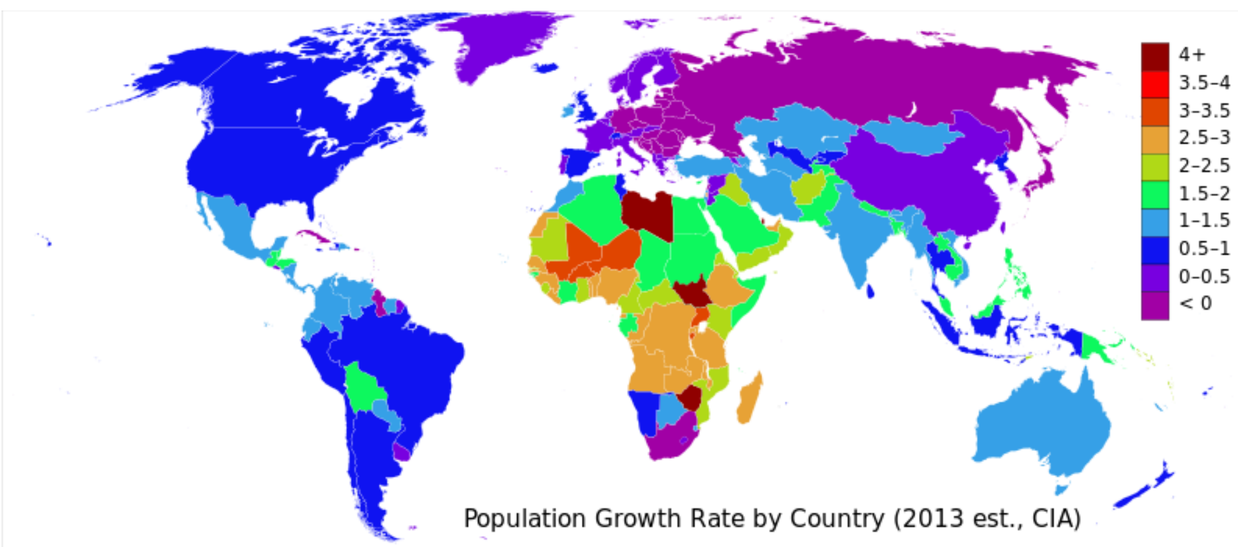


Figure 1.9: World Population Prospective

slowly the shift to corporate companies occurs. As the cost of products, often at the expense of quality, becomes the driving factor in what is purchased, production costs also need to be driven down. Countries that are able to produce goods with very low labour prices have offered to manufacture products that are less expensive to build offshore and ship overseas than they are to produce locally. Transportation of products leads to a higher embodied energy as fossil fuels are burned in the transportation process. The cost of goods does not fairly reflect their environmental cost. Furthermore, competitive pricing has led to a reduction in the quality of the products offered and encouraged their increased consumption.[11]

Historically, North America and Europe have been home to the majority of the fortune 500 companies and their manufacturing facilities. However, a shift is happening as can be observed in Figure 1.10 showing a movement of powerful corporations to Asia as that is where the vast majority of goods is being produced. The shift away from North America indicates a new direction not only financially, but in power as China has the ability to produce the goods that the first world nations have become accustomed to buying. The financial prosperity of China can be seen through China's increasing income per capita, an increase of over 200% between 2000 and 2010.[12] Because China is able to produce goods for less money, its economy is flourishing.

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[11] McDonough, William and Michael Braungart. "Cradle to Cradle: Remaking the Way We Make Things." North Point Press, New York, N.Y., 2002. Print. p.147

[12] Nicolas Rapp. "New Perspective on the Corporate World" Map Graph. July 2012. World's largest corporations mapped. Article Fortune magazine . web. November 2013. http://nicolasrapp.com/?tag=global-500

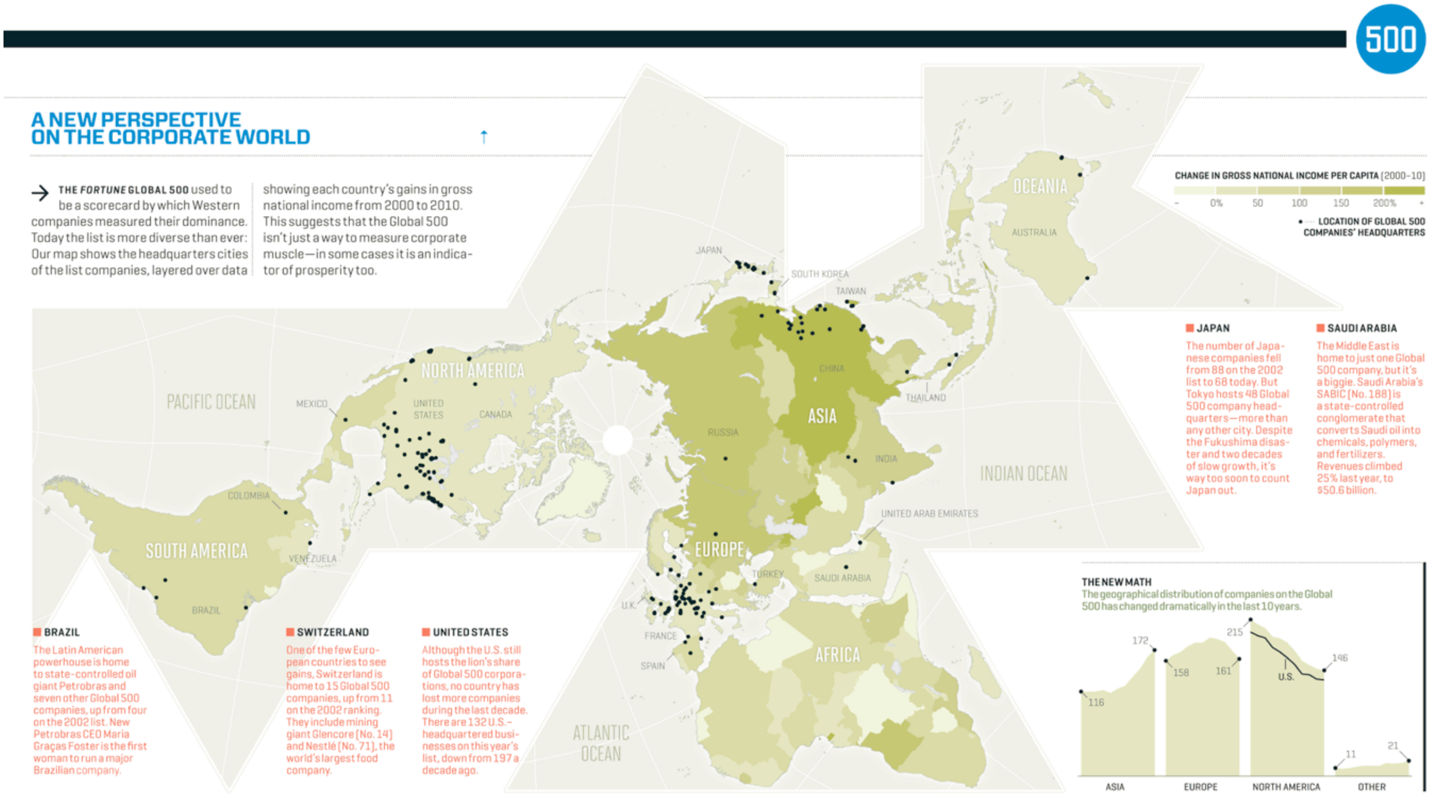

Figure 1.10: New Perspective on the Corporate World

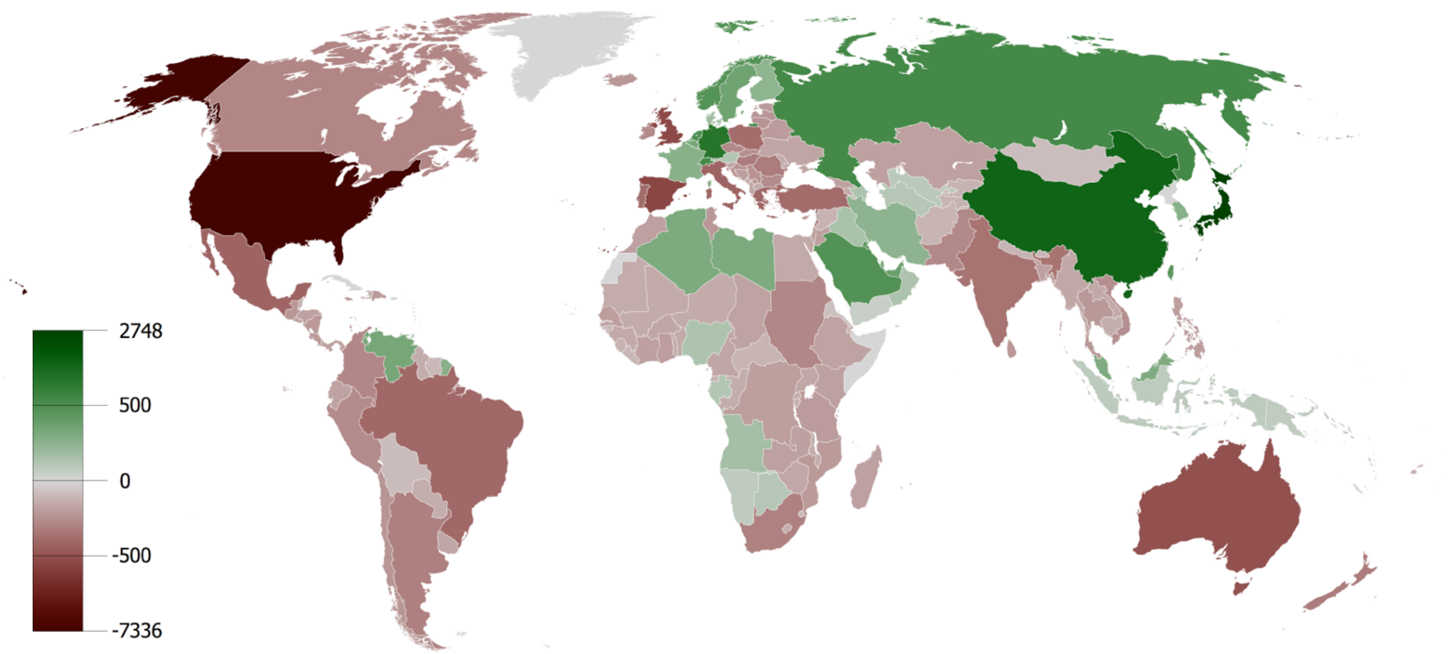

Figure 1.11: Cumulative Current Account Balance from 1980-2008 in Billions of US Dollars

By looking at the imports and exports of countries, one can weigh their total cumulative account balance. Figure 1.11 illustrates whether or not a country is getting more than it is giving through its financial prosperity. In terms of consumption a country's cumulative account balance is a valuable tool. A reliance on imports shows a reliance on other nations of the world to produce goods. It can be seen that America is a large contributor to the global consumption problem as it takes in more products than it puts out. The consideration in this is that America is still producing its own goods as well, creating large quantities of consumer goods, as well as importing from other nations. A shift in material production from America to Asia has created a change in employment opportunities. Factory manufacturing jobs are being eliminated and high tech jobs are taking over the market.[13] Cheap labour and low operating costs continue to cause the relocation of goods away from America, increasing the divide between the rich and the poor as the middle class production industry is reducing its work force.

At the same time, industrialization of fabrication practices has contributed to the reduced need for skilled labour.[14] Machines are faster, more accurate and require no rest between shifts. The ability to produce more goods, faster, is an advantage to businesses as more can be sold; however, the use of resources required to maintain such a high volume of consumable goods shows little consideration for the available carrying capacity of our world[15]. This leads to practices of natural material extraction, such as large scale mining and the clear cutting of forests, causing devastating effects on ecosystems. All processes involved in industrialized production require a constant supply of natural resources, the problem being that the environment takes longer to regenerate these resources than the rate at which they are being extracted.[16] The energy required to run such operations also poses environmental concerns. Constructions such as dams reduce the natural environment, taking up

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[13] Kenney, Martin, Richard Florida. "Beyond Mass Production: The Japanese System and its Transfer to the U.S." Oxford University Press. 1991. Print.

[14] Braverman, Harry. "Labor and Monoply Capital: The Degradation of Work in the Twentieth Century." Monthly Review press, New York., 1974. Print. p.86

[15] McDonough, opt. cit. p.22

[16] Nakamura, Takashi, Kohmei Halada. "Urban Mining Systems." Springer, 2014. Print.

huge amounts of land with man made conditions destroying biological area.

The obsolescence of skilled labour further reduces the need for public knowledge of fabrication processes, with the result that we have a population that has little idea how modern amenities work and therefore no idea how to fix the machinery it has come to rely on. The world is moving at such a fast pace that the reliance on technology is becoming a prerequisite in the daily lives of individuals.

Planned obsolescence, a concept of predetermined expiry dates in manufactured goods, ensures that the consumer must continue to buy new and improved products instead of fixing the old.[17] Even when purchasing the highest level of computing power available on the market, the product is soon obsolete and outdated, creating a constant need for upgraded components. Product engineering focuses on designing products to wear out, break down or simply look old, faster than necessary in order to ensure a continued stream of income for fabrication companies. This practice makes sense on a financial level but it is a complete waste of natural materials and an unsustainable approach for future generations. To cut down on the consumption of resources, designers need to think about making products that stand the test of time, are durable and will not become outdated before they fulfill their life cycle needs.

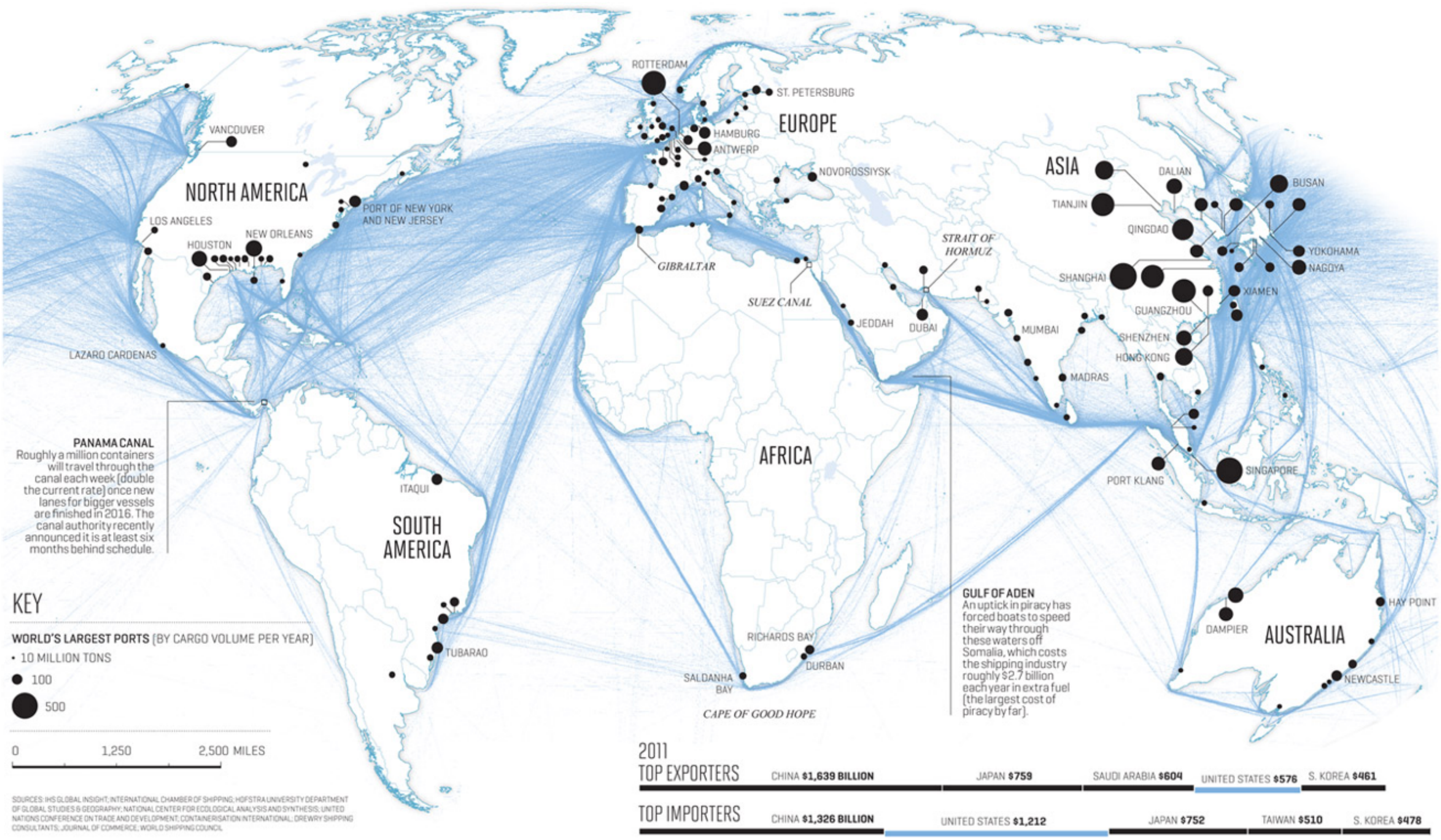
Historically, global trade has revolutionized the way consumer goods are produced, making it possible to manufacture products far away from where they are being consumed. The prosperity of nations allows goods and services to be purchased globally, making for a higher quality of life for the well off nations, meanwhile shifting industrial processes away from local populations. Embodied energy of products is high, as transportation of merchandise means burning more fossil fuels as it is the least expensive and only way in which ships move products today. This practice of trade is not a viable future solution as the concept of transporting merchandise relies on cheap energy that pollutes the earth as it is being consumed and destroys natural habitats as it is being extracted. Unfortunately, growing demand for goods has resulted in the continued growth of the shipping industry, leading to bigger ships and

[17] Fitzpatrick, Kathleen. “Planned Obsolescence: publishing, Technology and The Future of The Academy.” NYU Press, 2011. Print.

bigger ports. The environmental cost of transportation is not reflected in the price of products as of now, yet the global trade network flourishes as we continue to rely on other countries to build our consumable goods.

The mapping of shipping routes and the size of the ports seen in Figure 1.12 clearly show Asia's ability to dominate in fulfilling the world's needs for goods. The fact that China has the largest import and export volumes indicates that they are capitalizing on the need of greedy nations by producing goods that are cheaper than having them built in the countries where the goods are being consumed. Unfortunately for the richer nations of the world, labour costs at home are higher than financially makes sense for local production. Workers in wealthy nations have a comfortable lifestyle and are all right with paying less for products even though the ability of their nation to produce goods is being undermined. The consumer is always looking for the least expensive option, a condition that allows him to continue buying and consuming more. This cycle is showing its shortcomings as jobs become more scarce in developed nations. The skill set required for employment is changing as careers are no longer found in manufacturing but more in service based industries and technology. But people still need goods and so continue to purchase foreign made products without considering the effect on the environment or the long term effects on their own future prosperity.

Figure 1.12: Shipping Network



Building fabrication and its material investments are a major consumer of energy, so as a way of reducing our consumption I am interested in investigating building materials and where they are made. We have standards and regulations that dictate our construction methods with respect to safety to dwellers and energy use within the building, but these require specific construction practices that often do not lend themselves to responsible material choices. We rely on wood, steel and concrete as the primary construction materials of our built world, so I am interested in where and how they are produced.

Not surprisingly, China is a major producer of all three of these primary construction materials as seen in Figures 1.13-15.[18] This continued dependence on a single country for goods is dangerous as we rely heavily on trade to maintain our standard of living and construction practices. This ‘all our eggs in one basket’ approach is working for the time being to provide us with the items that we use, but the day when the environmental impact will be too great to recover from is unknown and the effects could be devastating to our way of life.

The transportation energy is only one disadvantage to importing goods. The embodied energy of a product requires a certain amount of energy for the material to be produced and refined. The energy in material is the same anywhere it is made, assuming technologies are the same - the difference is the availability of clean energy.[19] As we continue to burn fossil fuels as an economical solution to energy requirements, we are polluting the environment around us. Figure 1.16 illustrates the cleanness of energy production in each country, showing unsustainable energy production within a number of countries that specialize in mass production processes. Clean energy technology exists but its initial cost to implement is prohibitive. Being unable to envision the environmental impact in terms of dollars and cents, we continue to use dirty, inefficient methods of energy generation. Clean energy is often seen in first world nations, but industrial processes are primarily taking place where the energy still comes from unsustainable and non renewable sources,

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[18] Bengt Cousins-Jenvey. “Where are Building Materials Produced?.” map. October 2011. web blog. November 2013. http://www.c21buildings.com/

[19] Bengt Cousins-Jenvey. “Mapping Carbon Intensity of Electricity.” op.cit.

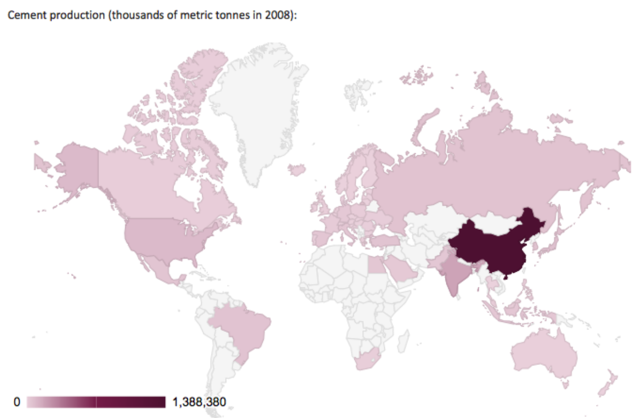

Figure 1.13: Cement Production

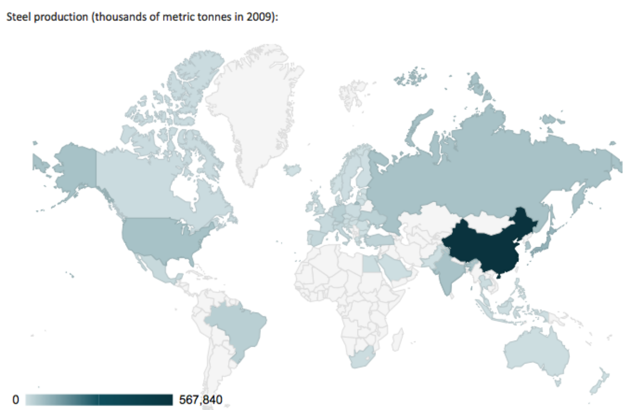

Figure 1.14: Steel Production

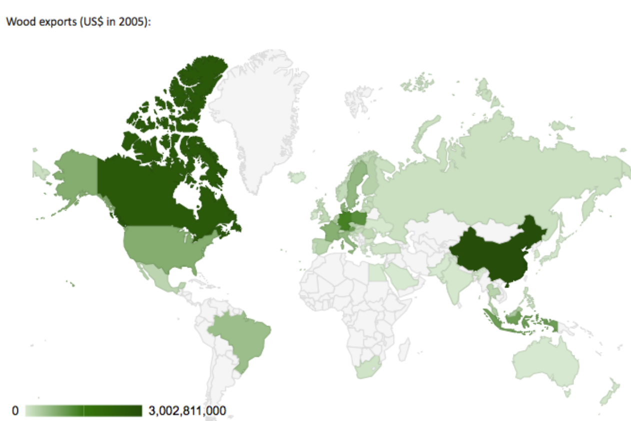

Figure 1.15: Wood Production

creating even bigger environmental impacts on the products we use.

Problems like water scarcity, desertification, acid rain and air pollution threaten the health and very survival of China's population as illustrated in Figure 1.17, as the continued consumption of natural materials permanently damages the country's ecological assets. Once environmental devastation like this has occurred, it becomes increasingly difficult to undo. The irony of China's situation is that now that their country has been polluted, possibly beyond the point of no return, more energy conscious systems are being implemented. It is a cruel example of human nature that we let our lands be destroyed and our people die unnecessarily, and that only when environmental concerns severely threaten human existence do we consider responsible change.[20] North America and other trade reliant nations have the benefit of inexpensive products, but have caused a nation to deplete its environmental assets to the point of extinction. Even though the harm is being done outside of our country it is still on our earth and we need to take responsibility for our actions.

[20] Woon. Damien. "Severe Pollution + Environmental Degradation in China." map. march 2010. web. December 2013. http://www.fastcodesign.com/1662226/infographic-of-the-day-chinas-monstrous-environmental-problems

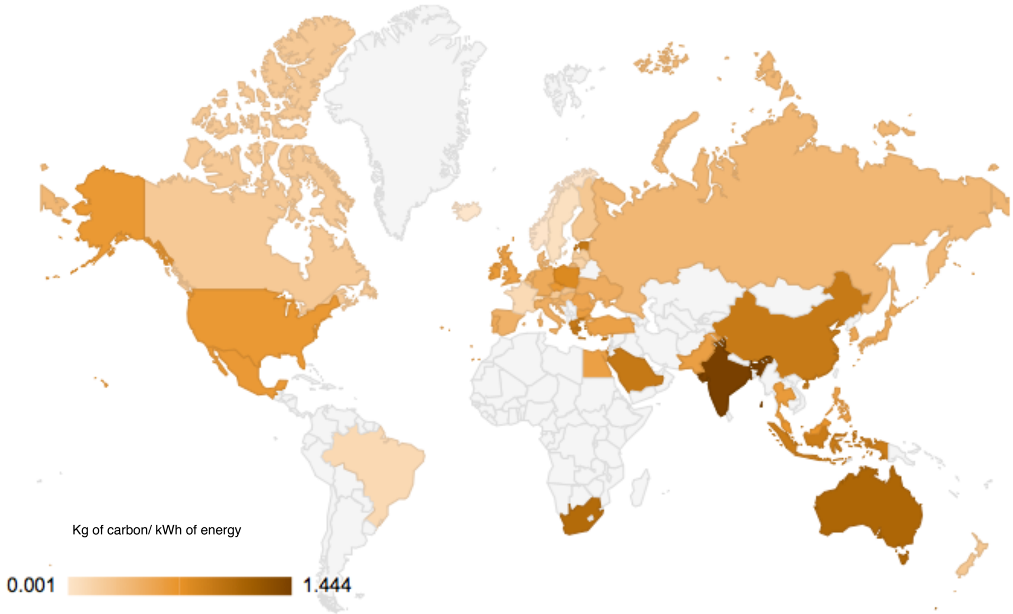

Figure 1.16: Carbon Intensity of Electricity

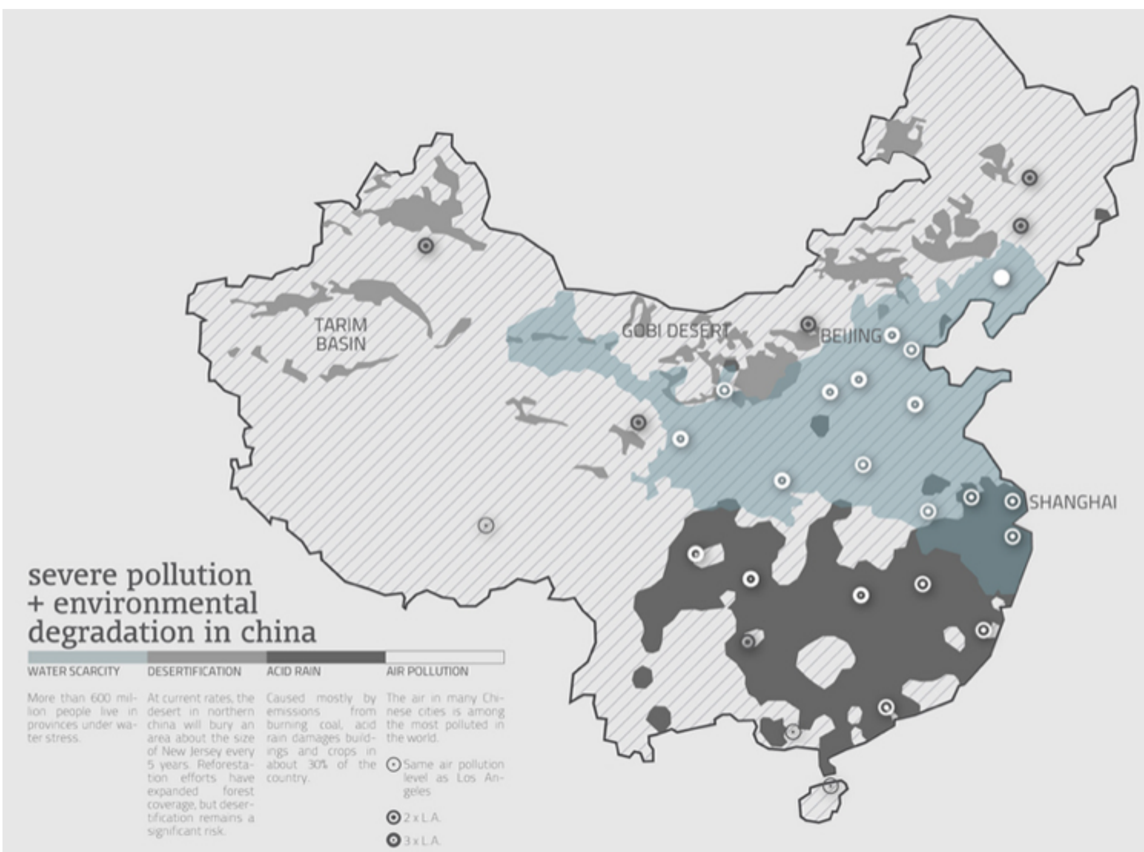

Figure 1.17: Severe Pollution + Environmental Degradation in China

Geometry of Structure

Studying the fundamentals of geometry in complex structures is essential to better understanding how to improve the efficiency of a building's makeup. Tension cables optimize materials by connecting components with a low material to strength ratio. By linking components together to create a grid shell arrangement, materials can be reduced without sacrificing the spanning capabilities of a structure. This construction method has historically been underused - mainly due to the complexity of the linked components and how multiple planes must link in space - but the use of computers is allowing it to become more mainstream. With software, structures can be designed more as a resolved kit, linking components with one another in a simplified tensile web.[1] The complexity of the form is no longer a valid reason to dismiss a building that is more efficient. Emphasis will be placed on reducing the complexity of this medium through the simplification of individual units and the repetition of similar components. This type of building does not appear in the conventional building codes, meaning that it would fall into the experimental category and require more testing. Tension requires much thinner components when compared to similar compression reliant components. A structure needs both tension and compression forces, as noted by Buckminster Fuller:

> "Tension and compression always and only coexist and covary inversely. We experience tension and compression continuously as they interaccommodate the eternally intertransforming and eternally regenerative interplay of the gravitational and radiational forces of Universe."[2]

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[1] Two examples of such software are: SolidWorks (SolidWorks Corp.)- component construction software, and SketchUp (Trimble Navigation Ltd.)- easily learned and accessible 3-dimensional modelling.

[2] Fuller, R. Buckminster and E.J. Applewhite. "Synergetics 2: Further Exploration into the Geometry of Thinking." Macmillan Publishing Co. Inc, New York, N.Y., 1979. Print. p. 165-166

Figure 2.1 : Spoked Wheel Rim

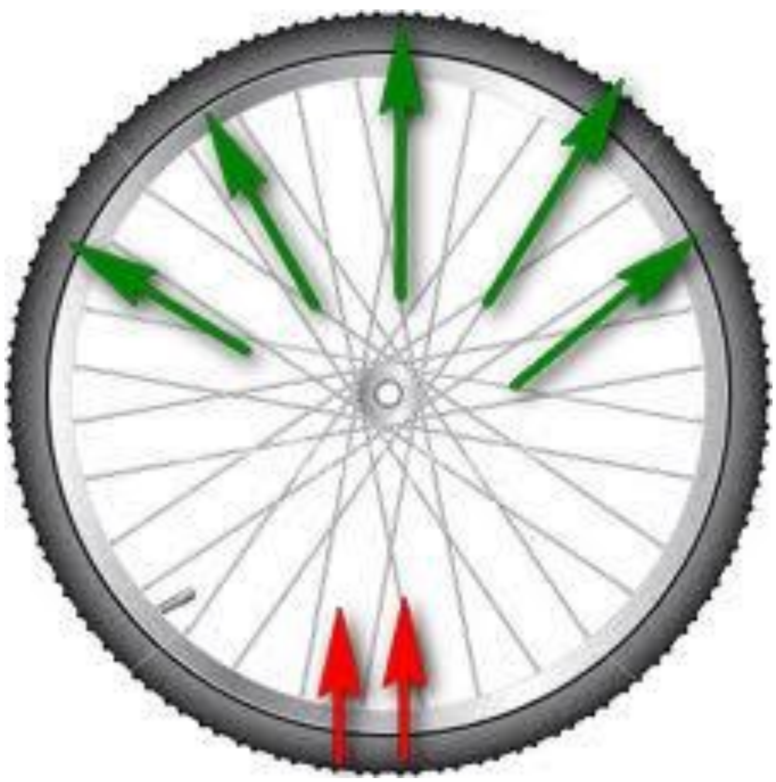

Figure 2.2: Spoked Rim using Tensile Forces

Structures mainly use components that can be both tensioned and compressed, regardless of which force the component is resisting or where in the construction it is located. Material such as tensile cable only functions under tension forces - it is more efficient but cannot resist compression. For structures that utilize the optimization of tension cables, geometry becomes more important. A balance of tension and compression components, with an understanding of the force relationships, is essential because components can not share both responsibilities when used in this manner.

Tension furthers its efficiency in that it travels the shortest distance between compression members, making for stronger connections as forces are resolved in the most efficient direction with no diversions. As seen in Figure 2.1, a spoked wheel is a perfect example of optimizing tensile forces.[3] There is a compression ring around the outside of the circumference and a central hub component, but the circular shape of the wheel is maintained by the triangulated structure of fine members (spokes). The weight of the rider as the wheel is being rolled forward converts the compression forces below the axle into tension forces, hanging the axle from the top edge of the solid compression ring, as illustrated in Figure 2.2. This allows the spokes of the wheel to remain in tension as the wheel rotates. The distribution of the tension forces is greater at the top of half of the wheel, but as the wheel is rotating it is important that all the spokes be tensioned equally or the wheel will not spin completely straight as a result of an unbalanced load. If a solid rim construction were compared to the spoked wheel, the weight to strength relationship would be found to be far more efficient in the latter, an example of the concept called "lightweighting."

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[3] Beukers, Ariaan and Ed van Hinte. “Lightness: The Inevitable Renaissance of Minimum Energy Structures.” 010 publishers, Rotterdam, 1998. Print. pp. 92-97

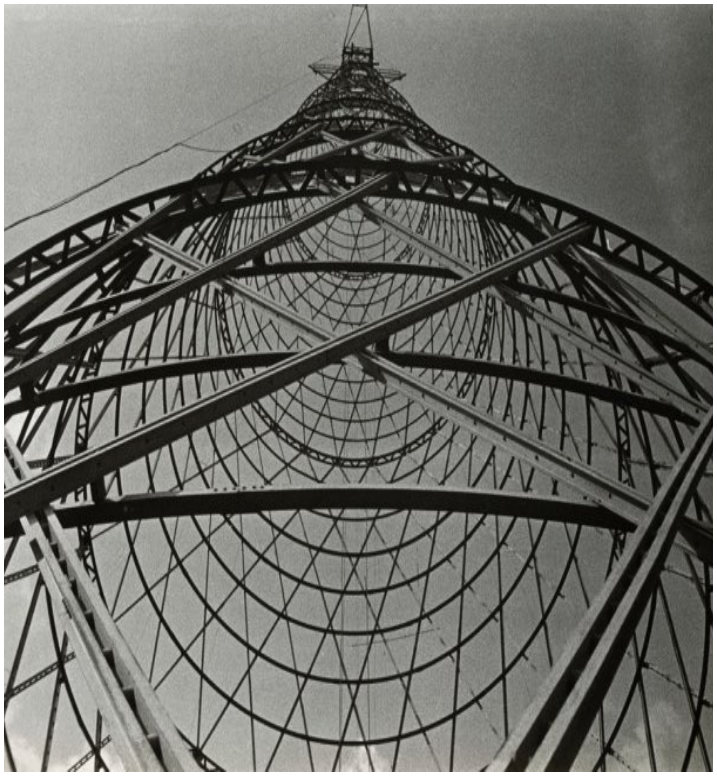

Figure 2.3: Shukhov Tower, 1922

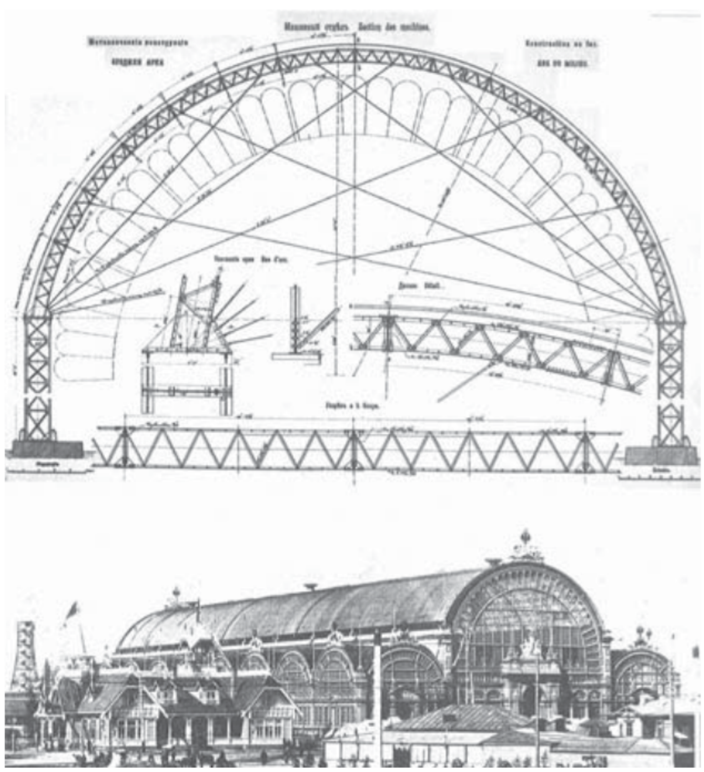

Figure 2.4: Shukhov, Machine Hall, Nizhni-Novgorod, 1896

Lightweighting

"Lightweighting" - the practice of reducing a structure's weight while maintaining its rigidity - is used extensively in the construction of bridges and other large spanning truss structures because, as well as reducing the amount of material used in a spanning member, reducing its self weight increases the spans that are possible.[4] There are several ways in which material can be reduced in a structure without reducing its overall strength. Some standard methods commonly used are: hollow parts, ribs, trusses, thin walls, posts, spot reinforcement, corrugation and gussets. All of these give strength where it is needed without adding more weight than is necessary. Specifically in large spans, keeping the weight of the structure to its absolute minimum is essential as self weight of any structure is a large portion of what the structure must support. Significant examples of such designs can be seen in the work of Vladimir Shukhov, and particularly in the research of Robert Le Ricolais.

In Vladimir Shukhov's work, large spanning structures with extreme amounts of glazing allow light to flood the building's interior; an amazing engineering marvel.[5] Shukhov pioneered the grid frame hyperboloid structure. Long segments of steel are woven together to create incredible, elegant structures which are extremely strong through their linking process, like in the Shukhov Tower shown in Figure 2.5.[6] His long spanning truss structures, reinforced by a fine tension member system running through the interior concavity of the arch structure, interest me. He is able to increase the strength of his truss system by reducing the lateral thrusting forces while adding only a very small amount of extra material weight. An example of such a structure can be seen in Figure 2.6 - his Machine hall, built in 1896. Shukhov's structures promote natural light while reducing the material requirements of a large span structure, resulting in a similar environment to the structures proposed in this thesis.

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[4] Autodesk sustainability workshop, Sustainable Product Design Strategy, "Lightweighting". published 2011, internet source: http://academy.autodesk.com/library/sustainable-products'

[5] English, Elizabeth. Arkitektura Mnimosti: The origins of soviet avant-garde rationalist architecture in the Russian mystical-philosophical and mathematical intellectual tradition. PhD Dissertation, University of Pennsylvania, 2000

[6] Silver, Pete, Will McLean, Peter Evans. "Structural Engineering for Architects: A Handbook." Laurence King Publishing Ltd, London. 2013. Print. pp. 122-23

The work of Robert Le Ricolais is an inspiration to my research. Focusing on lightweight and reduction, he used tensile components to achieve incredible theoretical experiments. It is interesting to note that my experiments in the search for a greater strength to weight ratio have led me down a similar path.

Le Ricolais' investigations began with experimental space frame construction at a time when this was at the cutting edge of technology in the building industry, a venture which he himself acknowledged could consume an entire lifetime with simple variation in scale and application. He redirected his work to a more theoretical practice, an experimental approach in how to make structures lighter and function with less material. His designs remain so extreme in terms of reduction that very few of his experiments have been applied in common building practice.[7]

Le Ricolais used physical models in order to feel the strains on the structures themselves, a technique that is as effective today as it was during the time of his research. Physical models that can be tested and examined give a greater understanding of the materials' tactile nature and materials' behaviour when failure occurs as seen in Figure 2.5.[8]

The tension research undertaken by Le Ricolais led to his investigation of tensioned tube structures, allowing for open flow through the core of the structure. An example of these designs is for a proposed sky rail, which was destined to revolutionize the transportation system of a modern city. This idea of a rope like tensile structure shows his understanding of the potential benefits to using tension in a structural system for optimization Figure 2.6 shows one of these experimental structures. Compression rings throughout a balanced web of cable allowed for this system to be stable possibility. Multiple variations and similar systems were attempted; however, the original concept of the woven cable to span long distances remained a common thread in his research.

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[7] In fact much of Le Ricolais' work remains largely unpublished and is currently accessible only through the architectural archives at the University of Pennsylvania. Interestingly enough, the site of the archives is the former location of Robert Le Ricolais' research workshop.

[8] A perspective on the merits of working with one's hands as a tool for problem solving can be found in Matthew B. Crawford's book "Shop Class as Soulcraft: An Inquiry into the Value of Work." Penguin Books, 2010. Print.

Figure 2.5: An Example of a Physical Model being Tested, Le Ricolais.

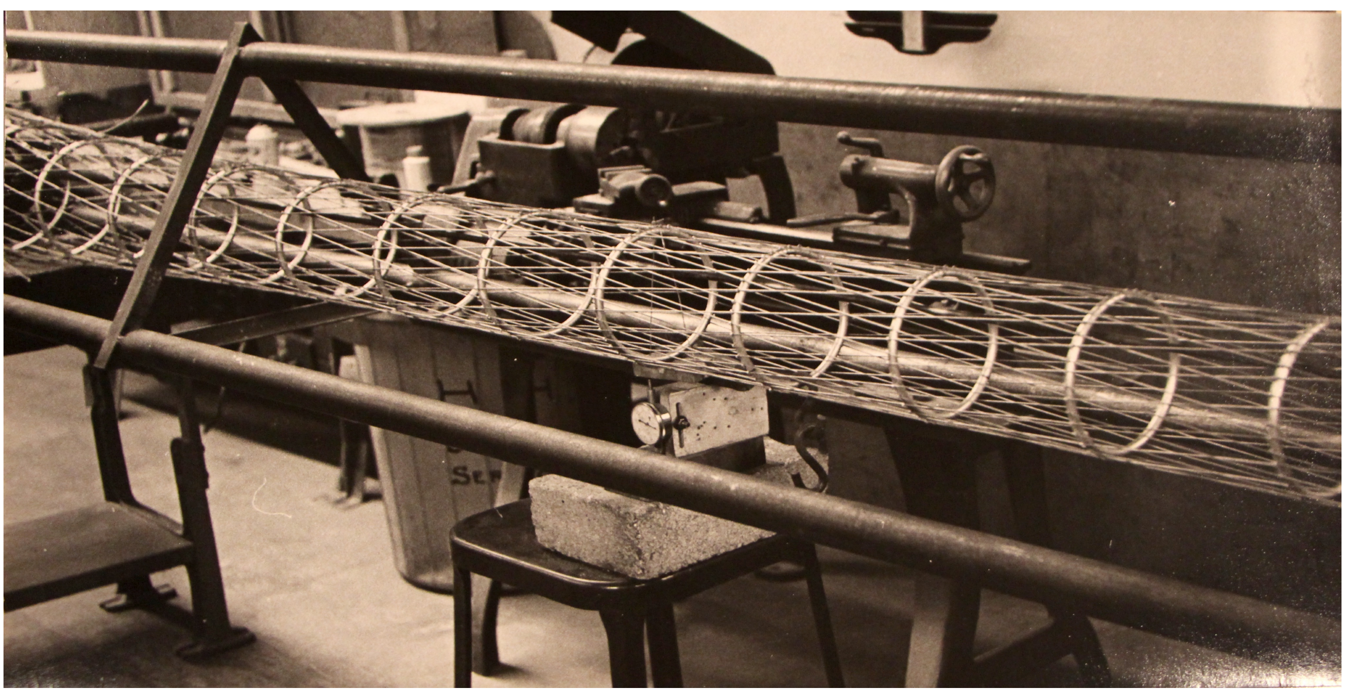

Figure 2.6: Catenary System With Web Under Tension, Le Ricolais.

Robert Le Ricolais used a combination of rigid strut compression members with tension components to create woven structures. Figure 2.7, shows two examples of his compression member designs. The relationship between opposing forces is seen throughout his work, as both space frame trusses and compression struts are made in the most minimal fashion but are capable of withstanding extreme loads. As he explained:

> "...if the member is an arch of parabolic shape following the thrust line of the loads, the bending moments within the member will be reduced to zero and the loads, when transferred to the ground, will produce only compressive forces in the arch."... "By decreasing the bending moments at the center of the network it becomes possible to increase the span."[9]

Robert Le Ricolais undertook parallel experiments concerning compression members to withstand extreme tension. As mentioned, his focus was on the creation of hollow braided nets held apart with compression rings placed within the cable. The tension was then held in place by anchors. The anchors in his tests were often not present in terms of earth anchors and, as a result, compression struts were often used in different locations to hold the necessary tension strand systems taut, as can be seen in Figure 2.8. The compression strut through the centre is only there to resist the force of the tension and is not being reinforced in any way.

[9] Le Ricolais, Robert. in English [PE I-4]; "Grids and Space Frames: An Investigation on Structures." *Dimensions* [publication of the College of Architecture and Design, University of Michigan] v.3 no.2 (Fall 1959): p. 7. Viewed in the architectural archives, University of Pennsylvania, document PE 1-4.

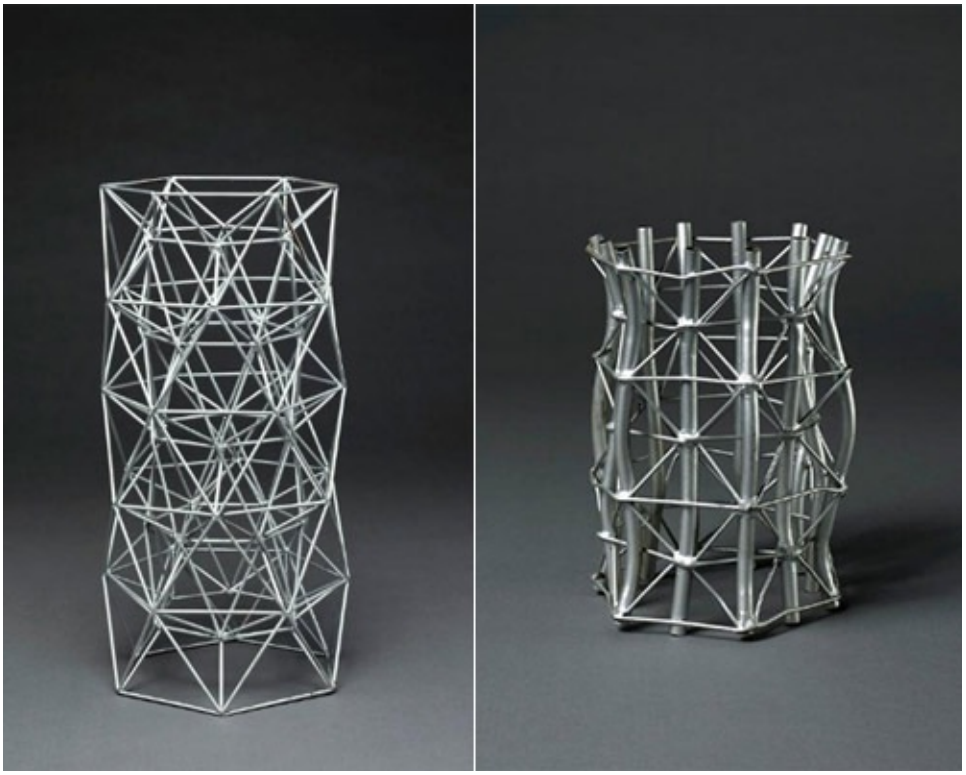

Figure 2.7: Automorphic Compression Member & Automorphic Tube Model, Le Ricolais

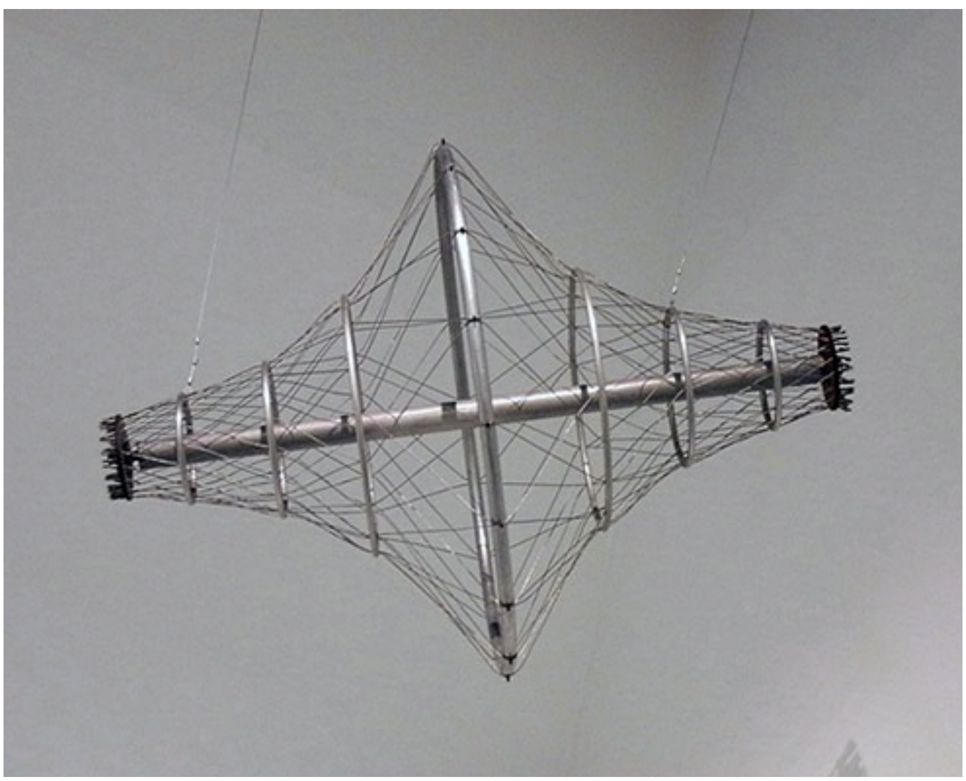

Figure 2.8: Funicular Polygon of Revolution Pseudosphere , Le Ricolais

These experiments generate some incredible shapes both in the cable and in the compression segments. The stabilizers are of particular interest to me because a compression language emerges from the necessary resistance to tension forces through the core. In Figure 2.9, the compression core is in direct contact with the compression rings, creating a shared loading situation. This connection strengthens the bending resistance of the compression core by distributing the forces throughout. Whether or not the abilities of this strut in compression were the goal of the experiment is unclear.

In Figure 2.10, the purpose of the model was to illustrate the concept of the empty core within the tension braid. The core was left completely open, while the compression forces were moved to the exterior of the tube. Connecting the curved compression members in the middle with spacing segments further resists the outward thrusting force created by the tensioned cable core. The concept of controlling the compression forces through bent members was a non-essential part of this experiment for Le Ricolais, but a critical observation for my own studies. The bands that hold the middle from bowing make the members function like a truss, breaking up the segment into smaller parts and exponentially increasing their resistance to deflection.

The use of king and queen post reinforcement is extremely common in Le Ricolais' work. In both Figure 2.11 and 2.12, examples of each can be seen. The idea of inserting one or more bridges is interesting here as it can be observed that he was experimenting with how best to support the compression member without adding excessive additional weight to the overall system.

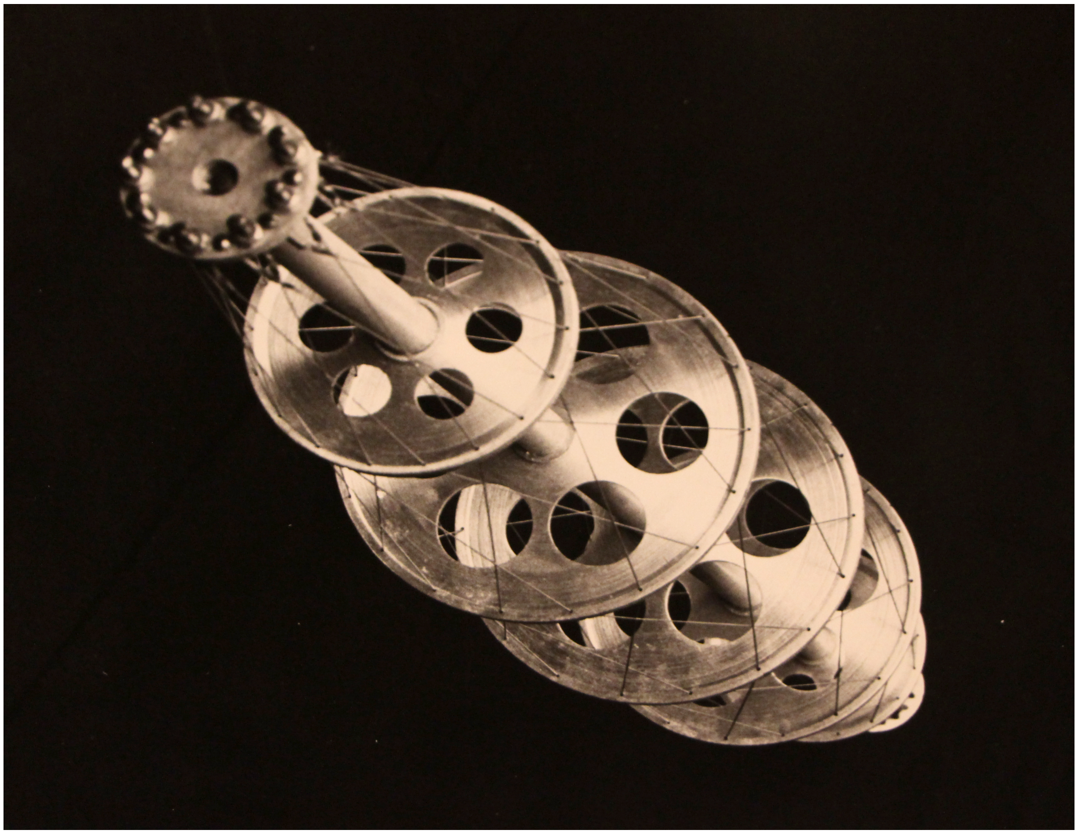

Figure 2.9: Funicular Polygon of Revolution, Lemniscate B; model, Le Ricolais.

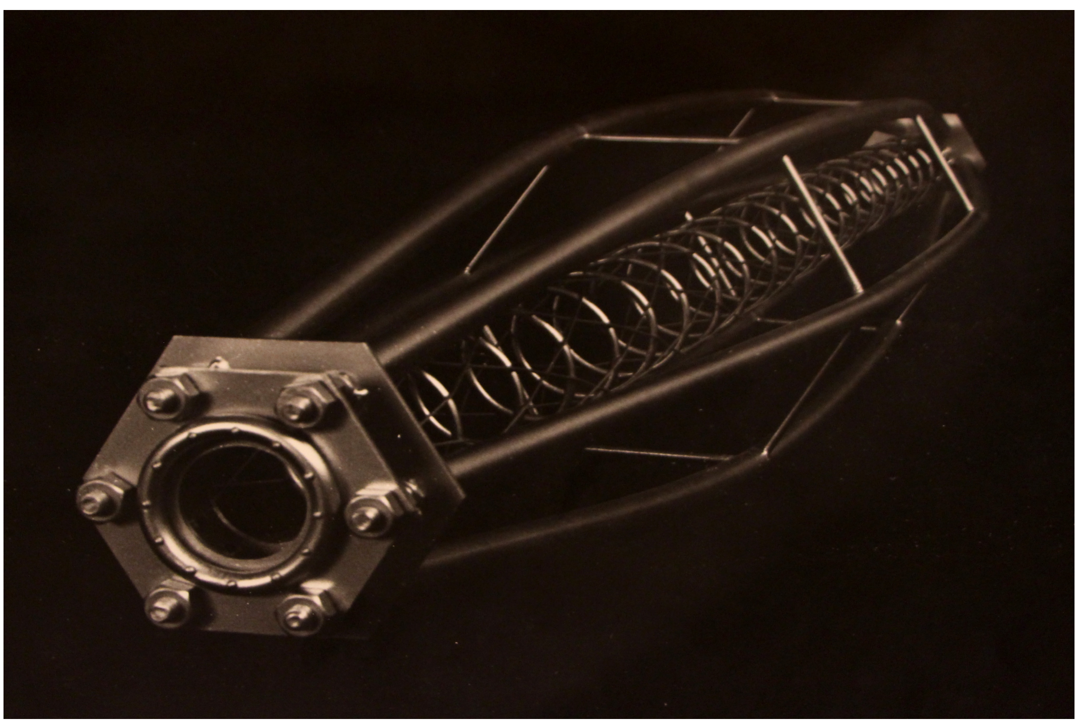

Figure 2.10: Aleph Bridge I, Tension Net Tube; model, Le Ricolais.

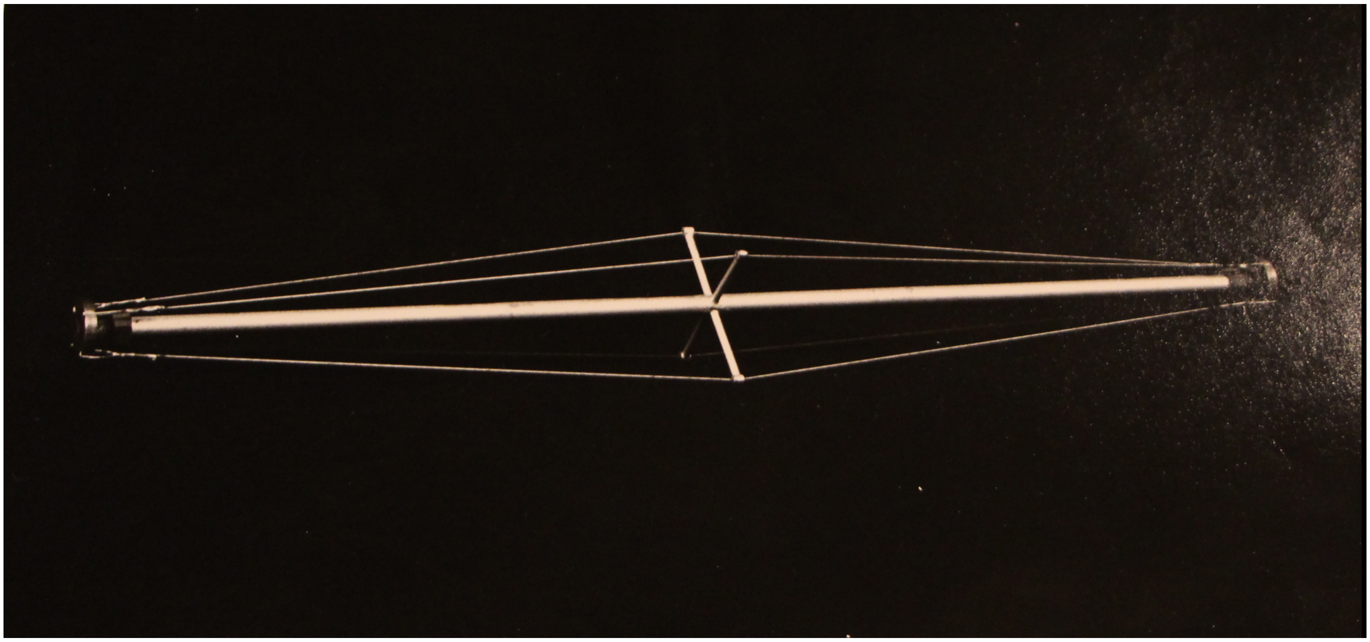

Figure 2.11: Spatial King Post; model, Le Ricolais

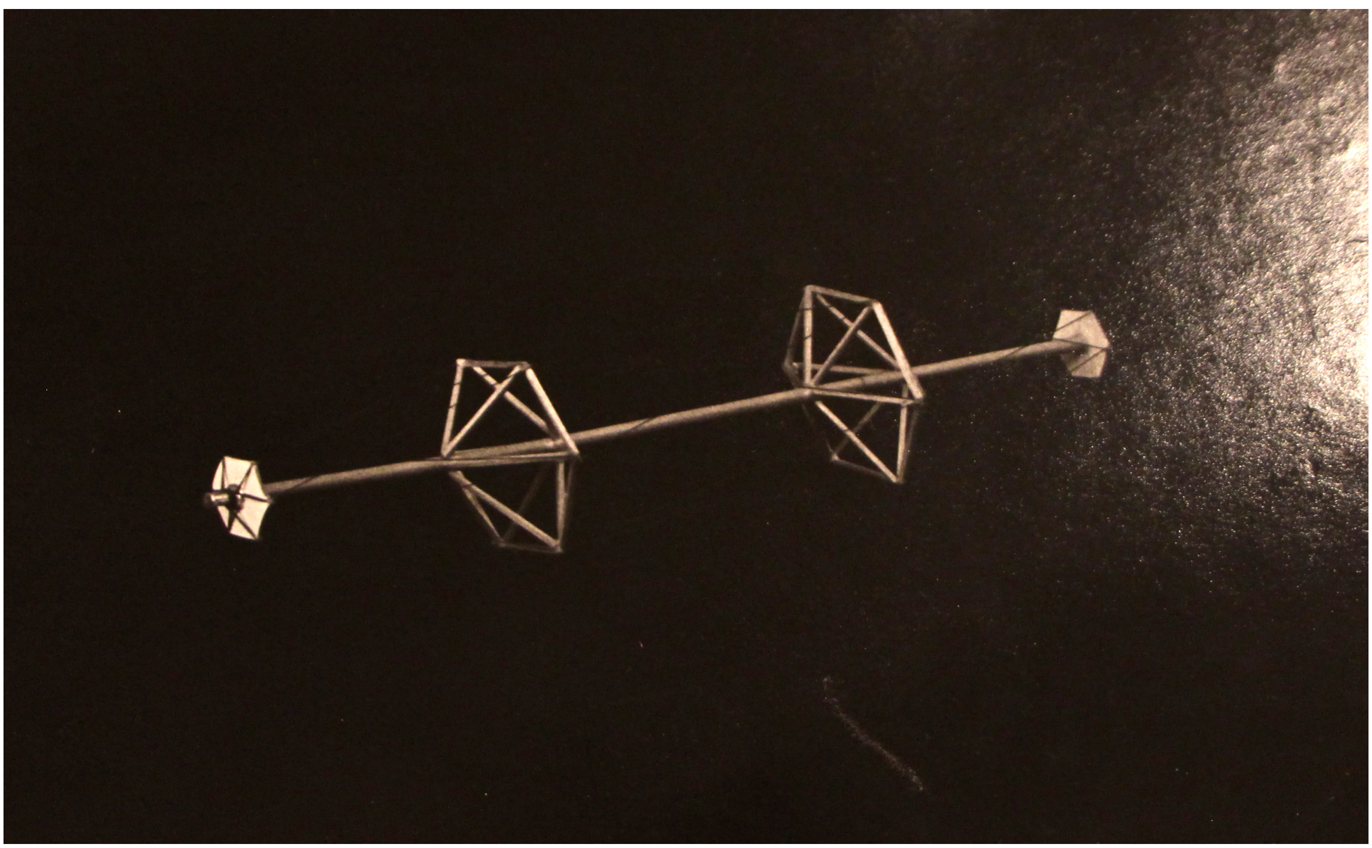

Figure 2.12: Spatial Queen Post; model, Le Ricolais

Complexity

As structures become more advanced, the need for controlled factory environments and the concepts of rapid construction and prefabrication become essential. In this way a complicated detail or construction part can be made quickly and easily with a low margin of error and inaccuracy.

Konrad Wachsmann was one of the pioneers of prefabricated details for construction processes. The details proposed in his prefabricated structures were often very complicated to fabricate but made the on site building process quick and effective. Wachsmann's designs commonly used wood as the connection material, especially in his earlier works. Wood is an economic building material as well as having a low environmental impact since it turns back into compost at the end of its lifecycle. In such details, Wachsmann was able to transform wooden components into a series of puzzle-like assemblies which fit together in order to link structural walls, ceilings and floors which he called a "packaged house system"[10]. His design of complex assemblies included space frame designs as well as structures which do not rely on joints for connections but have components woven directly into one another, locking into place as seen in his Study of Dynamic Structure, Figure 2.13. Although purely theoretical, this explorations into woven components and details of connections create extremely interesting forms which may have an application with current advancements in construction technologies.

Through the use of CNC technology and 3D printers, rapid prototyping as well as rapid fabrication of finished components are possible.[11] Packed and deployable dwellings can be economically viable, even if made with complicated components as can be seen in figure 2.14 showing an assembly detail for a space frame joint. The concept of perfectly formed parts that fit together in a simple way is an extreme advantage and the labour involved in complicated part fabrication is no longer a deterrent. The benefits of prefabrication are seen in today's housing stock where

[10] Broadhurst, Ron. "Home Delivery: Fabricating the Modern Dwelling" The Museum of Modern Art, New York, N.Y., 2008. Print. pp. 80-85

[11] Lipson, Hod, Melba Kurman. "Fabricated: The New World of 3D Printing." John Wiley & Sons Inc., Indianapolis, Indiana, 2013. Print.

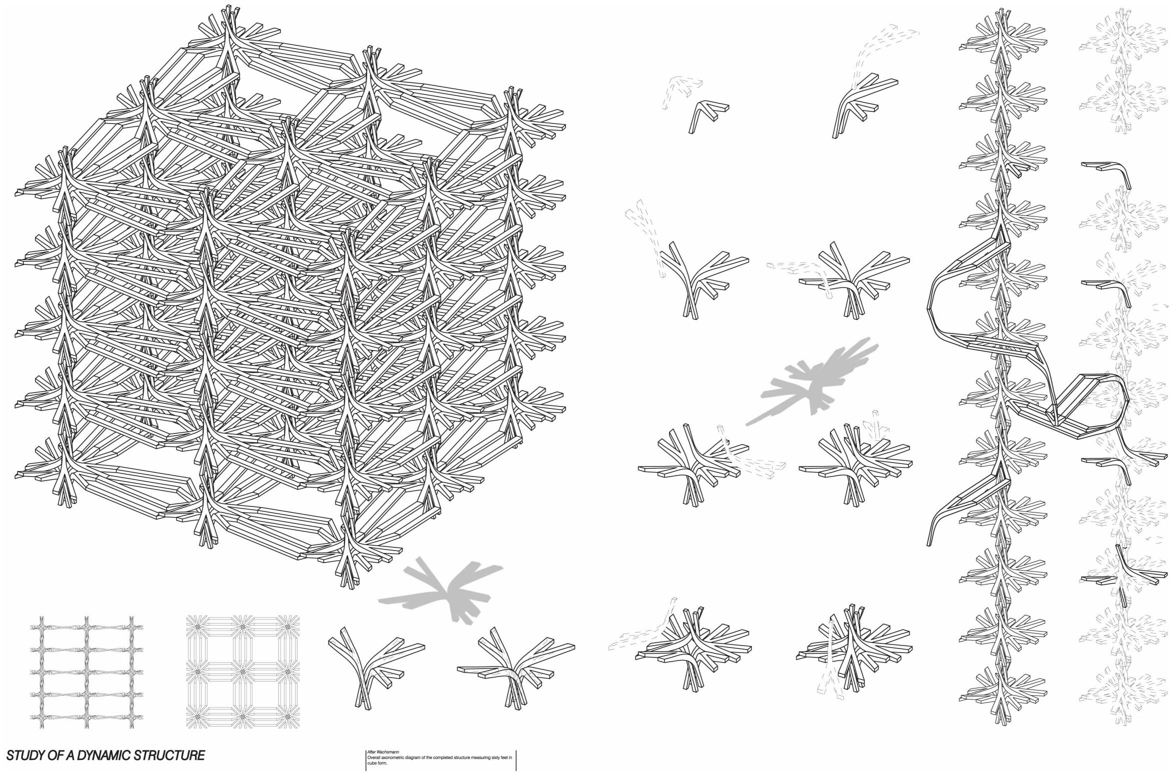

Figure 2.13: Study of Dynamic Structure, Wachsmann, 1953

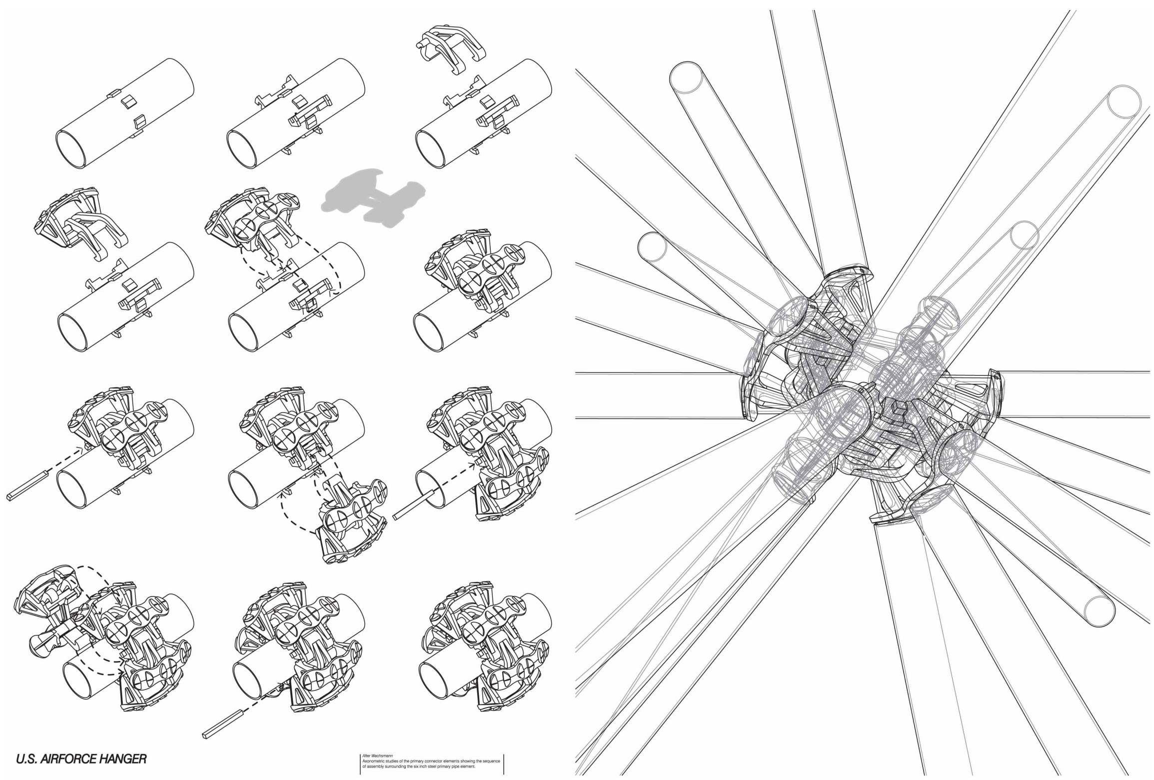

Figure 2.14:Us Airforce Hanger Detail, Wachsmann, 1950-53

entire homes are built in factories and then stitched together on site, making for very efficient and very time effective building units.[12] There is less time wasted with costly on site work and a home can be ordered and built in a fraction of the time that it used to take for a similar house to be completely built on site. The potential for fully deployable dwellings is there, allowing for multiple scales and needs in terms of building requirements.

In many of the preceding examples the pioneers of architectural technologies possess strong engineering capacities as well as the spatial sensitivity of architects. This characteristic leads to an innovative and experimental building which most times has not been attempted in the past. One of the most notable engineers who was responsible for many complex structures is Peter Rice. His work has contributed some spectacular construction feats to the industry. It is said that

> "He believed the best buildings result from the symbiotic relationship between the architect and the engineer where the engineer is the objective inventor and the architect the creative input."[13]

His work in the advancement of glazed enclosures made structural through the incorporation of tensile reinforcement is what interests me the most. Figure 2.15 shows a tensioning detail assembly. His work shows a strong separation of compression to tension components. There is no sharing of the forces - each component fits its structural requirement. This purity of structural language is an inspiration as it carries with it reduction in material as well as a clear and concise structural solution predicated on absolute necessity. His cable stay glass structure created a system which allows the inside to flow freely into exterior spaces with very minimal structure to obscure the purity of view while still allowing for environmental separation. One of the most powerful examples of this type of glass structure is seen in the pyramid structures of the Louvre, a co-operative endeavour with architect I. M. Pei and the engineering firm Nicolet Chartrand Knoll Ltd., completed in 1989 (Figure 2.16).

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12 "Landmark Homes" (www.landmarkgroup.ca) is an example of this type of construction approach and is the largest house manufacturing plant in Canada (Edmonton, Alberta).

13 Brown, Andre. "The Engineer's Contribution to Contemporary Architecture: Peter Rice." Thomas Telford Publishing. London, 2001. Print. pp.17-18

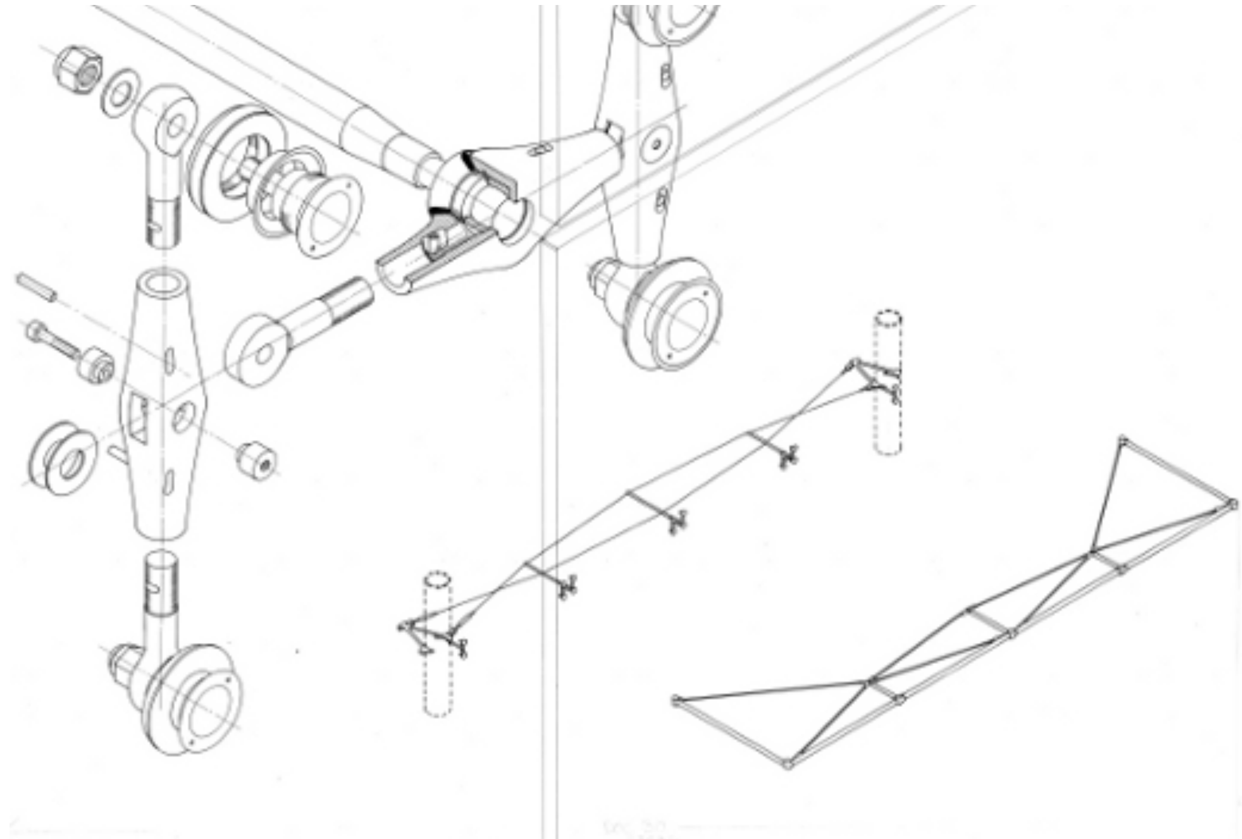


Figure 2.15: Cable Stay Glass Structure, Paris. Peter Rice.

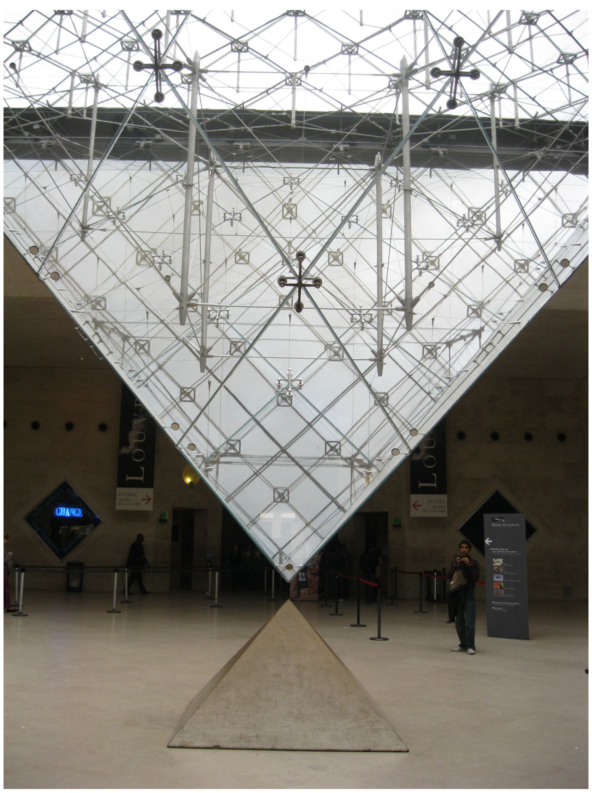


Figure 2.16: Inverted Pyramid at the Louvre, Paris. 1989.

Figure 2.17: Moon Light Theatre, Saint-André-de-Bueges, France. Peter Rice 1992.

Another source of inspiration to me is Rice's ability to combine humble low tech material in a high tech assembly to create projects that can be assembled by local labour using the materials of the region. An example of such a project is his Full Moon Theatre (Le Théâtre de la Pleine Lune), a project where he used the moon to illuminate a stage performance with the light source exclusively reflected from the moon's luminescence as seen in Figure 2.17.[14] This sensitivity allowed the rapid construction required in the project's deadline while maintaining the extremely small budget that this project had at its disposal.

The lack of collaboration between architecture and engineering is too often a barrier to innovation. I feel that buildings conceived and created with the two disciplines working together can achieve a successful balance of form and function in a project, and I have a great respect for structures that are designed in this way.

14 "Traces of Peter Rice". An Arup Film. 2012.

Stable Shapes

Through the understanding of geometry it is possible to manipulate shapes so that components rely on tension instead of compression forces. Triangulation of members creates extremely stable structures, while reducing the overall amount of weight added. It is useful to look at stable shapes like platonic solids, defined as: forms that share the same shaped faces which meet each other at a common vertex to make a solid. There are five solids that fit this criteria: tetrahedron, cube, octahedron, dodecahedron and icosahedron[15]. These shapes make extremely strong units that connect together well, allowing for repositioning and patterning, and are ideal for the construction of space frames and domes.

Robert Le Ricolais devoted much of his research to exploring the use of various shapes in his model designs. Figures 2.18-21 show models using the octahedron, with 12 rigid components making the unit's shape. Linked units in Figure 2.19 show the potential of connecting compression struts with tensile cables in order to make a grid structure that defines a plane. Whether the cable is used to stabilize a grid or a slender tower structure, as in Figures 2.20-21, the relationship between the tension and compression forces in these examples shows a clear efficiency - a distinct advantage over a standard space frame construction.

Le Ricolais' tetra joint is seen in Figures 2.22-24. Forming a triangular pyramid, this shape connects two perpendicular members together, while creating multiple planes in an assembly. It constitutes a very simple yet elegant way to give a greater volume to a grid, while also gusseting the connection for greater overall stability between its parts. Functioning as a grid, the shape allows curved segments as well as straight segments to be connected easily and quickly. The result is a parabolic shape which can be assembled quickly while not expending huge amounts of material waste/weight on the connection points themselves. Ricolais appreciated this flexibility in design and thereafter incorporated it into the many of his testing experiments. As this joint is a scalable solution, it was able to suit many needs in his prototypes.

15 Fuller. "Synergetics 2: Further Exploration into the Geometry of Thinking." op. cit.

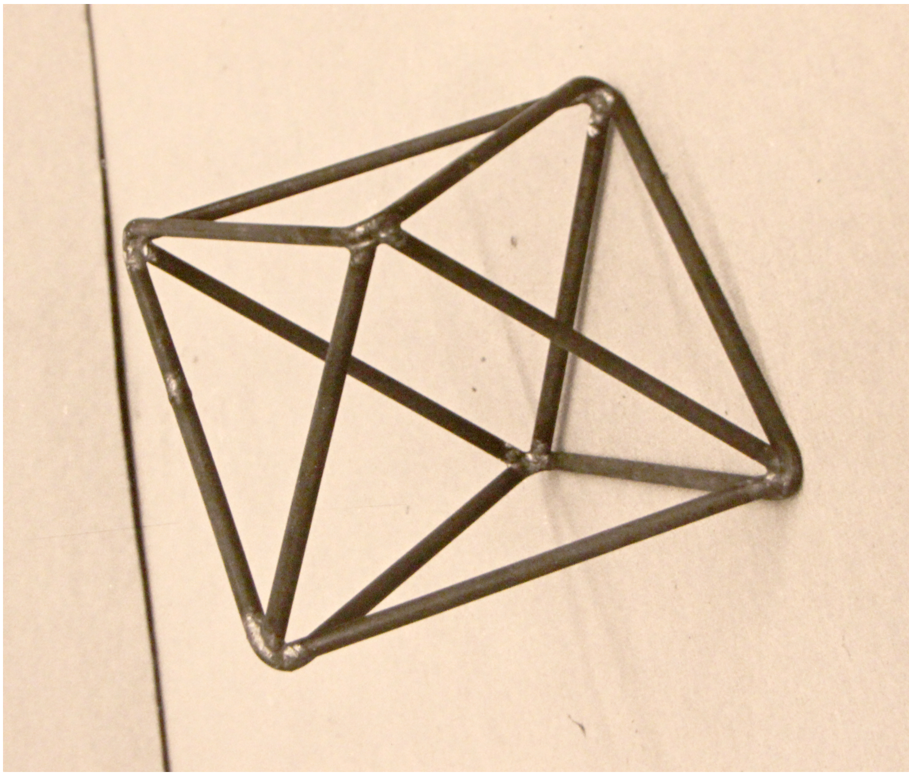


Figure 2.18: Octahedron; model, Le Ricolais

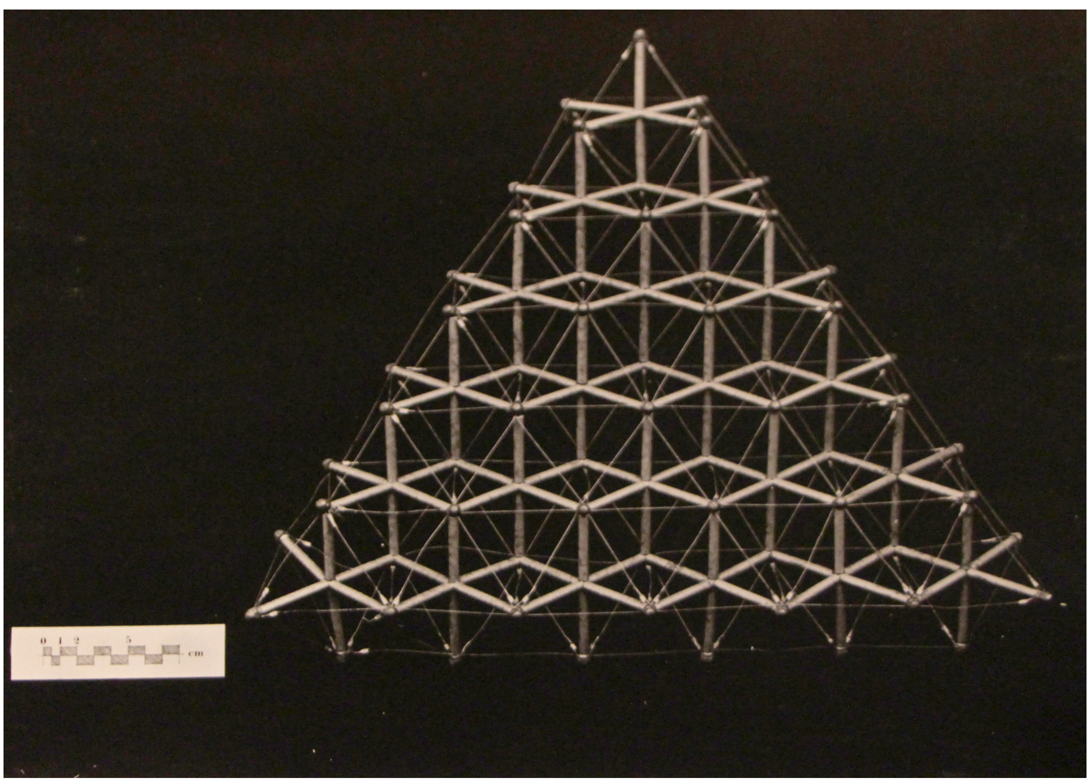
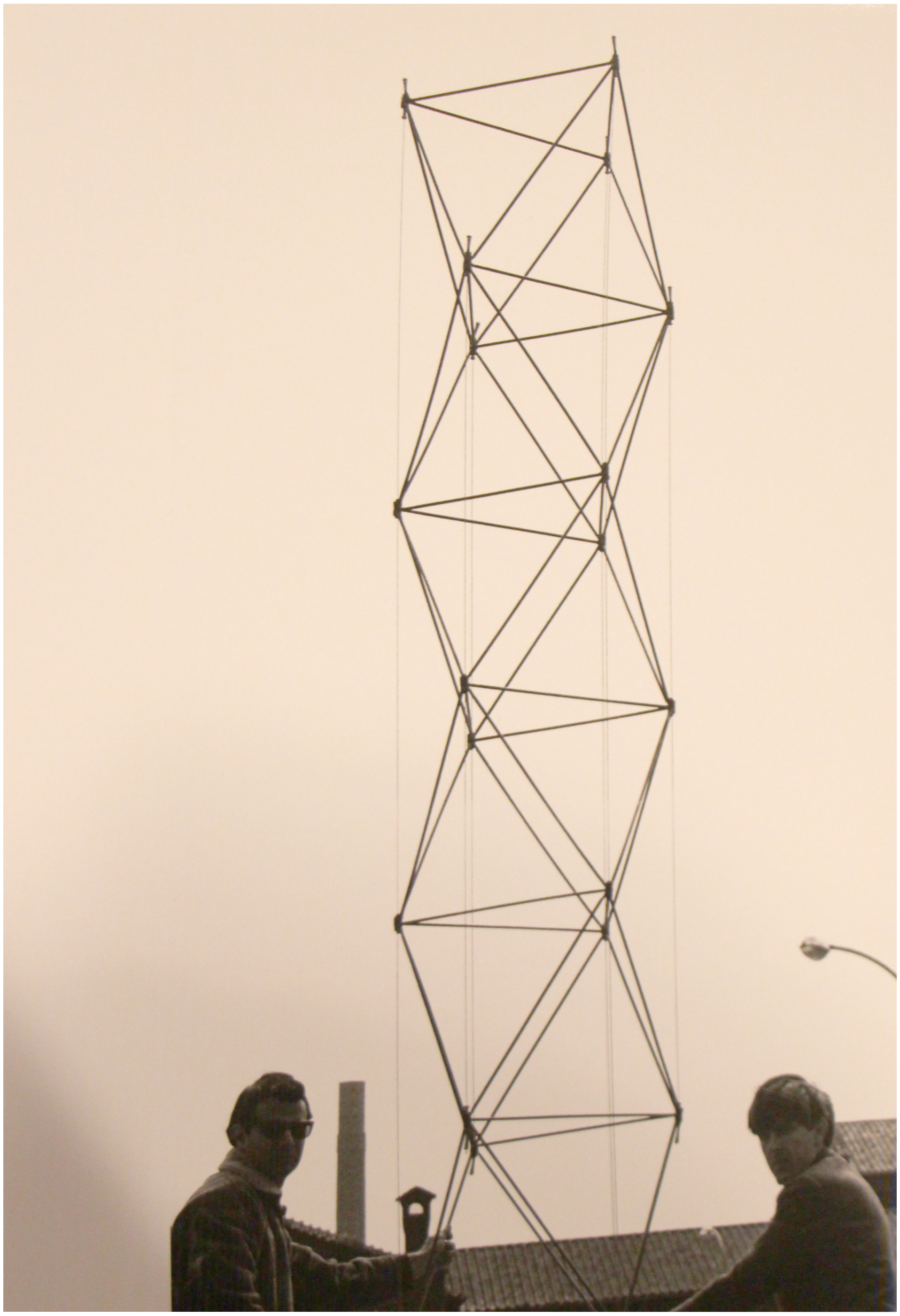
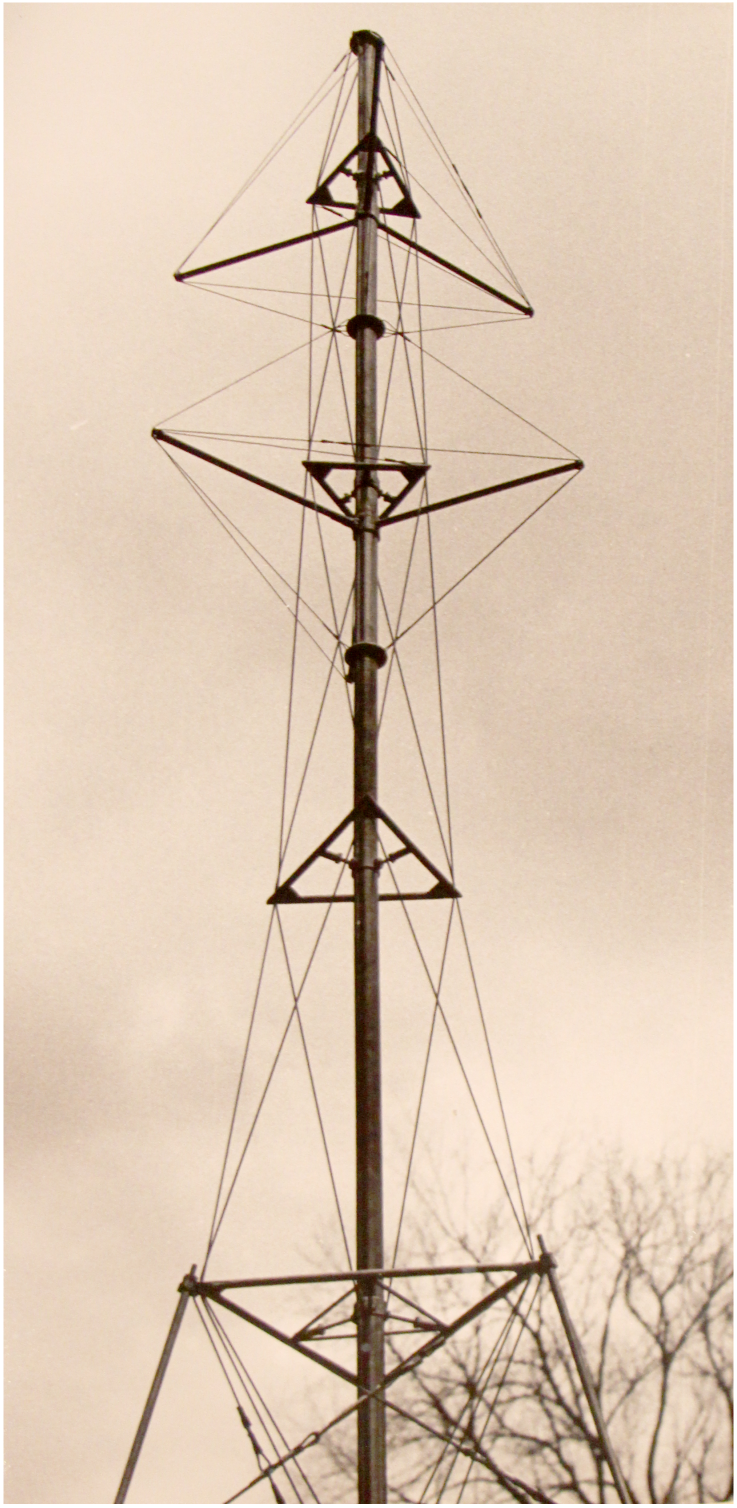


Figure 2.19: Space Frame; model, Le Ricolais.

Figure 2.20: Octen Antenna, 54' tall; model, Le Ricolais





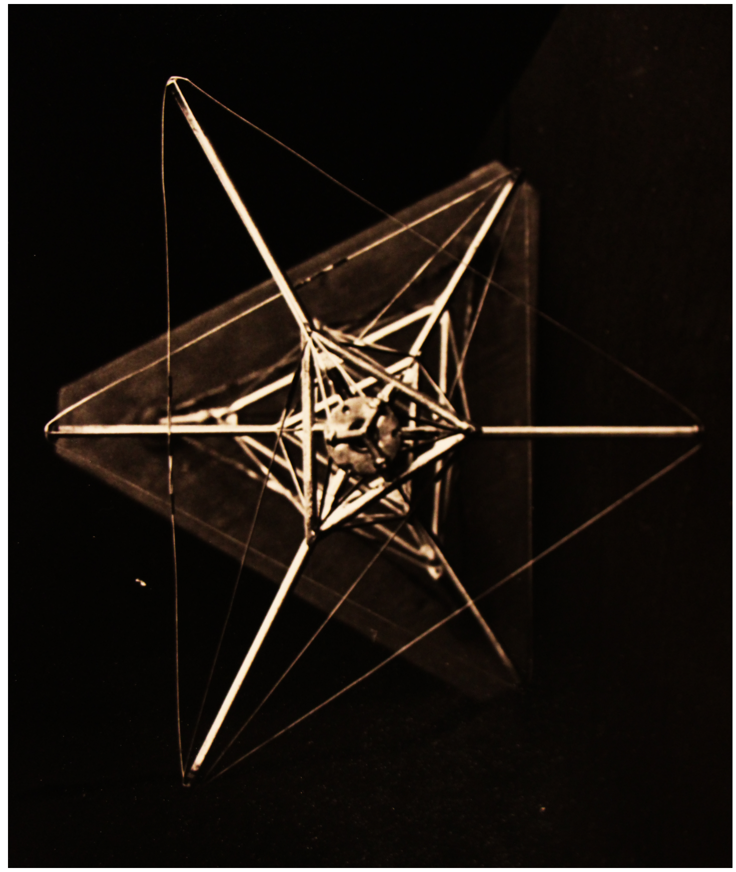


Figure 2.21: Pretensioned Transmission Tower; Model #3, Le Ricolais.

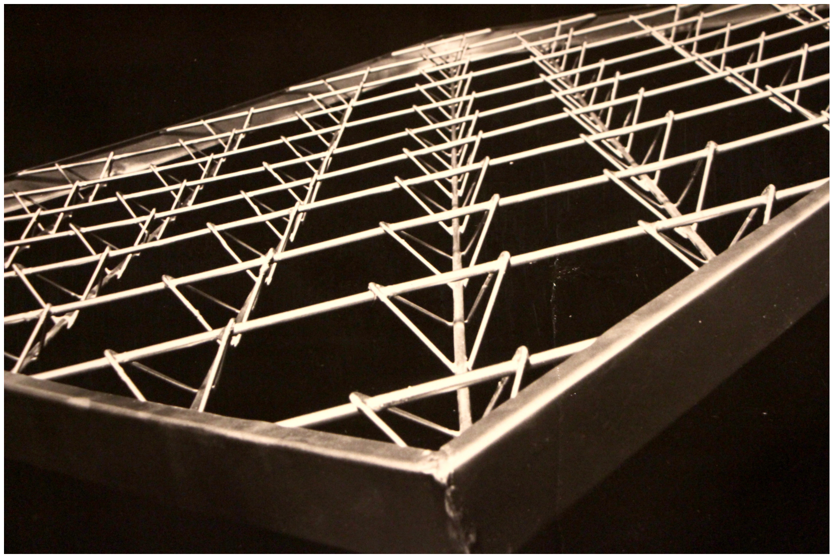


Figure 2.22: Diagonal Tetragrid Panel. Le Ricolais.

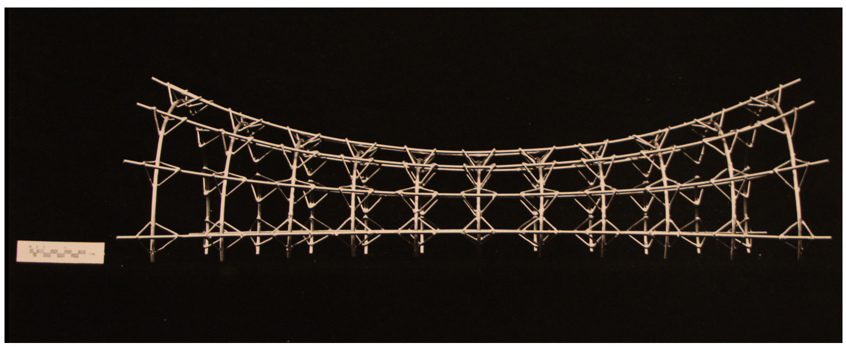


Figure 2.23: Tetragrid Circular Hyperboloid. Le Ricolais.

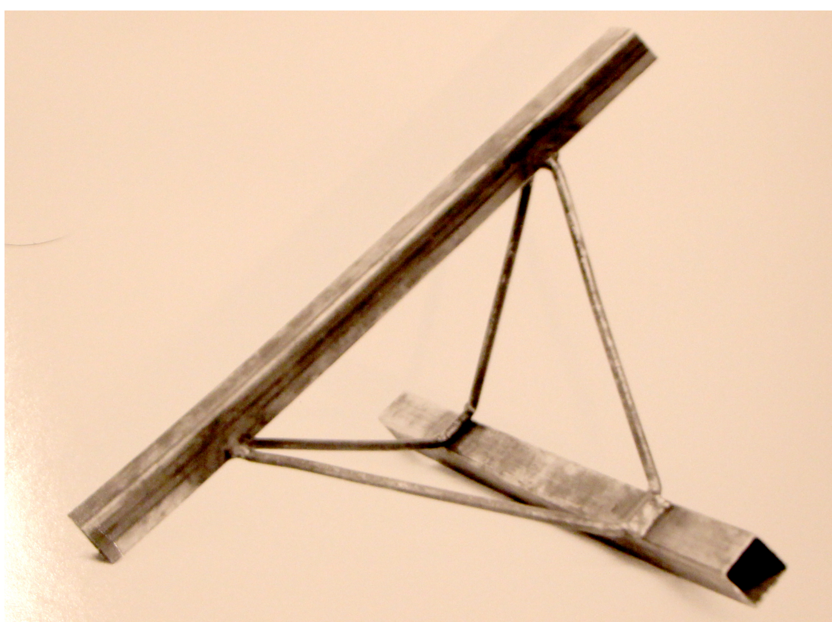


Figure 2.24: Tetra Joint, detail. Le Ricolais.

Buckminister Fuller favoured several platonic solid shapes in creating his lightweight domes and structures. Fuller was concerned with the consumption of resources and created a language of architecture in an attempt to correct the overuse of materials. His technologies include domes, where he relies on a geometric pattern of rigid components, creating spherical architecture that uses very little material relative to the volume that it encloses. An example of this structural system is the American pavilion at Expo '67 in Montreal, Figure 2.25.

Fuller was an inventor, engineer and architect responsible for many ground breaking ideas, all of which were intended to assist humanity with consumption tendencies, a concern which was as important then as it is today. His idea of a utopian human existence led to the conception of some extremely unique designs, including his Dymaxion House and Car, Figure 2.26. These inventions outperformed existing forms of dwellings and transportation[16]. Never accepted into the mainstream as a responsible alternative to convention, these experiments were too ahead of their time but extraordinary in their performance. Fuller's research into lightweight, transportable, and deployable compact dwellings constitutes a significant inspiration in this thesis work. His work represents similar goals for a sustainable future and illustrates how designers must take responsibility in assuring quality of life for generations to come.

Fuller was also interested in a structural language he called "tensegrity", where compression struts are held apart from each other using tension to make a self supporting structure.[17] He created tensile integrity structures by maximizing tension components. The design of his tensegrity mast, later applied to a dome arrangement called a tensegrity ball, used both compression struts and cables supporting each other in order to make rigid structures where there was not direct contact between the struts, making the structure held together with tension. (Figure 2.27)

[16] Fuller, R. Buckminster. "Utopia or Oblivion: the Prospects for Humanity." The Overlook Press, New York, 1969. Print.

[17] Fuller. "Synergetics 2: Further Exploration into the Geometry of Thinking." op cit. p. 165-76

Figure 2.25: Expo' 67, American pavilion. Fuller.

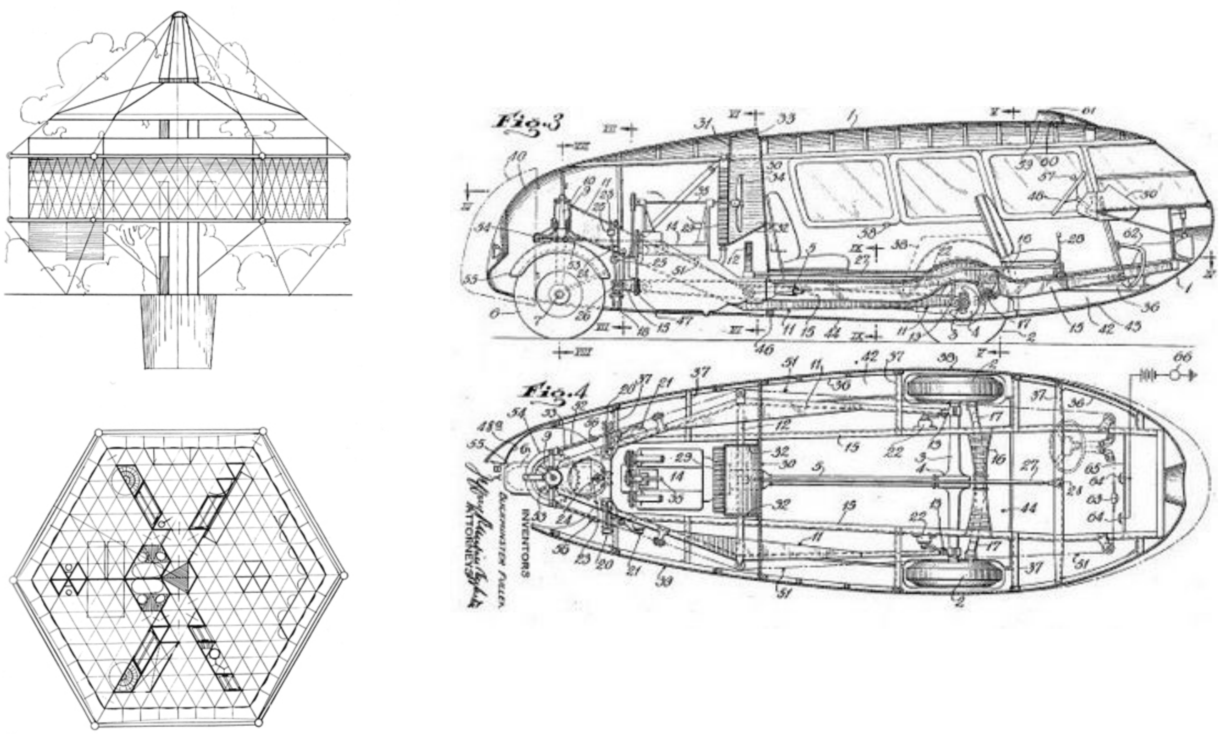


Figure 2.26: Dymaxion Car and House. Fuller, 1930-33

Similarly to Fuller, Kenneth Snelson used the relationship of tension to compression, but in a very different application. He was responsible for the first tensegrity experiments utilizing these structures for art installations, allowing rigid structures to be more playful and asymmetric.[18] His approach permits one to be less concerned with the space that is occupied within the structure, as it is the illusion of floating components that makes his pieces awe-inspiring. An example of one of these installations is his 1970 Easy-K project, Figure 2.28, which sparked the creation of multiple versions of this tensile expression. Snelson's work embodies the freedom and dynamic motion that only tension structures can offer but it is limited to art explorations. He does not explore the requirements of a building, in that no shelter is provided in any of his structures.

A building implies an enclosed space for shelter from the elements, that can be inhabited and experienced internally. This enclosed space does not necessarily need to be designed for human occupation, as Cedric Price illustrated through his use of tensioned components in the London Zoo Aviary in 1961, Figure 2.29. His structure combines large triangular forms with fixed masts to create the appearance of floating volumes. The triangles are hung off the masts and fixed to the ground, making a structure for a netting to be draped over. The effect is breathtaking and reflects the beauty of the airborne nature of the birds within its enclosure. The angular fabric is held in place by attaching it to the tensile cables, creating an almost origami quality to the building. The thin fabric keeps the birds contained but also creates an illusion of freedom as the natural sky is fully viewable, reducing the more confined feeling of traditionally roofed buildings. Using tensioned fabric as a structural component in a building allows for an elegant, light weight structure which encloses large spaces and uses much less material since the weight of the fabric and wind/snow loads is all that must be held up instead of truss structures.

18 Silver. op cit. p.156-7

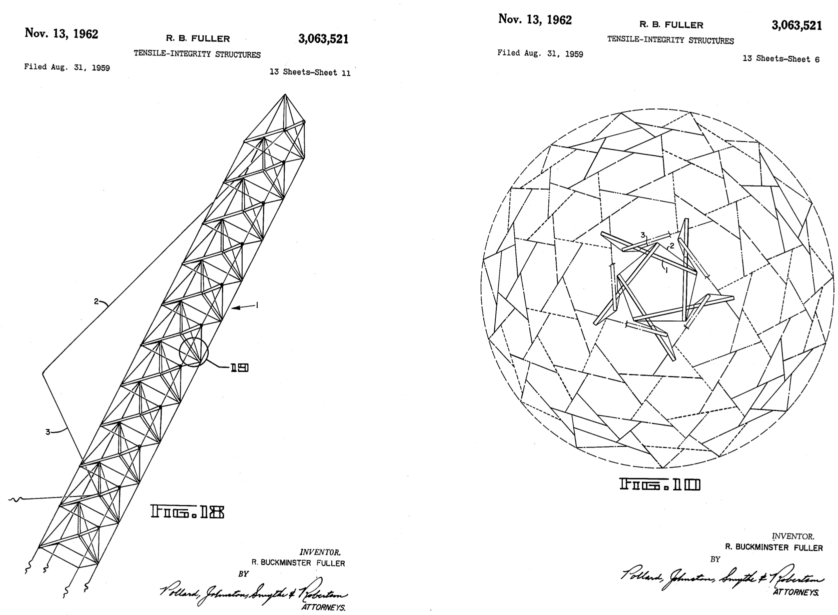


Figure 2.27: Tensile-integrity Structures. Fuller ,1959.

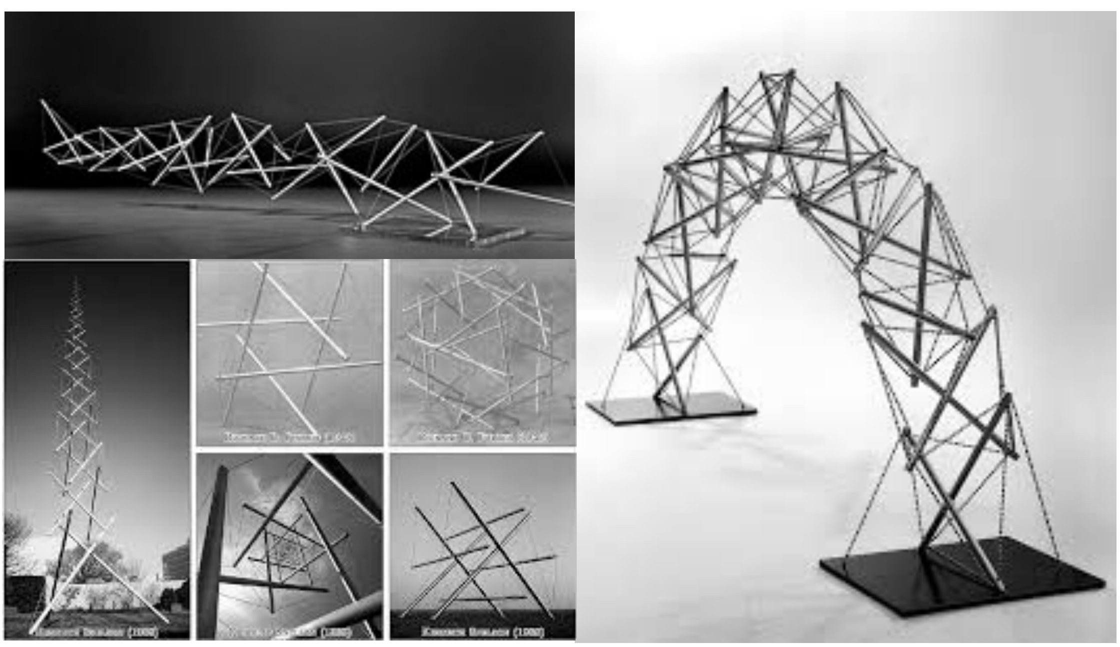


Figure 2.28: Easy-K and other Tensegrity Projects. Snelson,1970.

Best known for his soaring tent-like structures, Frei Otto uses tension forces through parabolic membranes which are capable of spanning entire stadiums, as seen in Figure 2.30, with his Munich Olympic Stadium Roof[19] as well as the German Pavilion at Expo 67. The beauty in his design comes from the seemingly weightless quality of the materials he uses, the roof structures almost float in the breeze. Commonly, reinforced fabrics are custom made to give the structure strength where it needs it but increase lightness overall. More commonly, large compression members are used much like a ship's mast to elevate and suspend the membrane of the structure from post to post. The fabric membrane carries within it a solid tensile cabling system which is stretched between these piers and helps stretch and hold the fabric in place.

Natural shapes such as the bubble create a mimicry of natural and organic forms and increase the overall efficiency of the structural members. Bio Mimicry, inverted gravity forms, spoked tensile members and grid shell methodologies all converge to make Otto's work incredibly breathtaking as well as incredibly efficient in a material consumption sense. His work and research is greatly dispersed between scales including dams and utopia schemes, with a design similar to that of a micro organism. The experimentation of material is astonishing from fabric weaves and steel all the way to precast concrete structures.[20]

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[19] Silver. op. cit., pp. 158-161

[20] Roland, Conrad. "Frei Otto- Spannweiten." Verlag Ullstein GmbH, Frankfurt/ M- Berlin, 1965. Print. German text, however illustration models and photographs thoroughly document the work of Frei Otto.

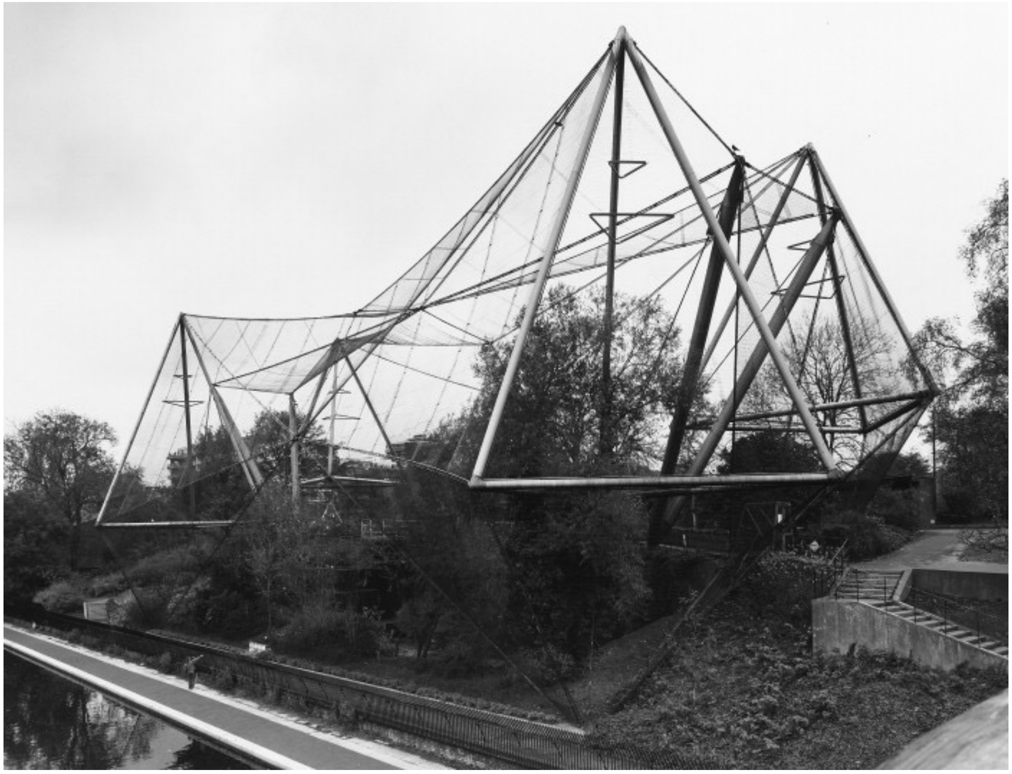


Figure 2.29: London Zoo Aviary. Price, 1961.

Figure 2.30: Left- Casabella. Otto,1966. Center- Munich Olympic Stadium. Otto,1972. Right- German Pavilion, Expo 67. Otto

Nature and Structure

The very essence of the structures discussed can be tied back to nature and the forms that thrive with in it. Optimization of form always carries a function in nature's design. The true essence of the minimal can be seen in the natural world as only the best designed species survive and adapt.[21]

Trees

The structure of a tree is similar in all species - the core or the trunk is anchored to the ground with a root system and the limbs of the tree protrude out from the core to form the tree canopy. Photosynthesis, the process of converting ultra violet light into energy, feeds the tree's growth. The taller the tree, the more light it can absorb - a simple concept but a complicated task. Trees use an advanced system within their structure allowing the same material to resist both tension and compression forces which can change drastically depending on weather conditions.

The core of a tree's structure is composed of ring-like shafts. Sap flows through the rings of the tree and the outer surface covers these moist interior sections with an armour of bark. The ring structure allows the tree to slide inside its structure, and as a result the wind loads are absorbed without the member breaking. This quality is complicated to emulate in the building industry as we lack the expertise to create sliding within a building component. In addition, the general population would not feel comfortable with floors which deflect when walked on, as would likely be the case if we could build such a member. Trees are balanced- even if the load of a tree is off centre, the tree is capable of growing in such a way that the very shape of its members maximize their structural need. When we use trees to make dimensioned lumber after the wood has dried, the strength in these flexible members is reduced greatly, as the layers will no longer slide on one another. Furthermore, the remnants of the natural stresses and inconsistencies in the tree's structure become apparent as lumber commonly has defects such as knots, twisting, cupping, bowing, kinking and crooking, all of which helped balance the tree's load in the original tree structure.

21 Silver. op. cit., pp. 10-21

Spiderwebs

Spider silk is the strongest natural fibre known to man. In tensile applications it is comparable to alloy steel. The material is also remarkable as it can be stretched an additional one third beyond its original length without breaking. The chemical process allows the spider to choose from different material properties, allowing the silk to function in multiple applications.

Spider webs are true tension structures, consisting of rigid anchors to string the webs, crossing to another rigid anchor point. The net structure is triangulated to the centre with radiating cords creating a sequence of thread types, allowing the spider to catch its prey as well as allowing it to walk through the maze of threads without getting entangled. The beauty of the design is that the web is so fine it is invisible to the prey until it is caught in the trap. These qualities of strength and "veiling" efficiency make the spider web a truly masterful piece of natural engineering.

The Human Body

The human body is a wonderful example of how tension and compression forces work together. In our bodies our rigid bone structure is held together with cartilage and soft tissue, allowing joints to move like a pin connection. Our tendons and muscles contract and expand, acting in tension to move the rigid bone structure on these pin connections. The system is not restricted to a single plane of motion but is able to rotate within space, a complex movement that we take for granted. The body itself is a tensegrity structure as the compression members (bones) don't meet in rigid connection but are held apart in space, making the most efficient joint possible.

Small but precise adjustments to the motion of these components allow humans to walk, a motion which is in itself amazing, as we are falling and catching ourselves with every stride. This motion is so complex that recreating it is next to impossible with mechanical processes. Similarly, humans have an amazing ability to move their bodies in the most effective way to counter forces applied; for example, leaning will cause your body to turn in that direction.

The bone structure itself is a marvel as it is made up of multiple densities and textures creating hollow pockets within a solid outer surface. This makes bones strong but also light with the capability to flex without breaking or bending, like a tube structure. Robert Le Ricolais states that the bone structure of a human body is incredibly lightweight for the forces it is able to resist. His observation can be directly applied to building design: “So we arrive at an apparently paradoxical conclusion, that the art of structure is how and where to put holes”.[22] The other incredible aspect of bones is that if they are broken they are able to repair themselves, a process that would be invaluable to the construction industry.

The Honey Comb

Robert Le Ricolais in particular explored the principle of the hexagonal shape found in the natural form of the honeycomb. As mentioned previously, he applauded the singular efficiency found in the construction of the beehive and was greatly inspired by the strategy it could afford when applied to structures. The hexagonal shape can be applied to many scales, which Le Ricolais did when planning a city - from individual houses, to city blocks, to the entire city grid, as seen in Figure 2.31. Once again, optimizing the traffic flow and housing stock units was the reasoning for his geometric reconfiguring of a typical square city block. The hexagon is seen as a single unit, then with several assembled together making a space frame structure in Figures 2.32-33.[23]

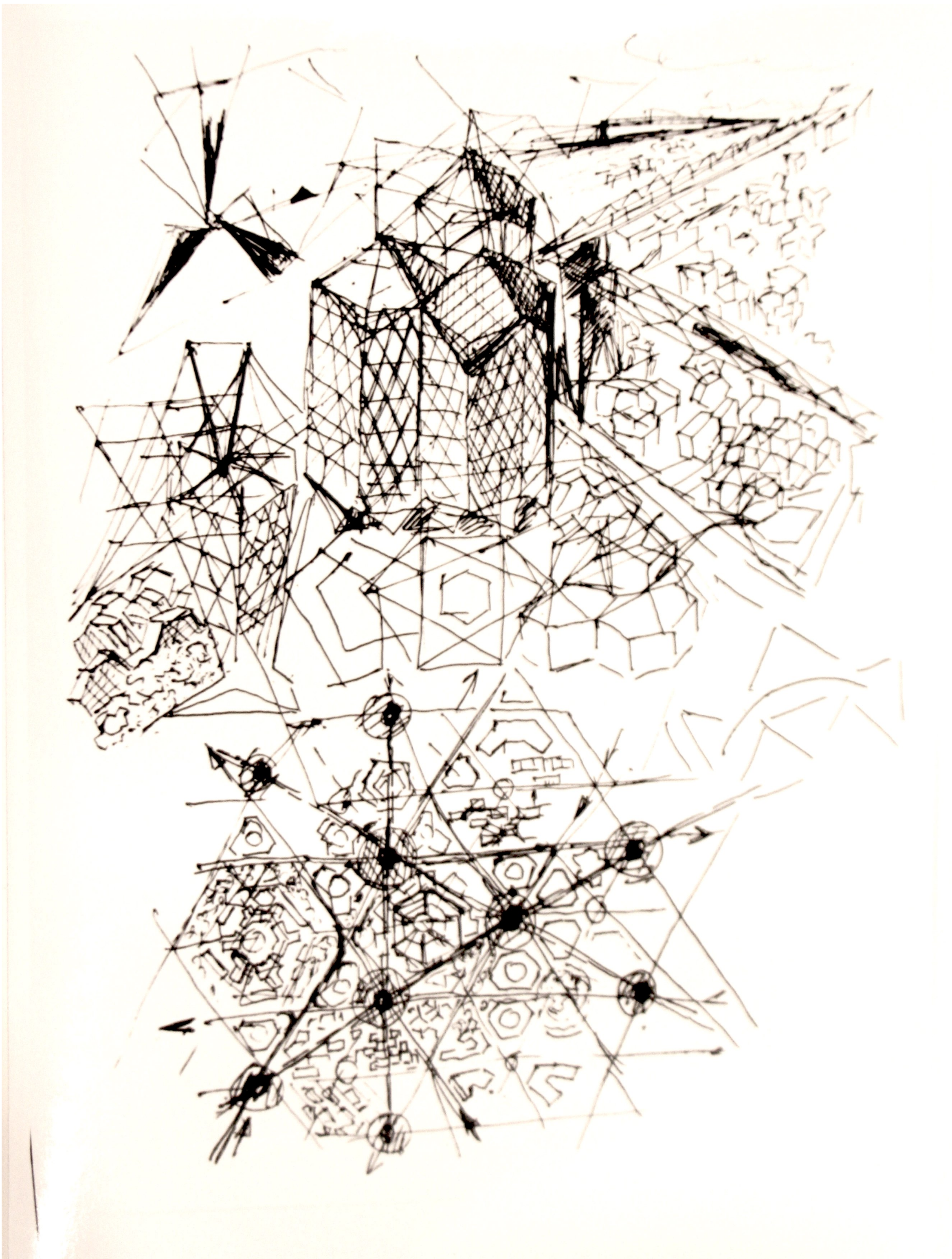
Soap Bubbles

Soap bubbles are incredible structures as they are so light that they can float in midair and yet still enclose space within their structure. This phenomenon works due to the surface tension gained by adding soap to water molecules to strengthen their bond. A soap bubble organizes itself to maximize the volume inside with a minimum surface area, therefore it

22 Le Ricolais, Robert, “Things Themselves are Lying, and So Are Their Images,” VIA 2, ed. James Bryan and Rolf Sauer, 81-109. University of Pennsylvania: Graduate School of Fine Arts, 1973, Print. p. 10

23 Le Ricolais, Robert in English [PE I-11]; “Structural Approach in Hexagonal Planning.” Student Publications of the School of Design, North Carolina State College, Raleigh, N.C. v. 3 no. 3 (Spring 1953): 10-15.

Figure 2.31: Hexagonal City Planning Sketch. Le Ricolais.



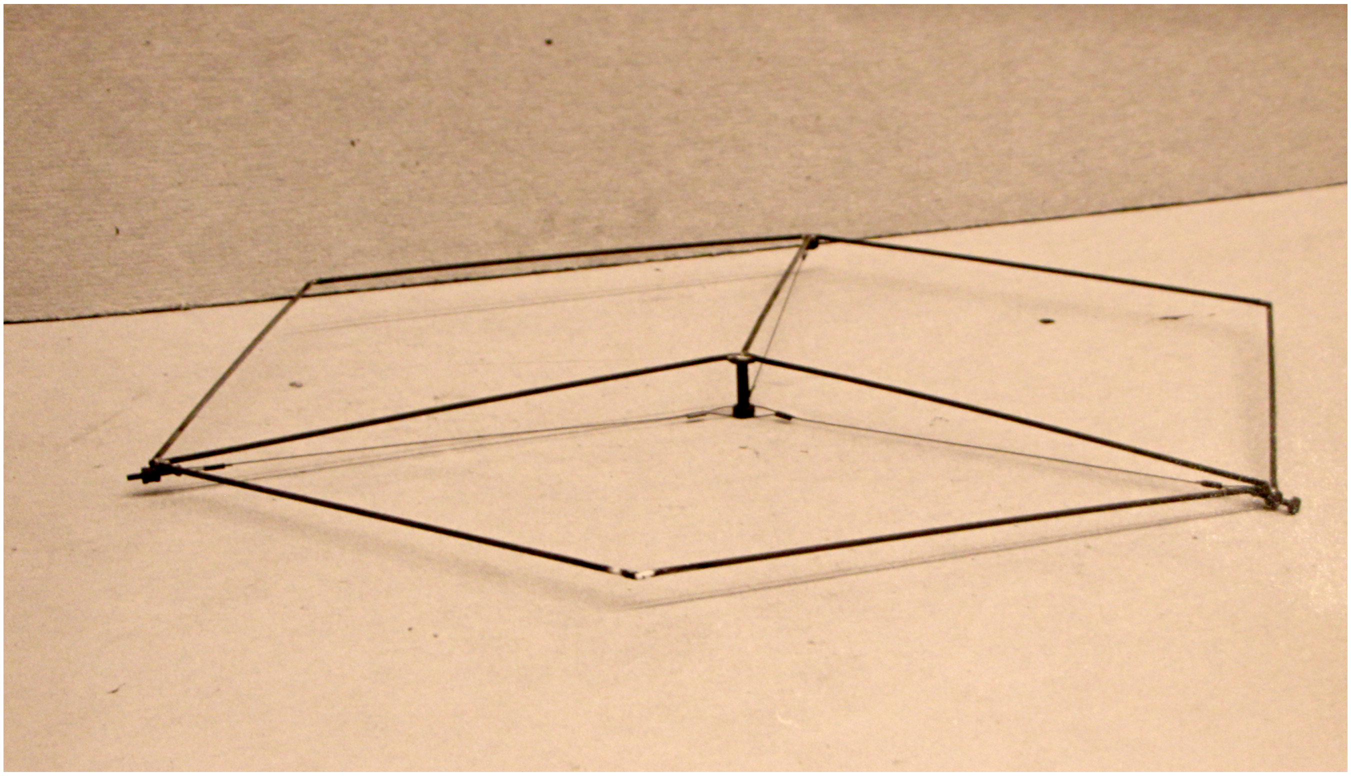


Figure 2.32: Rhombohedral Unit.
Le Ricolais.

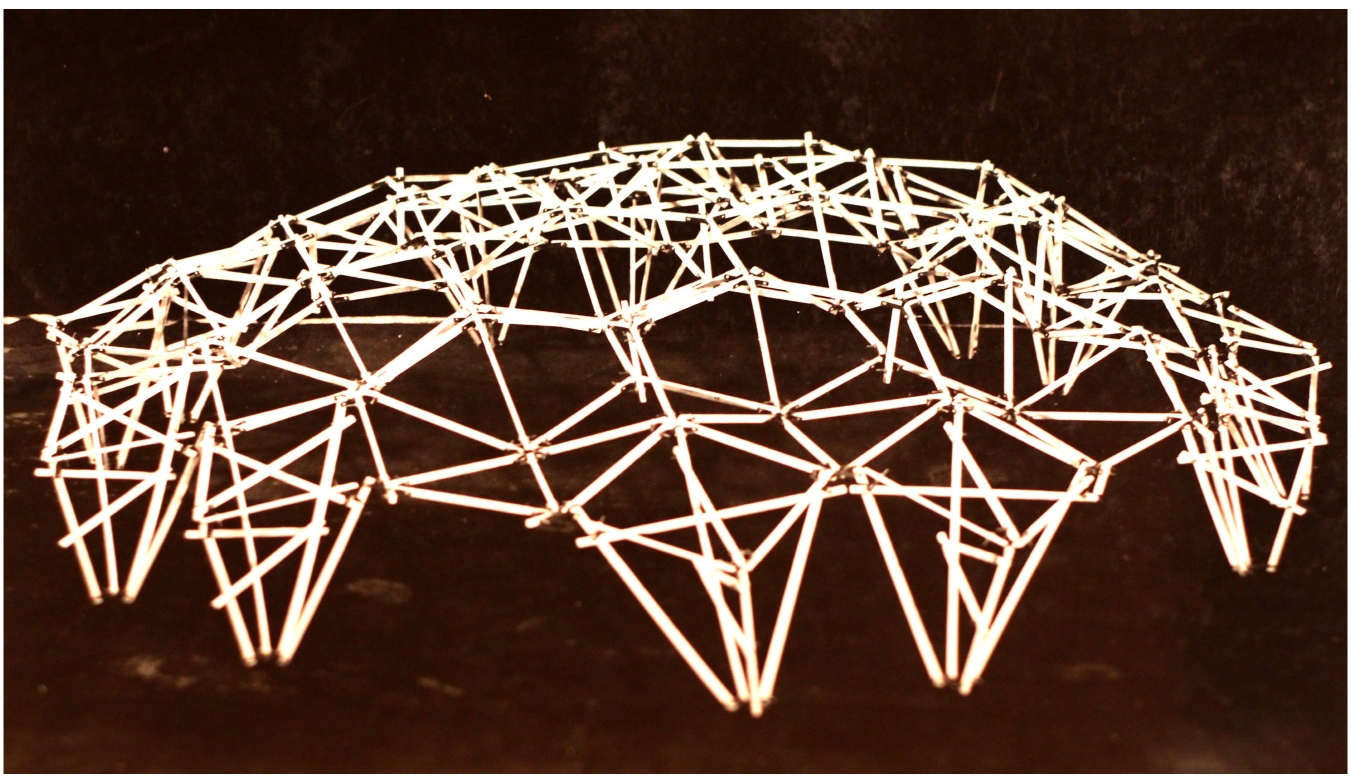


Figure 2.33: Hangar Model.
Le Ricolais.

forms a sphere. When combinations of bubbles form together in a group their shape is deformed, forming straight edges where they meet. Again Le Ricolais was able to turn to nature for inspiration. In the examples shown in Figures 2.34-35, Le Ricolais was experimenting with soap films in order to understand minimum surface structures and their relationship to construction. The shape used in both examples is an Octahedron, unique in that it is far more stable than a square as the sides are already triangulated requiring no bracing.

Not only Le Ricolais, but other pioneers in the lightweight field such as Frei Otto and Buckminster Fuller were all interested in the natural shapes and patterns created within the structure of a foam of bubbles. This merging of surfaces is known as the "double bubble theorem"[24] which has been the basis of several experiments with a view to optimizing the efficiency of structure.

24 Silver. op. cit., p. 16

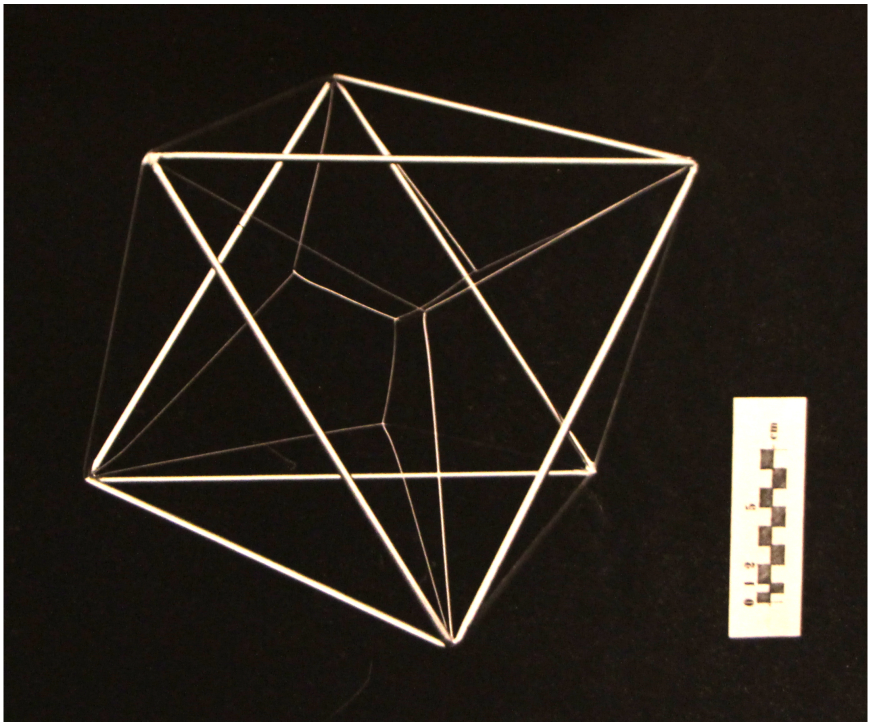


Figure 2.34: Octahedron, Minimum Surface Structure. Le Ricolais.

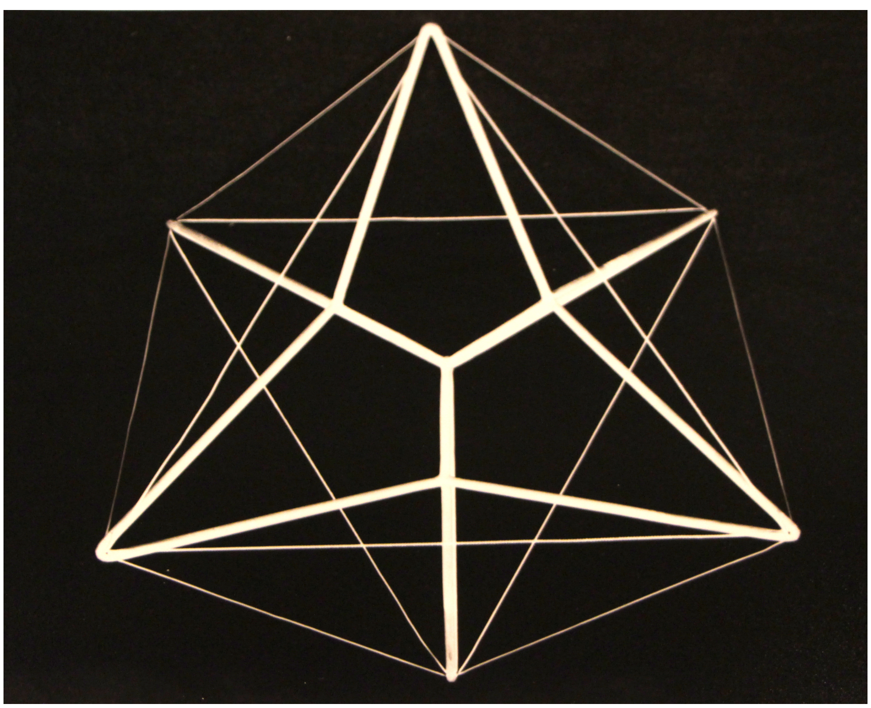


Figure 2.35: Octahedron, Minimum Surface Structure. Le Ricolais.

Energy Within a Building

Embodied Energy

In this study, the concept of a lightweight structure is being investigated for its ability to reduce material consumption. Choosing materials is a complicated task as several factors need to be considered in order to make a responsible choice. All materials used in the construction of consumer goods carry with them inherent physical properties which make the application of the material more beneficial in specific areas of a construction project. Too often, materials for design projects are chosen with only financial limitations in mind in terms of upfront cost.

Figures 3.1-4 constitute a series of graphs showing material groups and how they compare to each other. These graphs increase the understanding of how materials compare on multiple different levels. Building materials should all be put through a process which keeps all of the factors associated with the material in mind, with more emphasis put on the environmental cost in spite of the possibly increased financial considerations. If environmental impact is put at the forefront in all cases, production costs will go down as the item becomes more accepted, making the financial loss a temporary issue.

Operational energy measures a building's efficiency after it is completed, whereas embodied energy looks at the amount of energy that the physical building components have required for the building to be erected. There are two main categories of embodied energy in a building: internal embodied energy and reoccurring embodied energy.[1]

Internal embodied energy: when looking for an environmentally responsible material, direct energy considers the cost to transport the finished construction material and the physical ramifications relevant to its use on site. Indirect energy refers to the amount of energy required to produce the dimensioned building material. This includes its unrefined

[1].Cole J. Raymond and Kernan C. Paul. (1996), Life-Cycle Energy Use in Office Buildings, Building and Environment, Vol. 31, No. 4, pp. 307-317.

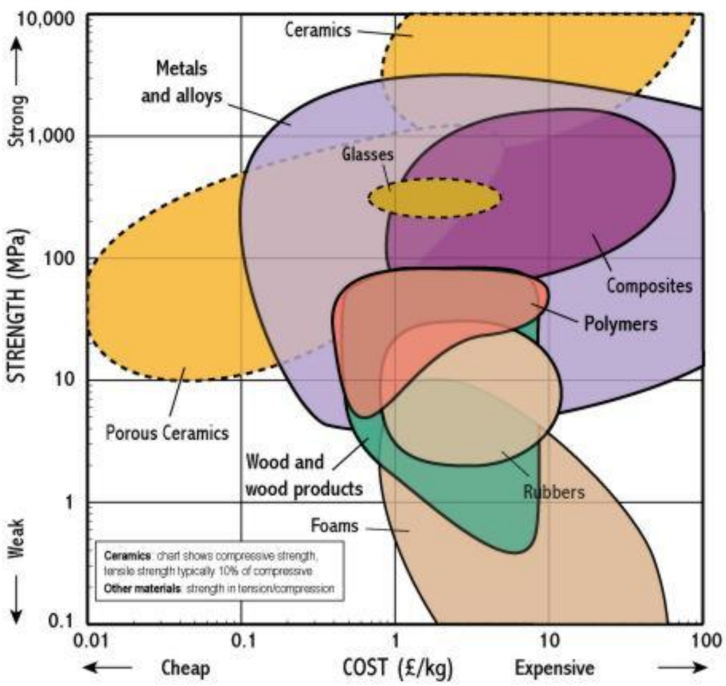


Figure 3.1: Strength-Cost.

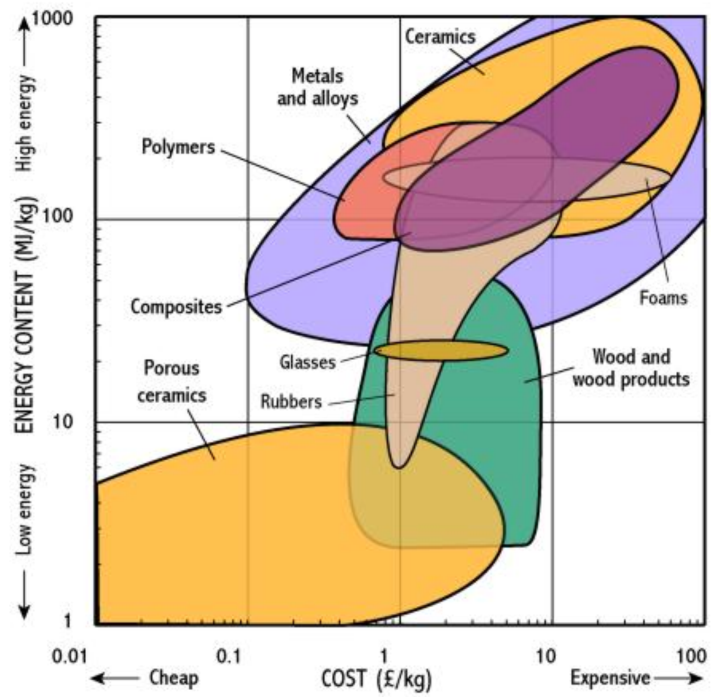


Figure 3.2: Energy Content-Cost.

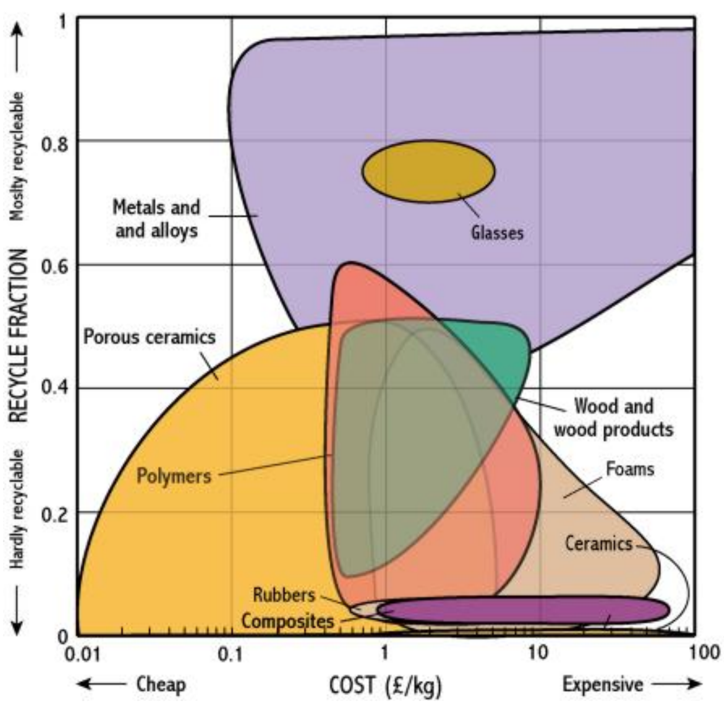


Figure 3.3: Recycle Fraction- Cost.

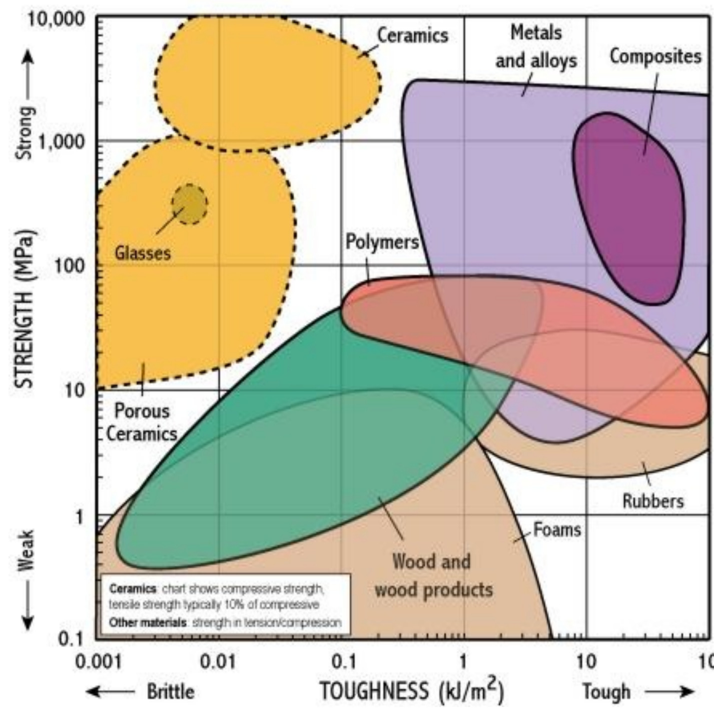


Figure 3.4: Strength-Toughness.

harvesting, refinement and shaping of the finished product, and all transportation of necessary components.

Reoccurring embodied energy: this type of energy includes the maintenance of a building. Initial choices in building material can reduce the need for updating original equipment which adds more energy requirements to the building's overall consumption. Issues such as components wearing out, needing updating and breaking prematurely should all be avoided as they will require greater amounts of energy to fix in the future. This relationship can be seen in Figure 3.6. The energy costs of disposing of the materials at the end of their lifecycle also becomes a consideration as some materials can be recycled while most have a greater environmental impact.

Embodied energy is measured through the quantity of non renewable energy required to construct a building product. The unit of measure is in Joules. Because of the large volume involved, mega joules (MJ) or giga joules (GJ) are used to understand each material's energy requirements. The systems in place for the production of the material - oil and coal burning electricity plants or dirty fuel, for instance - as well as the durability and the performance of the material need to be considered when making a selection. A look at the materials in Figure 3.7 shows values of common building materials relating to their embodied energy.

Buildings vary widely in their construction methods and therefore their overall embodied energy. As can be seen in Figure 3.5, the average energy requirement in a typical structure in 4.82 GJ per square meter. Of the overall embodied energy in an average building, 26% is envelope and 24% is structure to make up half of the total energy usage. Exploring ways to reduce this energy usage constitutes the focus of the present research.

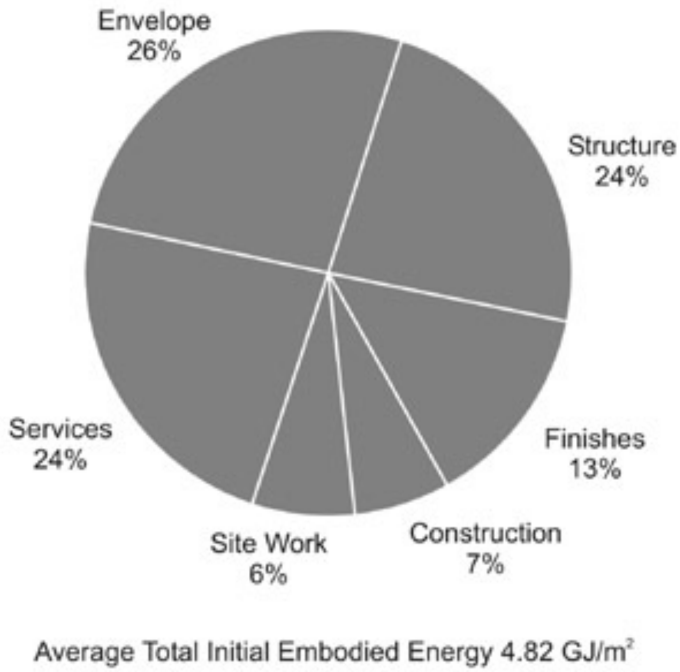


Figure 3.5: Embodied Energy Breakdown.

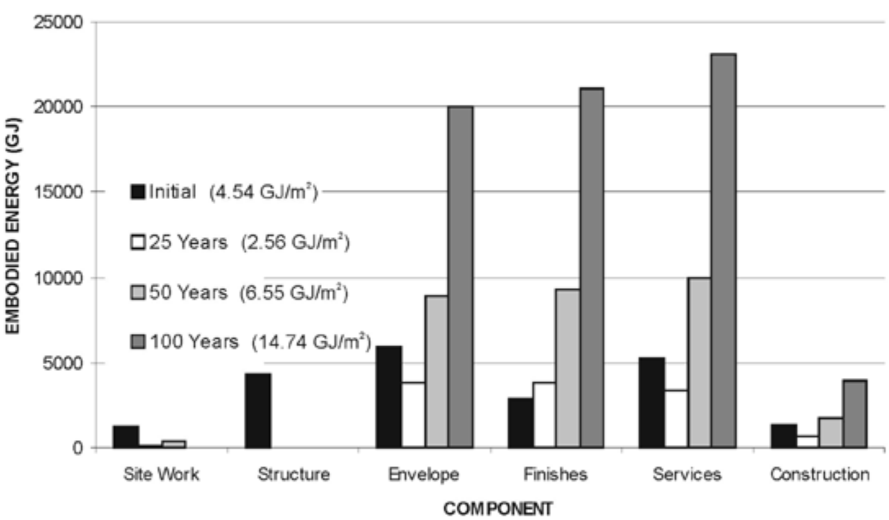


Figure 3.6: Embodied Energy Throughout Lifecycle.

MATERIAL	EMBODIED ENERGY MJ/kg	EMBODIED ENERGY MJ/m3
Aggregate	0.10	150
Straw bale	0.24	31
Soil-cement	0.42	819
Stone (local)	0.79	2030
Concrete block	0.94	2350
Concrete (30 Mpa)	1.3	3180
Concrete precast	2.0	2780
Lumber	2.5	1380
Brick	2.5	5170
Cellulose insulation	3.3	112
Gypsum wallboard	6.1	5890
Particle board	8.0	4400
Aluminum (recycled)	8.1	21870
Steel (recycled)	8.9	37210
Shingles (asphalt)	9.0	4930
Plywood	10.4	5720
Mineral wool insulation	14.6	139
Glass	15.9	37550
Fiberglass insulation	30.3	970
Steel	32.0	251200
Zinc	51.0	371280
Brass	62.0	519560
PVC	70.0	93620
Copper	70.6	631164
Paint	93.3	117500
Linoleum	116	150930
Polystyrene Insulation	117	3770
Carpet (synthetic)	148	84900
Aluminum	227	515700

NOTE: Embodied energy values based on several international sources - local values may vary.

Figure 3.7: Common Building Material, Embodied Energy.

Wooden Structures

Historically, wood has been a vital construction material. Even when not used as the permanent structure, temporary scaffolding and formwork assemblies use wood for their construction process. It is extremely economical, easy to work and plentiful. It is the most natural option when looking into structural systems.

Dimensioned building lumber has 2.5 MJ/kg associated with it as indicated in Figure 3.7. Hardwoods take longer to grow and therefore are not as sustainable when compared to softwoods, however they offer greater strength and longevity. Through strategic and responsible forestry practices, wood can offer a continuously regenerative source for building material.[2] The regrowth process allows desired species with straight and continuous attributes to father the next generation of trees. Although it's a relatively slow regenerative process, the trees produce oxygen throughout their lifecycle, a valuable biological process.

Sawmills choose the grade and cut wood for the most economical use of the log. Material is cut into desired patterns for strength and sometimes the look of the wood such as quarter sawn. The waste can be burned as heating fuel or simply composted, making the overall process very environmentally responsible as few harmful byproducts result from refinement. Some transportation costs are incurred as raw and finished material still need to be moved to and from the milling facility. If local wood is selected for a project, long haul shipping can be kept to a minimum and therefore overall transportation costs reduced.

Wood as a structural material does not last as long as steel or concrete. Its susceptibility to moisture is its greatest downfall, leading to decomposition. This attribute makes it a poor choice for connections to the ground in structures as it reduces the time that the material can be expected to last. Being a relatively easy material to work also makes it susceptible to insects. Its greatest environmental advantage is unfortunately also its greatest disadvantage when it comes to longevity. Replacement of decayed material is an option although this often takes as much labour as simply building a new structure. On the other hand, Japanese temples made entirely of wood can be upwards of 1400 years

[2] Responsible forestry practices like those set forth by the Forest Stewardship Council (FSC) https://ca.fsc.org/

old and are still standing.[3] This is due to rigorous maintenance routines in which every part of the temple is replaced with an identical new component. Although the practice of replacement is an extreme case, it shows that it is possible for wooden structures to last for a long time. The common life span expected for most wooden structures is around 100 years. Many factors including geographical location, species, dimension and application all have an effect on the life cycle that can be expected for the material.[4]

Building practices have changed considerably with respect to wood construction. As technologies changed so did the typical construction details for wood. Thermal bridging in cold climates is less of an issue as wood does have some insulating properties and therefore will not transfer cold through a wall section to the degree that can be expected in other materials.

Heavy timber construction using large dimensioned wood, often hardwood, can be expected to last a long time. It also has the potential to be jointed together with slots and pin connections, requiring only wood. Such connections are made easier due to computer aided fabrication where a more streamlined process reduces the amount of labour that was once associated with this type of work.

Light or stick frame construction is a common building technology in residential housing stock. Putting smaller pieces together offers a great opportunity to increase efficiency in a building as insulation can be added easily. Relying on mechanical connections such as screws, nails and bolts has made it possible for rapid construction of such building systems. In addition, easy adaptability on site makes this an extremely desirable building approach.

Engineered woods such as glue laminates and plywoods have increased the strength of wood dramatically. Multiple layers in the wood allow it to be much more versatile and overcome the limitations of natural

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[3] The East Pagoda at Yakushi-ji temple was built in 730 and is still standing today, though it has been disassembled a few times. Discoe, Paul, Alexabdra Quinn. “Zen Architecture: The Building Process as Practice.” Gibbs Smith. Layton, Utah. 2008. Print. p.16

[4] Wood Design Manual. 2010. Canadian Wood Council. -Engineering Design in Wood. Canadian Standards Association.

products. Resins and other additives, however, reduce the recyclable capacities of the wood as harmful chemical processes must be incorporated into its making.

Wood is a flammable substance, making its safety for inhabitants a concern. Such concerns lead to a maximum allowable number of stories being specified in the International Building Code, which renders its use in larger buildings an impossibility. Only recently has this been modified, allowing for larger buildings to use this technology as their structural system. The allowable maximum has changed from 4 stories to 6 for specific occupancies within a building.[5] Although wood structure is usually only seen in smaller construction projects today, the code seems to be moving in favour of this method, opening up new potential for future structures.

Metal Structures

Metals have been used for tools, weapons and other merchandise for centuries. Made popular during the industrial revolution, iron revolutionized the future of building forever. Today steel is the desired metal for construction, differing from iron by the amount of carbon mixed into its composition. Different alloys common in buildings include: lead, tin, zinc, nickel, iron and aluminum, all of which have very different properties that make them desirable in distinct circumstances within building components.

Steel requires large amounts of energy to produce, 32 MJ/kg. Yet steel is one of the least energy consuming metals with zinc at 51MJ/kg, copper at 70MJ/kg and aluminum at a massive 227MJ/kg (Figure 3.7). The process to produce such metals differs greatly but mining of raw materials followed by a melting and refining process uses extremely large amounts of energy and produces byproducts which are harmful to the natural environment.

Transporting the raw material requires massive infrastructure and is commonly found in sea ports, as maritime shipping of raw materials was and continues to be common practice. However, rail systems are also

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[5] International Building Code. article sponsored by reThink Wood and WoodWorks. Multi Story Wood Construction: A Cost-effective and sustainable solution for todays changing housing market. Originally published in the March 26, 2012 issue of Engineering News-Record; update February 2014.

used to bring in the raw materials. Recycled metal can be used in the production process yet needs to be transported to the site to be remelted. Once materials are on site they begin their path through multiple melting and additive measures to produce the desired mixture of parts. This extreme heating process uses large amounts of energy as the liquid metal stays liquefied throughout. Once the desired mixture is obtained it moves to a rolling mill which works the steel into the desired profile/shape. The finished steel then must be moved to the work site or fabrication shop to be assembled into the specified building component. [6]

Steel can rust due to its iron content which is the metal's weakness in terms of longevity. Additives which make alloys can increase the metal's resistance to breakdown but they require an altered process with materials that also need to be mined and therefore require more energy to construct. As a result it is common to choose building materials based on their resistance to exposure to the elements as well as on their strength as a structural material.

Unlike wood, steel is able to undergo a fusing process in fabrication known as welding. This additive process melts the metal so that two pieces become one. It is far superior to mechanical connection as well as being economical, as any piece of similar material is capable of being combined into an incredibly strong element on a molecular level. Steel is far stronger than wood as it does not have a grain and therefore is not susceptible to cracking and splitting but can be bent or formed to any shape needed, often using a heating and cooling process to maintain the strength of the steel. In addition, as the material is man made it has a constant strength with no flaws and holds its shape because it does not contain internal stresses as natural products do. The shapes that are formed optimize the weight to strength ratio desired for the specific project, including hollow tubing and channelling.

Steel is extremely strong in tension. For this reason it is added in concrete structures in the pouring process. Rebar, as it is referred in this form, is positioned for reinforcement within the poured forms. Another form, steel cable/rope, is used in many applications both in industrial processes and in construction. Most notably, bridges use cable

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[6] Allen, Edward and Joseph Iano. "Fundamentals of Building Construction: Materials and Methods." John Wiley & Sons, Inc., New Jersey, 2004. Print. p.p. 372-373 fabrication process. Steel construction details and methods p.p. 367-441

technology as light weight but strong spans are produced allowing the bridge to span great distances as the cables tie the thin deck to compression piers.

Steel structures, like wood ones, are susceptible to failure in fires. Although not combustible, when subjected to extreme heat, steel begins transforming into a liquid, which weakens the material. As a result, a steel structure must be covered to maintain its rigid capacity for longer periods in the case of a blaze. Steel is capable of resisting incredible forces allowing for the modern skyline as well as modern transportation methods which without such a material would be impossible.

Steel is incredibly durable and easily can be expected to last well over 100 years. The maintenance of steel as a material is minimal as more material can be added if components are damaged. Rusting do to climate factors is its only real downfall. When the building/material is no longer wanted or useful it can be recycled and the steel made into a new form.

Concrete

Made up of three main parts - water, aggregate and cement - concrete is a vital material in building construction. An ancient material that has been around for centuries, it became more useful in spanning when used in combination with steel as reinforcement. Concrete is very effective at resisting compression loads, making it a great base material.

Three main applications of this material are common in construction: concrete block (masonry unit) using 0.94 MJ/kg, poured on site concrete at 1.3 MJ/kg and precast concrete at 2.0 MJ/kg energy usage (Figure 3.7) All of these involve the pouring of the material, however precast concrete is formed off site and then brought to the site in its formed shape. On site poured concrete is much more project specific as larger sections are poured all at once creating continuous connections and surfaces.

The material itself is very dense but can be made using a variety of mixtures and formulas based on the purpose it needs to fulfill in a building. A constant temperature is required during the curing process which can be troublesome in cold climates. Transporting the raw materials to the mixing site uses some energy as the aggregate and cement all need to be brought in. When the concrete has been mixed at the plant the truck brings the liquid concrete to the site. Another complication in the delivery process is that the liquid state concrete must have constant agitation in order to slow the setting process. Timing the delivery is crucial since concrete which is held up in transport will be less effective as setting will have begun before the material is in its desired position. This flowing liquid state allows the concrete to take the shape of the form that it is poured into.

Concrete is ideal for building at or under ground level. Moisture has less of an effect on this material. Although concrete still can absorb water it is far better at remaining functional during this process. Concrete acts more like a sponge with different grades of concrete being better at repelling water infiltration. It is seen as the most common base/foundation material as it resists compression and functions in humid conditions.

If utilized properly, concrete can last a long time. Evidence of ancient remains are still around in today's time attesting to the durability of this substance. However if the process is not carried out properly - including anything from mixture amounts to drying conditions - concrete can crack and need repairs that often become complicated. For instance, if cracking occurs leading to the rusting of steel reinforcement, concrete may begin to spall and crack away from itself, reducing its effectiveness in resisting forces. In this case parts of the concrete need to be removed and replaced, usually a laborious task.

Hardened concrete has much the same quality as a rock, making it more resistant to fire since it is not flammable. This quality makes it a much safer building material compared to wood and steel. It is used as a fire retarding separation within combustible construction. Concrete can be used in both interior and exterior applications not limited to structure.

Concrete does transfer temperatures extremely easily, meaning that it is not ideal for cold climates without the use of a thermal break. Insulation and other such materials, however, can be used on top of as well as within the concrete to help address this issue.

Disposal of the material at the end of its life cycle has in the past been very poor, with it most of the time ending up in the landfill. Now, however, processes are in place which crush the concrete into small pieces that are then used in roadways as the base material, in this way reducing the environmental impact.

The chart in Figure 3.8 shows a comparison of the three materials in order to better understand the use for each.

	Wood	Metal	Concrete
Energy Cost to Produce MJ/kg	2.5 -responsible forestry, infinite supply	steel- 32 aluminium- 227 -high heat process	block-0.94 site poured-1.3 precast- 2.0
Transportation	local species, local mills	heavy transportation costs	more local as aggregate can be substituted
Servicing, Maintenance	wears	oxidizes but long lasting structure	extremely durable
Structural capability	versatile	extremely high performing and versatile	optimal for compression loads
Fire resistance factors	combustible	non combustible but susceptible	non combustible
Recyclability	very decomposable	can be remelted to make new material	crushed into rubble and used as fill
Construction considerations	metal connections common	extremely useful as reinforcement or on its own	rebar support increases tension resistance
Atmosphere created	warm and welcoming	industrial	monolithic, clean

Figure 3.8: Comparing Building Materials. Jensen.

A Hybrid Approach

A hybrid of materials is the best solution. By using each material based on its strengths and substituting alternate materials where a material is weakest, the best construction method can be realized. A hybrid approach requires an understanding of materials and their properties as well as understanding how to create connections that allow a combination easily and efficiently. Robert Le Ricolais recognized the importance of combining different materials to their best advantage:

> "In the early trusses, the top chord was an ordinary wood section, working very well in compression, in a limited amount of bending too, and for the bottom chord they had metal, with its advantages in tension. I think the invention of ways to use materials of such different properties together by differentiating their possibilities has had a great impact on the evolution of structures."[7]

A good example of this hybrid use of materials is seen in the construction of bicycle frames in Sao Paulo by Flavio Deslandes and his Bicycle Schools initiative, Figures 3.9-13. In this example, bicycle frames use bamboo components as the main frame components with aluminium connection components linking the bamboo together. The frames use bamboo for its strength and low embodied energy, while relying on the aluminium to provide the connection components of the frame - a clear example of using each material to its strength. The assembly process was taught to local workers, providing them with a skill for the future as well as providing the community with a cost effective means of transportation.

Historically, bicycles are a perfect example of how designs can be light weighted through optimum use of material. Tubular frame design, spoked rims and lightweight alloys create a structure perfect for propelling yourself using your own body as opposed to fossil fuels. A bicycle also employs minimal structure through optimizing forces in a triangulated form as well as reducing compression members and optimizing tension forces wherever possible.

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[7] Le Ricolais, Robert. "Things Themselves are Lying, and So Are Their Images," VIA 2, (University of Pennsylvania: Graduate School of Fine Arts, 1973), p. 31.

By allowing components within a building's assembly to be interchangeable, locally sourced alternatives may be used instead of relying on imported components. In this way, a smaller embodied energy can be expected as transportation resources can be reduced. Utilizing less refined materials such as unmilled wood components reduces the amount of energy needed for the building materials and reduces waste as more of the tree is used in the construction. A system that allows for multiple species of trees would require size constraints based on the type of tree selected but could have hardware capable of accepting multiple sizes of lumber to optimize a component's usability. The ability to replace component parts that wear out as needed will increase the overall life expectancy of the structure.

Figures 3.9-13: Bicycle Schools in Sao Paulo. Flavio Deslandes.

Social Implications

Living in Experimental Spaces

Standard construction methods typically all use post and beam solutions to enclose space. Post and beam are standard organizing methodology that utilizes plumb level and straight components in order to balance the load and transfer the mass of a structure to the ground. This system is accepted as calculations are understood and standard as far as sizing components to spans. On site construction benefits from the post and beam method as standard tools and measuring processes can be used. However, there are more efficient uses of materials to enclose space which use non linear components, arched or curved assemblies in order to optimize materials. Domes and curved hyperboloid shapes offer many advantages in terms of structure and stability while reducing the overall required materials of building.

Flat walls are one of the sacrifices of arched structures. How can someone occupy a space such as a dome? Yes, materials may be saved and optimization of volume can be obtained when comparing the conventional to the alternative but where is the volume gained and can it be used? Curved walls make for complicated internal spaces. For instance, how can a shelf be hung on a curved wall, or a window be installed? Is it comfortable for an occupant to live in a non linear space?

A dome is mathematically superior when comparing volume of the building to standard box shapes. The problem is that the sphere shape of the dome or arch meeting the ground always results in a compressed, and in some cases unusable outer wall section. This space can reduce efficiency unless the designer understands this limitation in the form and is able to design stable occupations in these spaces. In addition, the height of such a shape is complicated to optimize in the sense that the structure is not stacked in levels but takes on a very open and external loading. Levels therefore need to be built internally using more material in conventional ways that ignore the optimized curved roof above.

In the case of a tension structure it is very common to either require a tensile member or a compression strut to break up internal space, in this way reducing the usability of the interior. This is common as these structures rely on integration of components to make truss-like triangulation through the structure. Keeping the structure of the building on the outer skin increases the internal efficiency but creates fixed shapes for the overall structure itself. From an architectural point of view these structures are limiting - even if they are great for optimizing structure they do not lend themselves easily to the needs and wishes of the public.

What is needed is a language of structure that can be adapted to the needs of the users. A language that can be manipulated into structurally superior forms while addressing the needs of the space it is covering will allow a truly optimized building both in structure and function. It can be tall with long spans such as needed for a airplane hanger or can be compact and adjustable for an addition to an existing structure. Using curvature and external structure can be an advantage if designed for the application both in terms of scale and function.

Acceptance of Alternative Shaped Dwelling

Currently our housing stock is made up of dated and reused designs. The designs are dictated by historical definitions of what a home must be. For instance, the use of brick as a nostalgic material has seen the material move from a structural system to a rain screen facade which is far from its original conception of material application. Brick is accepted as a strong and durable material, which when used in its original construction method, that included multiple rows creating a thick and durable shell, was indeed very durable and long-lasting. Used as a rain screen allowing an eclectic and common facade, brick makes a building appear as an idealized structure to the public's eye when in reality this wall will only last as long as the exposed steel lintel it rests on, fifty years perhaps. Misusing such building materials adds unnecessary environmental and financial burden to a project as more economic and increasingly more durable facades are available in today's building materials. Using such materials is a waste of energy and a discredit to the material itself.

However, institutional scale buildings often utilize new technologies and push the limits of what the public will appreciate and even expect from modern solutions to functionality. Stadium designs and large theatre spaces commonly use groundbreaking technological feats to increase the use of a building. These examples are realized as architectural marvels whereas a modern dwelling in a residential neighbourhood is still extremely uncommon, and cause for public upheaval and overall disapproval. The root of the problem comes from a natural nostalgia for the history of structure. People are drawn to what they know and trust, so adding a new alternative to building stock will come up against a large amount of opposition. Commonly the building styles seen in larger buildings move into common practice for larger scale housing complexes, however it is an extremely slow process.

Time may be required in order for alternative structures to be accepted in the eyes of the consumer. Yet a change is required to allow for a reduction in the use of our natural resources. The advantages of experimental structures lie in the reduction of materials but also in allowing the less fortunate to have a chance at a better quality of life as these structures offer a financial incentive as well as innovative design.

Economic Benefits

The decision on what is built often comes down to the least amount of money that can be spent on construction. If alternative structures can be built for less money and yet function in much the same way as existing conventional buildings, the benefits of environmental efficiency and reduction in a building's impact can become a feasible alternative that will prove acceptable to the masses. Creating an alternative that is economical to construct and maintain is a large consideration in this project.

The financial cost to construct a building has many considerations. The price of land is always a factor regardless of the proposed structure. Similarly, costs such as utilities and taxes are all predetermined based on the location. However, the costs of materials and labour which make up the brunt of any upfront building project cost can be reduced through technological advancement.

Reduction in construction costs can be realized through:

Reducing the construction time required

Labour in a standard construction typically consists mostly of on site work. Creating a packaged building which has the potential to unfold on site and be erected in a matter of days greatly reduces the labour costs. Factory mass fabrication is a proven method of optimizing construction of products. First seen in the automotive industry through Henry Ford's assembly line, great efficiency can be realized when components are made offsite in a controlled environment. The labour force can be sheltered from the elements and trained to fulfill a single task, in this way reducing the skill required on site. This strategy is being used in current building stock where entire structures are built in a factory setting and then transported in pieces and assembled on site[1]. In these examples volumes of space are already enclosed with all standard finishing and utilities standardized and protected.

Less specialized installation by means of prefabrication

With its ability to fit into the smallest volume possible, the ready made building in a box method can make construction much more efficient while reducing transportation costs. A different language of construction must be applied as hinged and pivoting connections are essential to the smooth on site assembly. In this thinking a house in a box which unpacks to form a structural system when erected would not have to resemble a box. This construction method does not require the use of highly skilled labour to execute. Less specialized on site work greatly decreases the overall cost of a construction project.

Decreasing material requirements

Breaking out of the box, both literally and figuratively, requires building stock to take on a new form leading to a reduction in the overall materials required in a building. The tradition of post and beam construction can be improved upon through the use of hyperboloid forms and adaptive material selections. A smarter structural system where each component is optimized will greatly reduce waste on both environmental and economic levels.

Local materials

Not only do natural materials and environmentally friendly alternatives reduce the amount of embodied energy in a structure, they also allow for optimal use of local resources. Using locally available standard building materials such as lumber can reduce overall costs. Local material

[1] "Landmark Homes" (www.landmarkgroup.ca) is an example of this type of construction approach and is the largest house manufacturing plant in Canada (Edmonton, Alberta).

selection and refinement also increases local economies and skill levels, thereby strengthening nations by empowering their citizens and and allowing them to responsibly manage their own resources. A construction strategy that is adaptable to the needs of any building environment and location will create a truly globalized building solution.

Difficult Building Location Solutions

Building a structure in a hard to access location is made easier and more efficient with a system where a few small containers can be packed to hold everything necessary to erect the main structure of a building in a few days. Obviously the structure's required use will dictate how it must be equipped as a house has needs that differ from a commercial facility, but a design can be personalized for the owner to allow a wide range of uses.

Alternatively, for complicated locations that have abundant natural resources on site, specifically forested areas, simply ordering all steel connections and sheathing and using the trees on site is possible. Recalculations based on the species of wood located on site would be needed as wood has many compositions, some of which are more apropos for structural purposes. Small mill operations are possible using on site material processing and fabrication. This concept is more labour intensive as a wide range of on site skills are needed, adding much time to to the construction process, however a significant reduction in both financial and environmental overall costs can be realized. This type of construction method may seem dated, a throwback to pioneer settlement situations. However, with technological advancements such mobile dwellings offer an improvement in function as the building itself is still constructed quickly once materials are refined.

Adaptive use of Existing Buildings

Additions make up a large part of the building market. When more space is required in an existing building it is often extremely expensive to add more volume. This technology would allow an addition to be erected very quickly for considerably less money than a conventional structure. As it is common to incorporate an addition with its own unique building language that differs from the original, this may be a great opportunity for new structures to gain favour before they are accepted into mainstream practices.

Seasonally used spaces would also benefit from this type of structure, erected for cover in the winter months and then collapsed over the summer. This flexibility is seen in utility structures housing cars and machinery from snow and the elements. The opposite scenario could also apply - using such structures for summer cottages or children's camps then collapsing and storing them away over the winter months. Heating and insulation are not a concern making this alternative extremely useful and versatile. In another example, if a specific social event demands increased space, a structure that could be erected quickly and then dismantled after the function ends would be a extremely desirable. Solutions to such function requirements exist but are often crude in their construction involving many internal columns that break up the inside space and make it less useful.

A further application could be seen in dense cities as a way of increasing the capacity of existing buildings. The roofs of buildings are often underused flat spaces. These lightweight deployable structures could offer increased living space while not dramatically increasing the load on an existing building. By elevating the structure off the roof deck, drainage issues can be avoided or even improved depending on the overall shape of the proposed structure, as water can be shed off instead of collecting on the roof surface. In cities that are seeing incredible population inflation as is the case in India, using this type of system offers the potential to cost effectively house more of the population.

PART 2

Preliminary Investigations

The use of tension has long been a fascinating topic of research for me. The following projects are a cross section of the early works that led me to the explorations in this thesis. The benefits in transportation and reduction in material is a common theme in these projects. The knowledge gained from these investigations is invaluable for developing the building systems proposed.

Furniture Development

The creation of furniture offered a practical means of experimentation which furthered my understanding of the relationship between tensile and compression forces and their co-dependent nature. The structural needs of furniture relate to the structural requirements in architecture - the design must address how to support weight and connect materials to suit its purpose. The ability to design, build, test, and refine is not something that is possible in architecture, like it is in furniture. Costs and safety concerns are more manageable with furniture, allowing for a greater ability to experiment with forces.

If a piece of furniture fails, it is possible to trace the cause to either material connection, size of material or unbalanced loading. The financial and time considerations in creating a furniture piece are such that they allow for details to be experimented with, altered and refined. All of these rapid prototyping tools have been used in the following pieces. In most cases, multiple versions were built and tested before these structurally successful designs were obtained. Friction joints and connection details allow the pieces to be packed tightly for transportation while allowing them to be rapidly assembled.[1]

[1] Composite Angle Design Inc. - A furniture company owned and operated by Natalie Jensen and myself, founded in 2011. www.compositeangle.com

Tension Bookcase, Figure 4.1

In the design of this bookcase, a symmetrical cable structure is used to support upright members which act as piers to support the shelves. Simple metal tubes, held together with friction only, are used to join the wooden pier components to the base at pin connections, making the cable essential to holding up the load in the structure. The cables are fixed in, both at the base and at the top of the piers, creating a stable support, however requiring an extended base component for the cable to be anchored to. The challenge was where to place the cable, as the shelves needed to be kept clear to allow for easy access. The base structure required large components as the cabling tension led to extreme deflection in earlier versions.

"Cat's Cradle" Coffee Table, Figure 4.2

In this coffee table, the idea of supporting parallel planes was investigated. The table is broken up into two main components: the base and the top surface, which are connected using a centre post. The post is on an angle, supported by cables anchored to the base. With this compression post holding the two parts away from one another, a cabling system attaching at the corners of the two planes holds the entire unit in parallel through the use of tensile forces.

Tension Stool, Figure 4.3

This piece uses a similar technique used in the tension table to support an angled post which pivots at the base, but has a fixed seat. The pivoting joint in this stool is held from falling forward with a simple cable system.

Figure 4.1: Tension Bookcase - Maple and Steel - Cable and Connections. Designed and Built by Author, Kyle Jensen

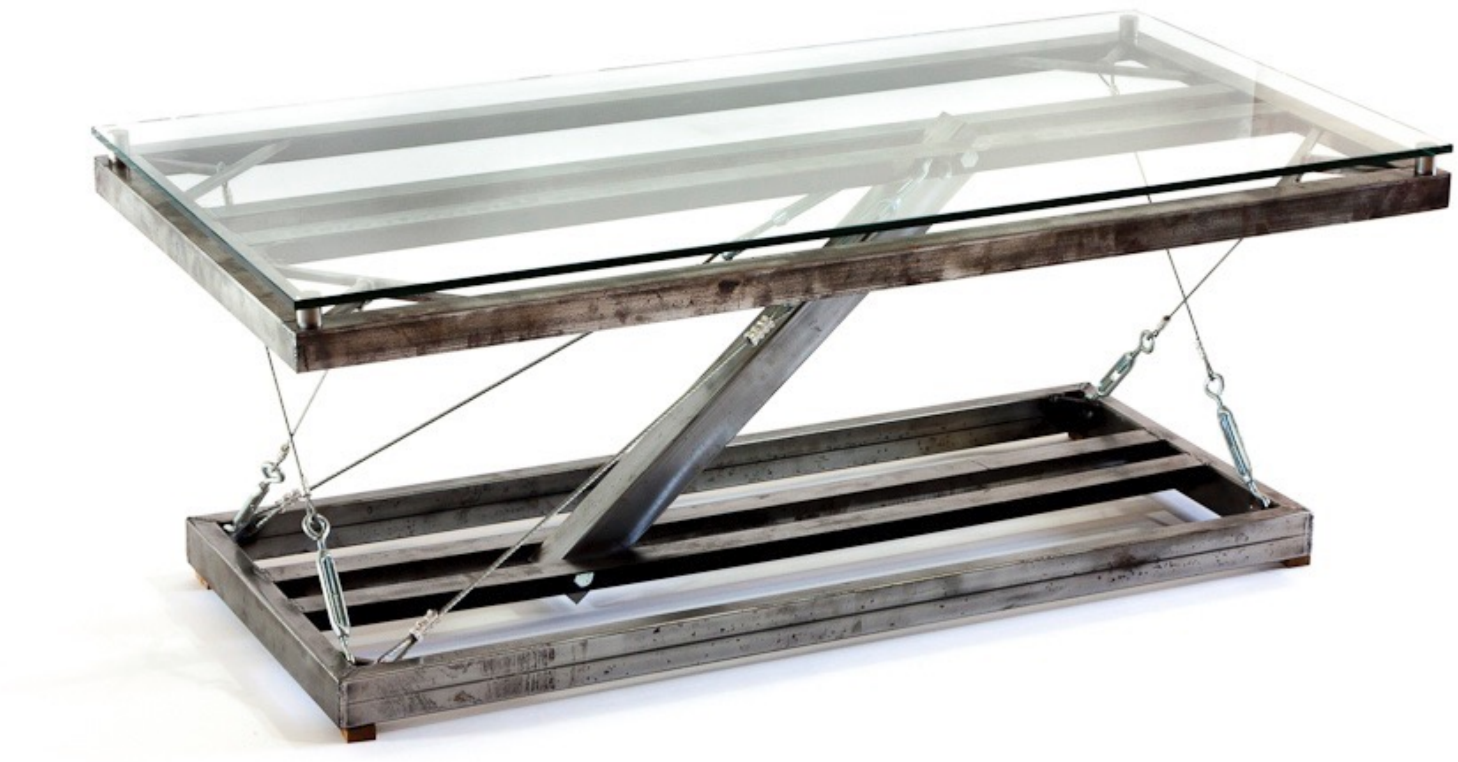


Figure 4.2: "Cat's Cradle" Coffee Table - Steel and Glass. Jensen.

Figure 4.3: Tension Stool - Pine, Steel and Leather. Jensen.

Chess Board, Figure 4.4

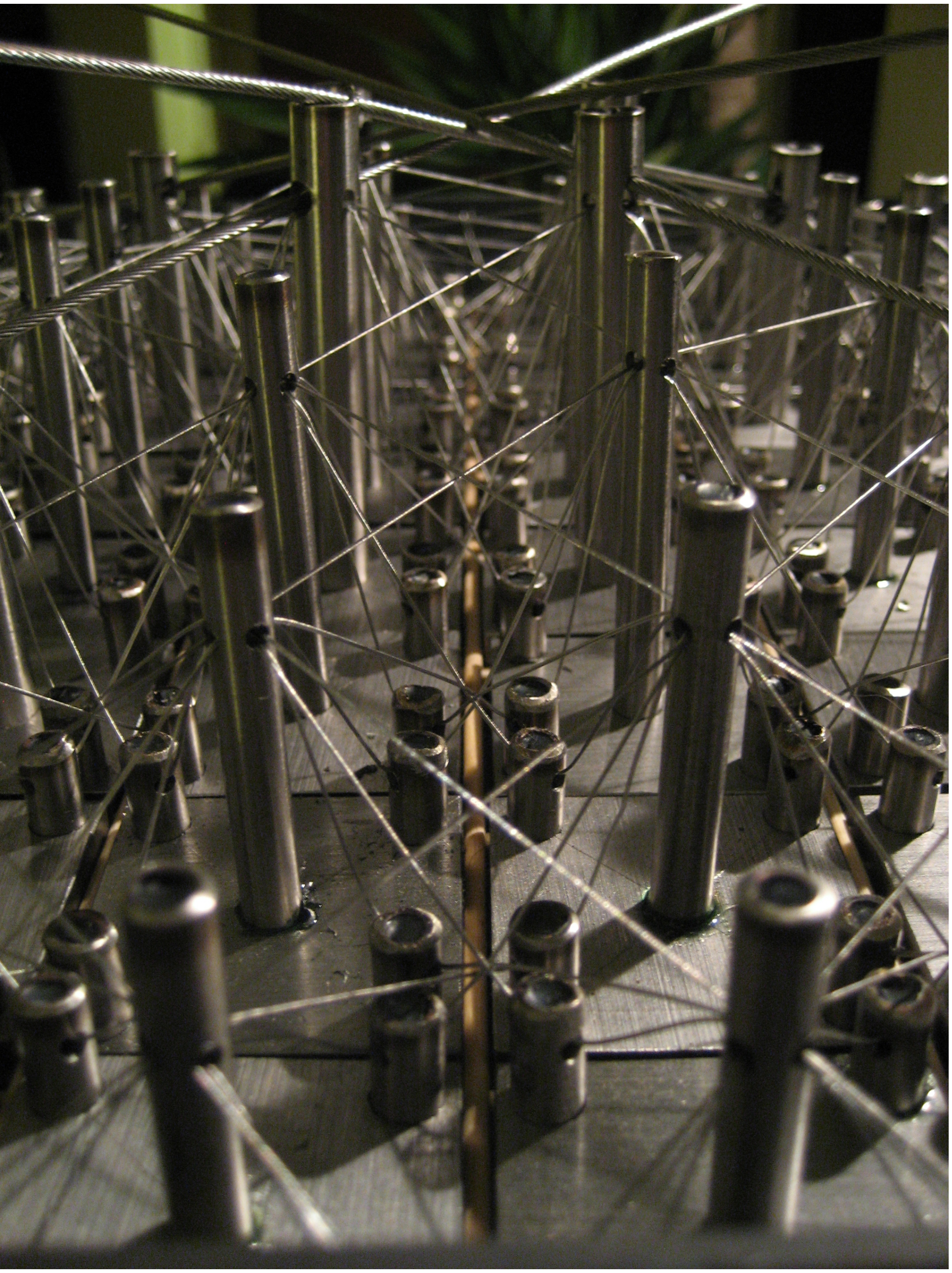
In this project, the experiment included making a flat plane using small squares of suspended steel pieces. An 8x8 grid was used, allowing for a chess playing surface to be achieved. The 64 individual tiles are held suspended from a rigid frame on the perimeter of the board, connected and held in place only via tension cables. This was achieved through a series of pegs on the bottom side of each square, allowing for a complex cable weave to hold the pieces in place. A floating illusion is created as the pieces are held in place without touching one another.

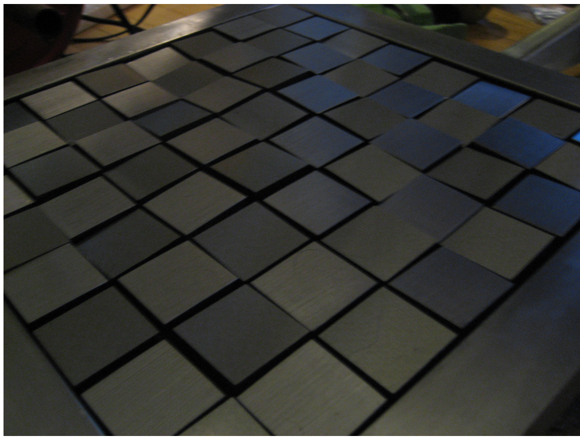
It was clear through this experiment that fixed tension segments would be more effective in ensuring that the units do not realign with each other, as was the case with my unbroken tension lines. Stretching of the tensile cabling in this project caused a slight sagging across the top surface plane.

Tension Bridge

For the bridge design in Figure 4.5, a single piece of flat stock steel was reinforced by using a tension network and triangular compression components within. Adjustable segments were utilized, in contrast to those seen in the chessboard, allowing each tension segment to hold its own length within the system. A turnbuckle system on one side of the bridge was used to tighten all the cabled parts of the assembly.

The project was successful in dramatically reinforcing the flat stock; however, it was observed that the cabling anchor - fastened below the level of the flat stock - resulted in a deflection on both edges of the bridge “deck”. This example illustrates why the tension components need to be fastened on an ideal plane to ensure that the forces they exert do not deflect the overall component in an undesired way.





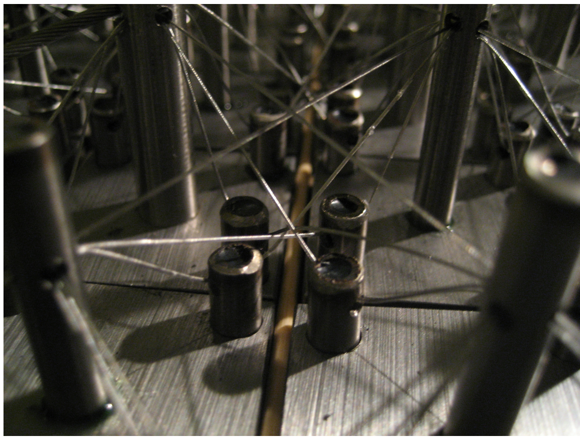


Figure 4.4: Chess Board. Steel.
Jensen

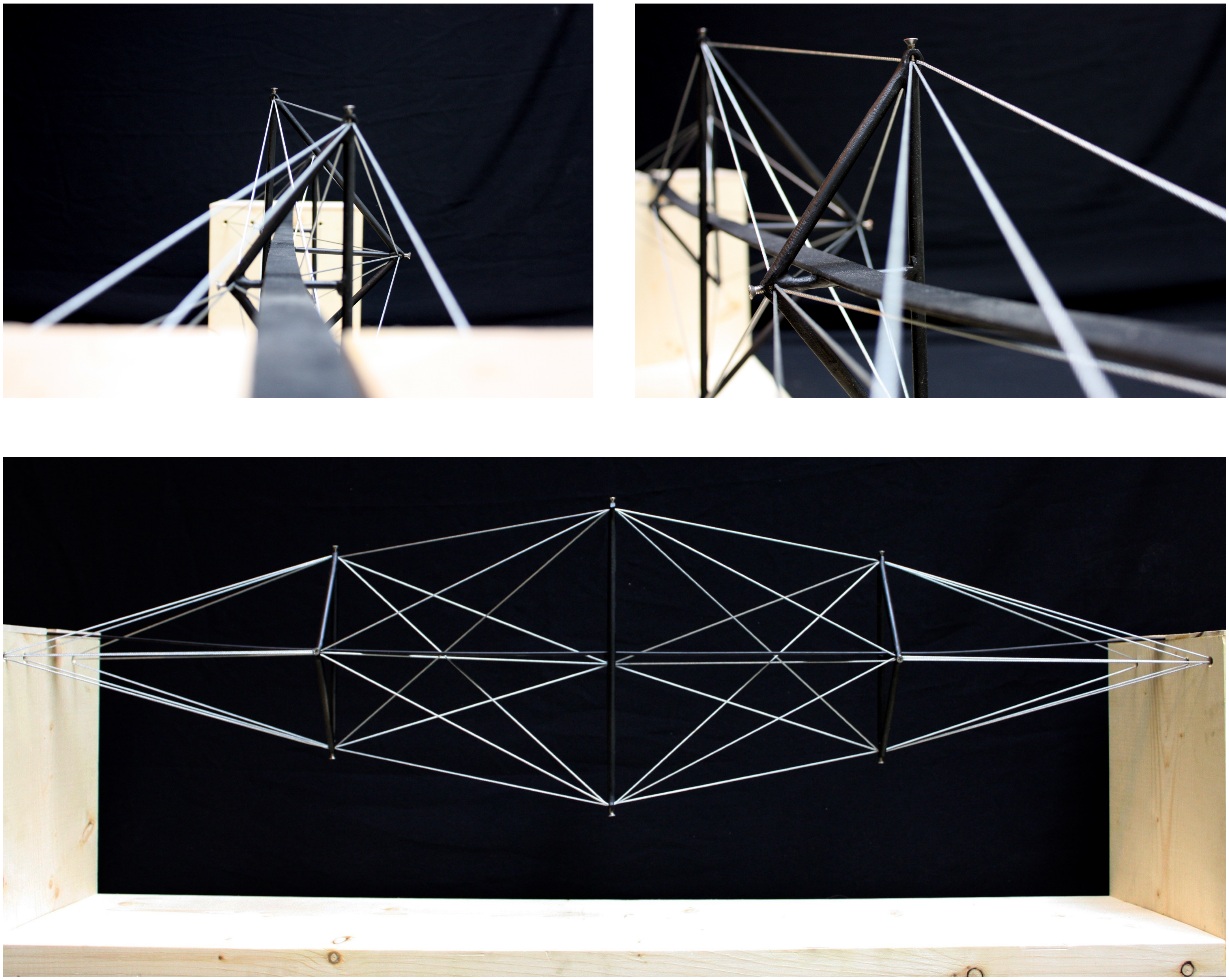


Figure 4.5: Tension Bridge. Jensen

Moving Life, Mobile Living

Fuller's philosophy of "doing more with less"[2] embodies the concept of using materials and technologies that reduce the amount of consumption in the building industry. Using this line of thinking, this project was an investigation into what kind of structures can be designed with the idea of transportability, without losing the quality of life associated with a standard mobile dwelling. There are precedents in nomadic dwellings through the ages where it was absolutely necessary to bring as little as possible in order to stay mobile and allow for a large distance to be traveled. I am interested not only in creating a liveable mobile dwelling but one that utilizes every aspect of its composition to the fullest degree. The solution I am proposing below is a transformable trailer made using light weight materials, allowing a compact car with high efficiency mileage to move it from place to place.

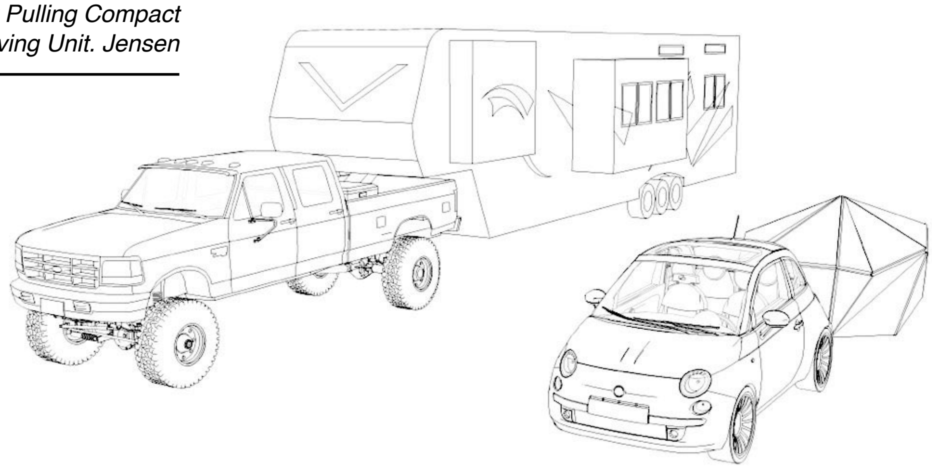
The trailer is constructed of carbon fibre and aluminum, allowing it to weigh under 500 pounds. The utilities are stacked for transport, the extra room in the body of the trailer allows for some luggage space as well as the space for the fabric storage that makes up the enclosure. The utilities rotate and telescope into two counter height stations (a galley kitchen) with a platform underneath, turning the rigid footprint of the packed trailer into the kitchen floor.

The panels, made of a carbon fibre honeycomb construction with light weight hinges, allow for the deconstruction of the triangulated body. By allowing the body to be collapsed flat, the body itself is transformed into the floor deck of the living space. The panels are extremely strong for their weight. They weigh only 4.9 ounces per square foot, making the outer enclosure weigh only 60 pounds in total.[3]

[2] Fuller, R. Buckminster. "Utopia or Oblivion: the Prospects for Humanity." The Overlook Press, New York, 1969. Print.

3 ACP Composites, Inc. 2010, Carbon Fiber Sandwich Panel, http://www.acpsales.com/Carbon-Fiber-Sandwich-Panels.html

Figure 4.6: Fiat Pulling Compact Transformable Living Unit. Jensen



3.0 km/L.
13,000 kg.
18m.

12 km/L.
1,400kg.
7.5m.

A challenging aspect of this type of tent dwelling is privacy, as it consists of one large room. However, a certain measure of privacy is afforded by the judicious use of space (Figure 4.7). The main entrance is at the back of the tent with two secondary exits on the side. The exterior platform acts as a threshold for the entrance into the main living/dining area. The kitchen utilities join onto the main living area as a small, but well equipped galley kitchen, complete with sink, stove, and fridge. Moving further into the tent, the bathroom is sheltered from the open living space by a heavier fabric enclosure. The sleeping quarters are separate pods that hang off of the main mast structures and consist of a compression ring supporting a hammock style bed and its own small tent enclosure, again respecting privacy.

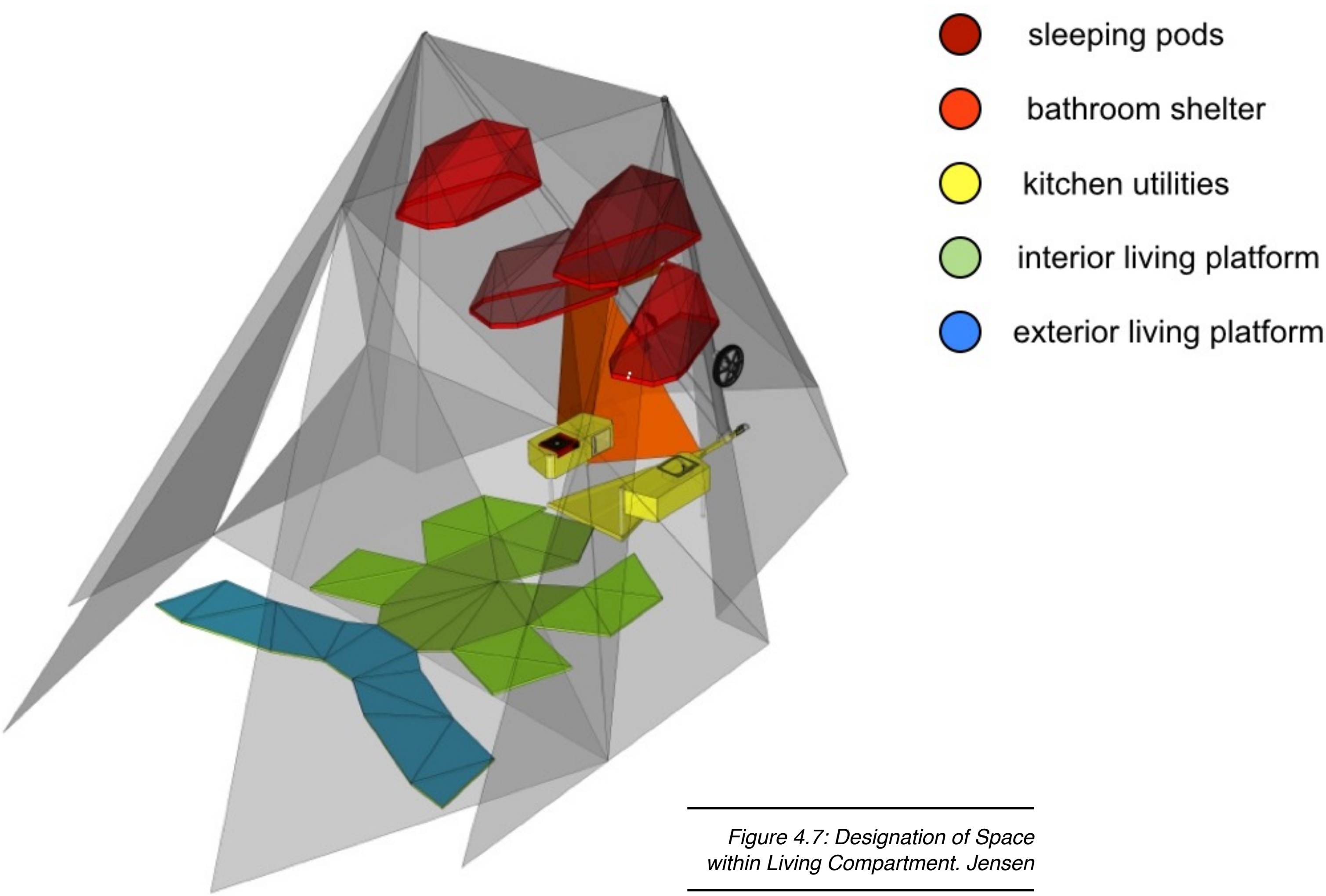


Figure 4.7: Designation of Space within Living Compartment. Jensen

Learning through the building and investigating of practical applications has proven its usefulness in these studies. By creating furniture and the tensions bridge, I experimented with the fine balance of tension and compression, and the compact trailer brought to light many of the spacial difficulties of lightweight, transportable structures. These experiments opened the door to further investigations and led me to the conclusion that it would be possible to develop a construction method superior to the one in current practice.

Exploring the Optimal Structure

Unit Studies

Research of stable shapes through the use of scaled physical modelling is how my investigation and experimentation of designs began, reminiscent of Le Ricolais' approach to design. In discussing Le Ricolais, McCleary states:

> "Le Ricolais relies on 'the test as a companion to intuition' to help in 'uncovering some privileged arrangement of things'. His intuition or 'looking into' does not limit itself to an 'an immediate apprehension by the mind without reasoning, but by a sense'."[1]

In a similar fashion I work to find structural solutions, starting with tangible objects. The following outlines my investigations.

Figures 5.1-2

This concept proved to be effective when pressure was applied directly down on the point of the compression members. The unit is capable of folding down very small, which would work well for creating a packing unit. Unfortunately, in a grid its structure was very ineffective as there was not the strength required to resist forces from multiple directions, creating critical deformations and loss of structural integrity.

Figures 5.3-4

This failure of the first component led me to consider an adaptation of more than one. If two such components are assembled together and connected by a turnbuckle device or some other means of holding tension on the cable, a solid and stable shape is made in the form of an octahedron (a platonic solid). Once a stable shape is made, tension cables can be strung between the components, making a stable grid. The reduction in compression struts in the unit reduces the weight in the overall truss configuration while still allowing the segments to be easily

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[1] Le Ricolais, Robert. Visiones y Paradojas. Visions and Paradox. Exhibition Catalogue. Madrid: Fundación Cultural COAM, 1987. Peter McCleary, p. 27.

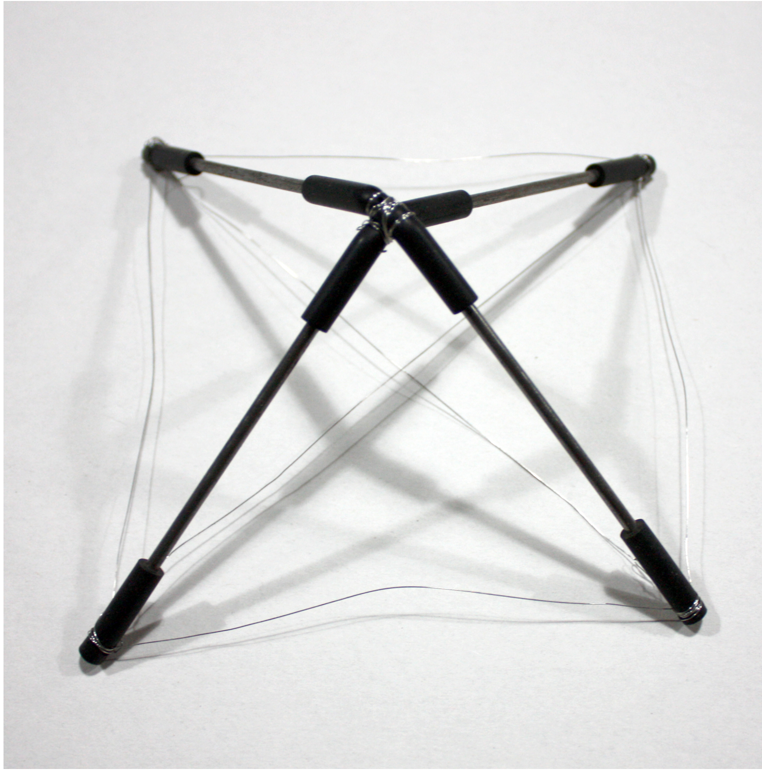

Figure 5.1: Four Member Unit.
Jensen.

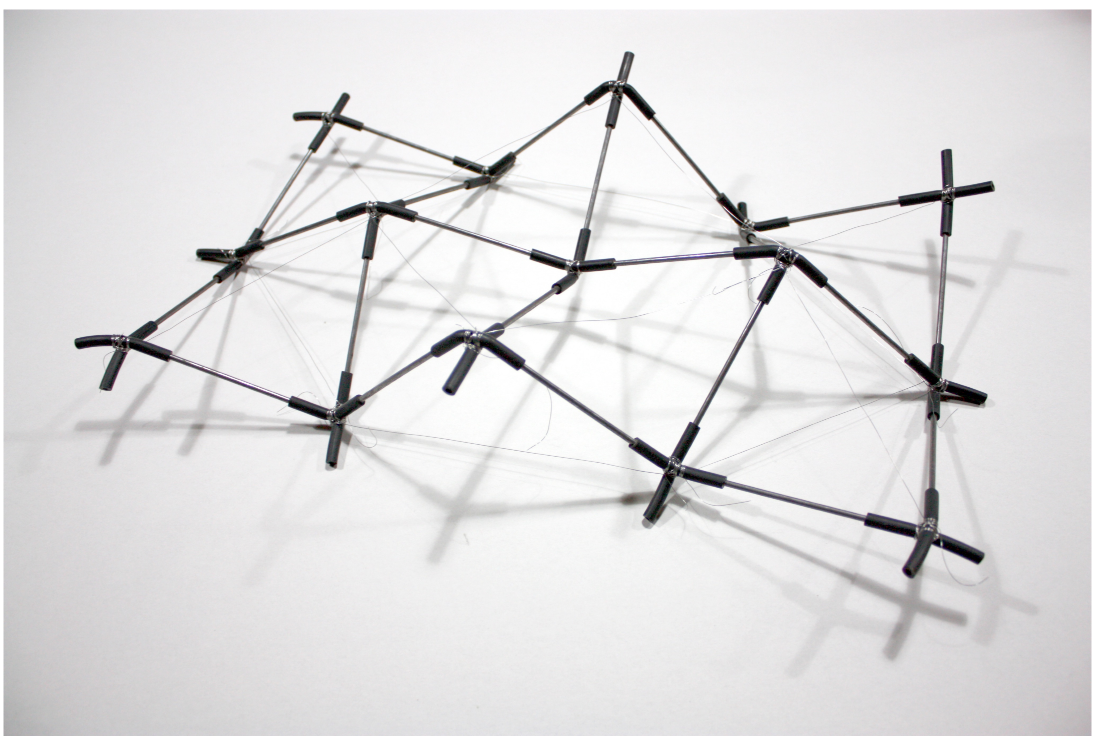

Figure 5.2: Four Member Unit Grid.
Jensen.

Figure 5.3: Stable Octahedron Unit. Jensen.

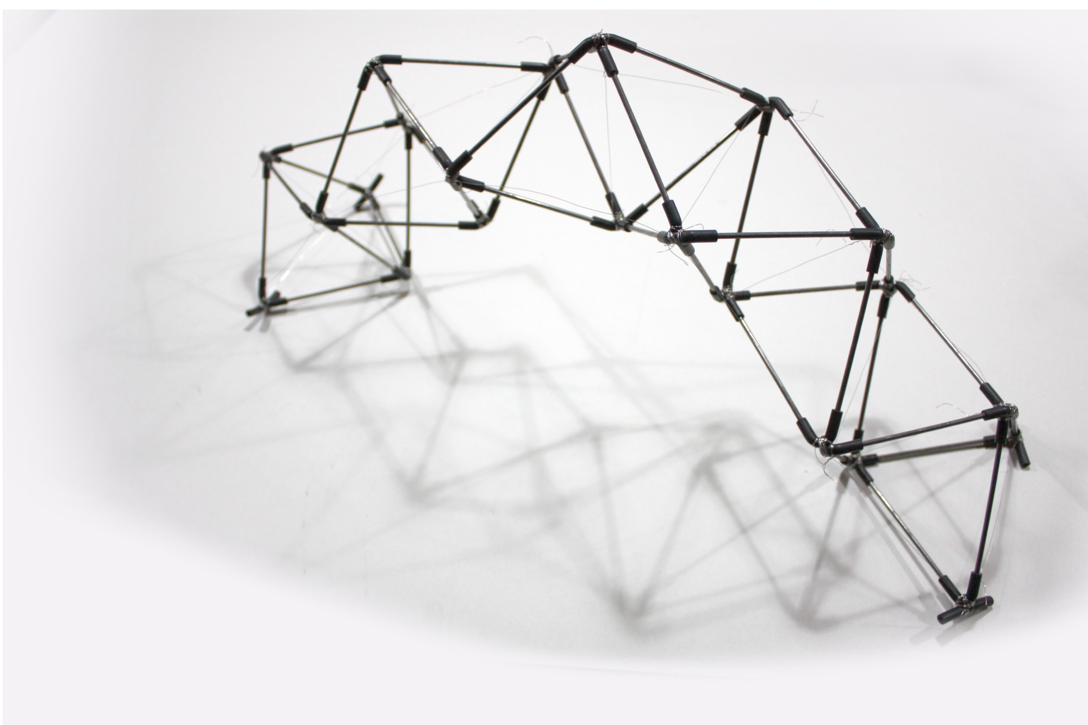

Figure 5.4: Octahedron Grid, Jensen.

collapsible and even interchangeable. Interchangeable strut components would allow for a wide range of substitution based on the availability of building materials, making the use of local materials a possibility.

Figure 5.5

The unique idea behind this object was that tensioned perimeter segments hold the unit's shape. The cable is held in place by internal compression components which, when tightened, push against the vertices of the shape, giving form to the cable netting. The initial goal of creating a building block unit was met, but the turnbuckle acting in compression through the centre of the unit was not ideal. By having a compression member through the middle, the forces exerted to the compression struts were simply transmitting the load down, in a sense creating a spaced out four member component, similar to the unit that failed in the first experiment. It has no cross members to triangulate the rectangle and therefore it is susceptible to rotation around its central axis, skewing the overall shape and weakening the unit.

Figure 5.6

As was expected, stable shapes are made when the object is triangulated, leading to the idea of making three sided objects that can still be attached to one another in a grid. The shape that showed the most promise was a octahedron (eight sided platonic solid) that used compression members internally to tighten an external net of tension cables. Differing from the rectangular experiment, a triangulated variation was extremely stable in all directions and resisted torsion forces because of its much more refined shape. Like the rectangle experiment, the triangulated variation uses a single turnbuckle to tighten the cable net; however, the key difference is that the turnbuckle is acting in tension in this version. The three sided compression members actually slide between each other requiring tension to pull them together. The result is a very stable shape made up of a tensioned cable exterior and the tensioning struts as the tightening device within the shape itself.

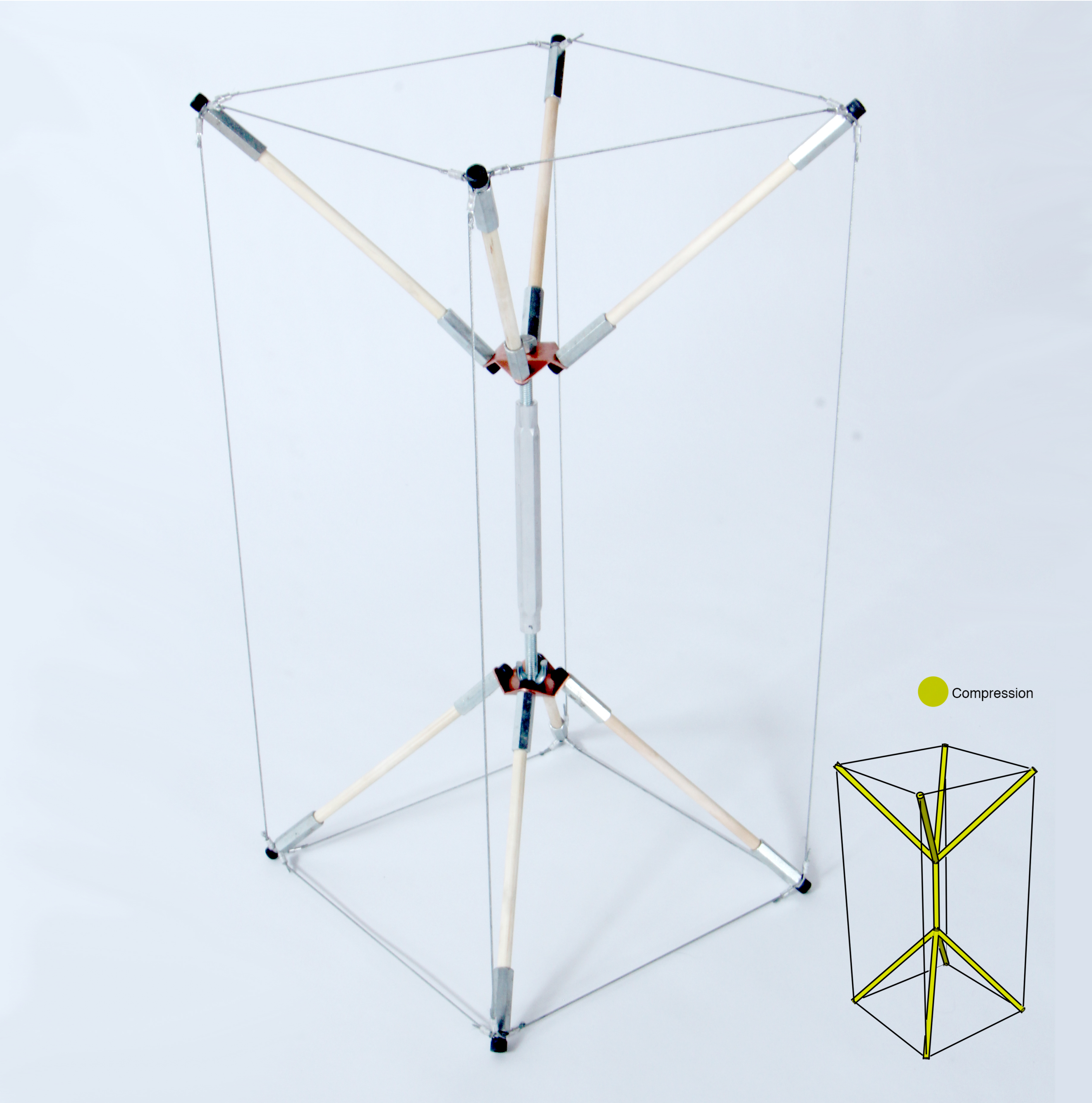

Figure 5.5: Rectangular Unit. Jensen.

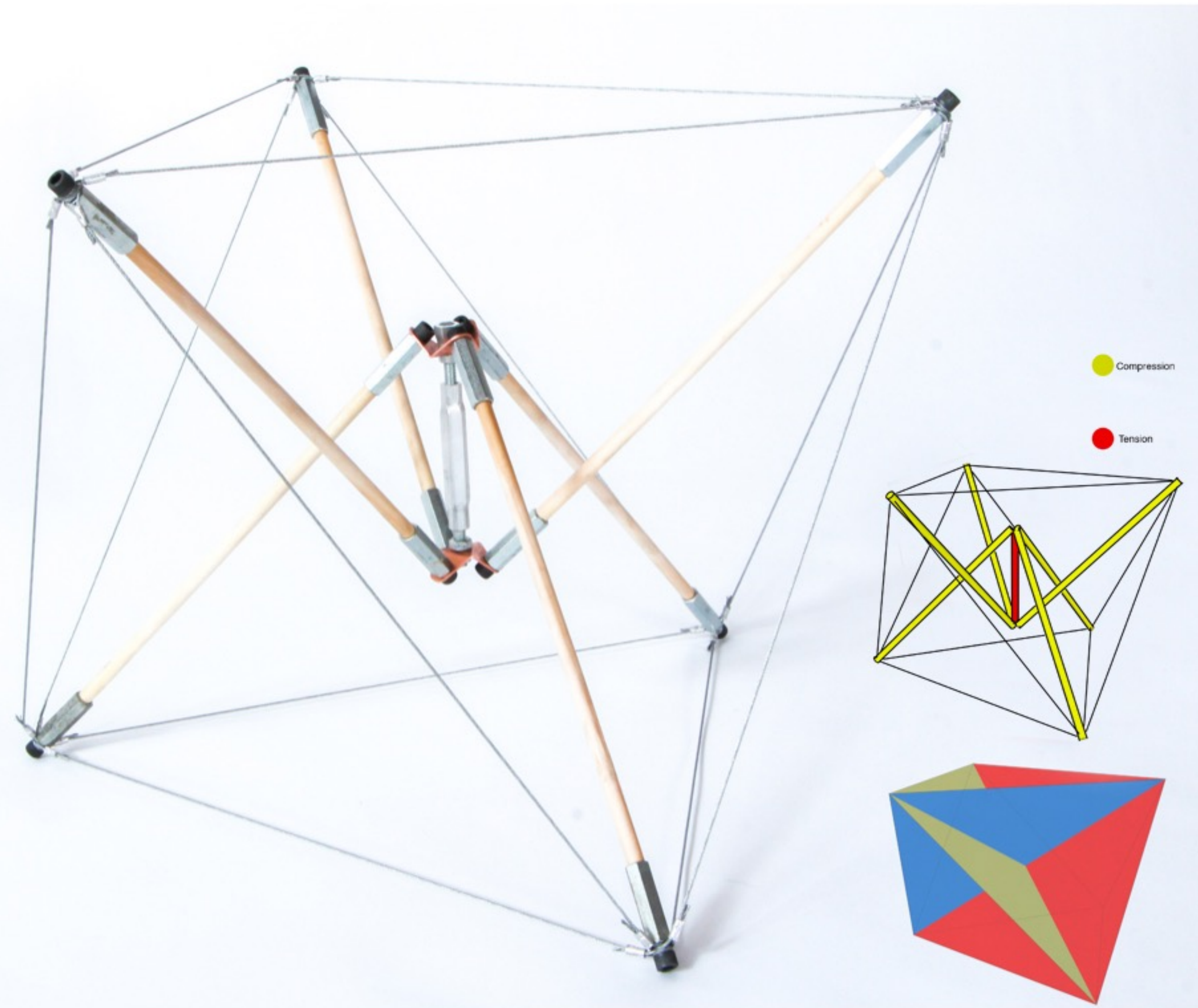

Figure 5.6: Octahedron Stabilized Unit. Jensen.

Figure 5.7

A large number of variations can be seen in this grid model experiment. The grid is not stabilized, as no tension segments are present, allowing the model to be skewed and distorted in many different directions and orientations. The grid can therefore be designed to hold the required shape by fixing the nodes of the units with a designated length of cable.

Figures 5.8-10

A rigid unit is only the first building block of a grid construction. The units must be capable of connecting together in a formable sheet. The structure of each unit then shares the load across the entire grid until connected to the ground. In this sense the shape of the unit can be modified infinitely, simply by altering the angle between units and distorting its components to match up with the neighbouring unit. By altering only tension members the struts are capable of remaining the same and maintaining standard characteristics, ideal as the tension segments are much easier to alter in any given assembly.

Figure 5.11

This shape, starting with the octahedron base unit (8 triangular faces), allowed the grid to be built in a square geometrical pattern with each side of the unit touching the next. It was soon realized that creating a barrel arch was the easiest grid shape that held a form. The high points of the unit dimensions could change depending on the desired concavity. More complicated shapes involving parabolic curved surfaces would require custom joint details connecting the struts, with angles unique to the location on the curved surface. This form was chosen for further investigation, where a dimensioned version of such an assembly was load tested and embodied energy was calculated.

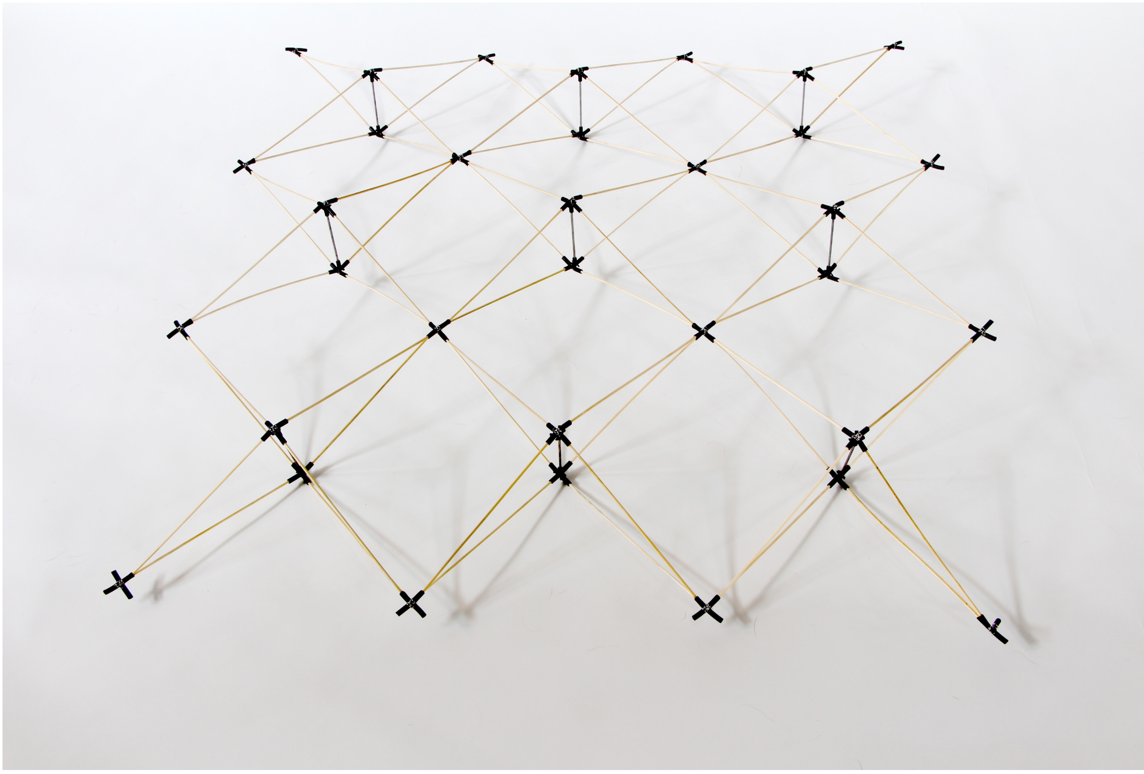

Figure 5.7: Grid Distortion Model. Jensen.

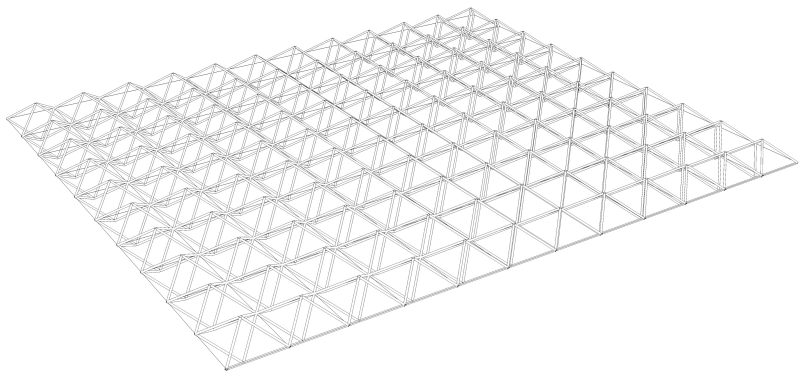

Figure 5.8: Flat Grid. Jensen.

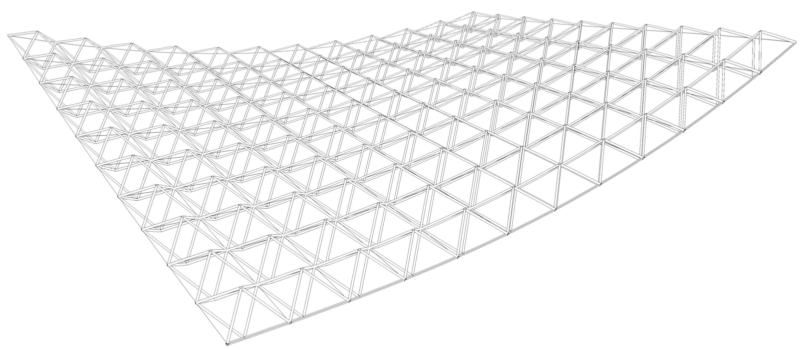

Figure 5.9: Saddle Distortion . Jensen.

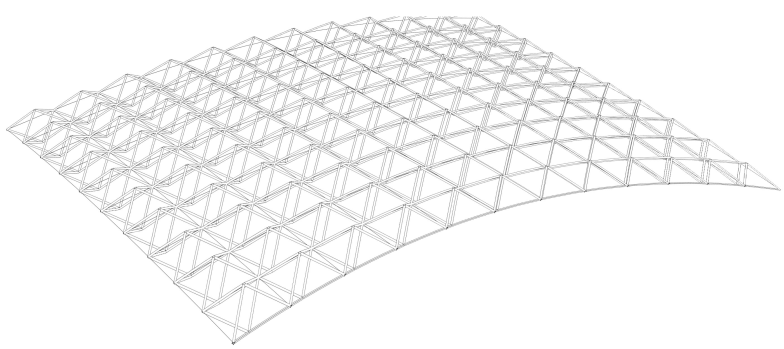

Figure 5.10: Dome Distortion. Jensen.

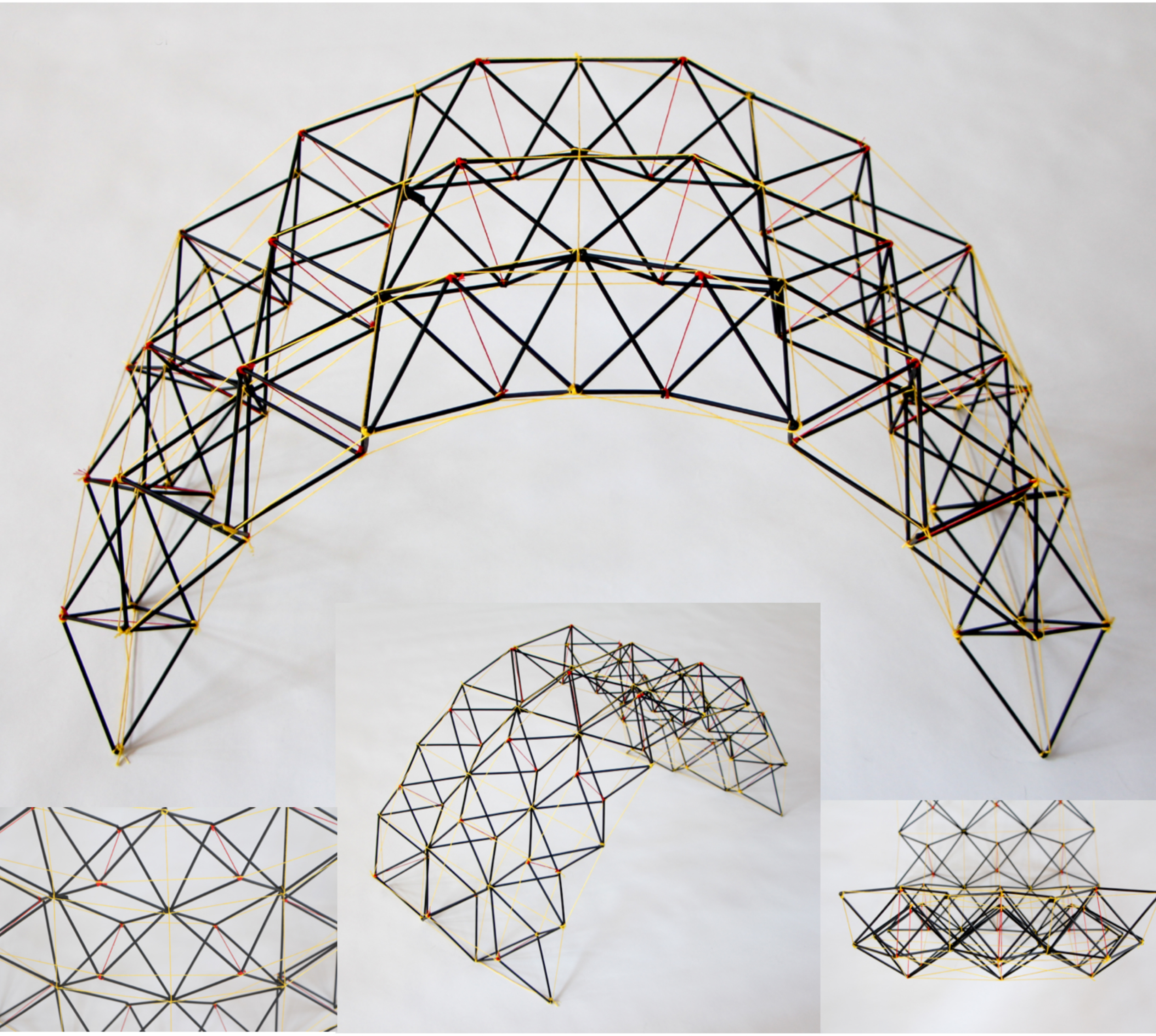

Figure 5.11: Barrel Vault Model.
Jensen.

Figure 5.12-15

A scaled model that could be collapsed and built very quickly was made. The following set of figures illustrates the assembly process of two units. A similar logic could be imagined on a full grid structure scale just as easily.

Figure 5.12: Unpack contents from packaging.

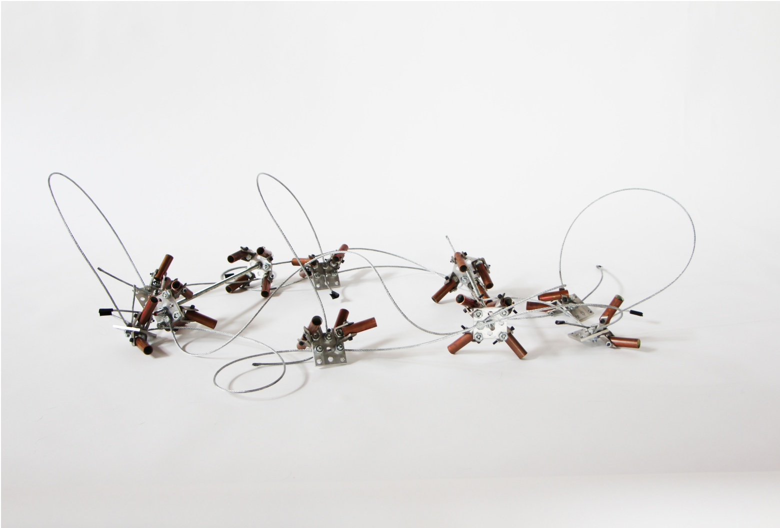

Figure 5.13: Lay tensile components flat on the ground, making sure turnbuckles are in fully opened position.

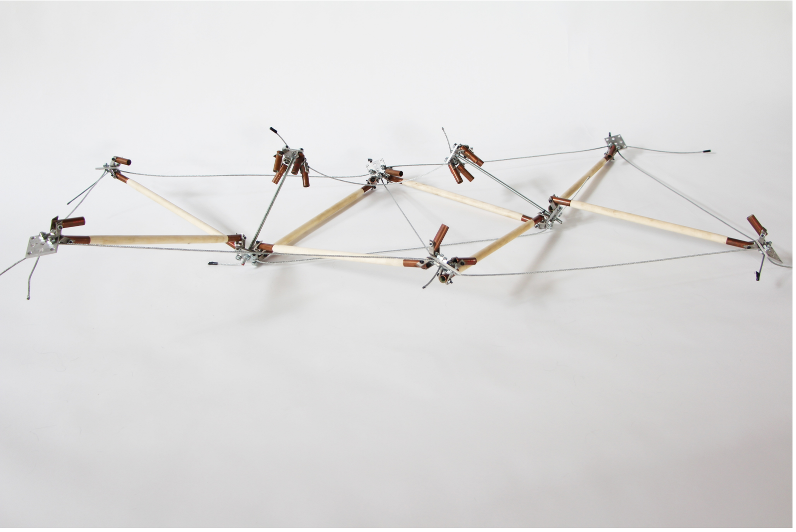

Figure 5.14: Insert compression members into open end of weave components, making sure to have 8 per group (image showing lower half of component).

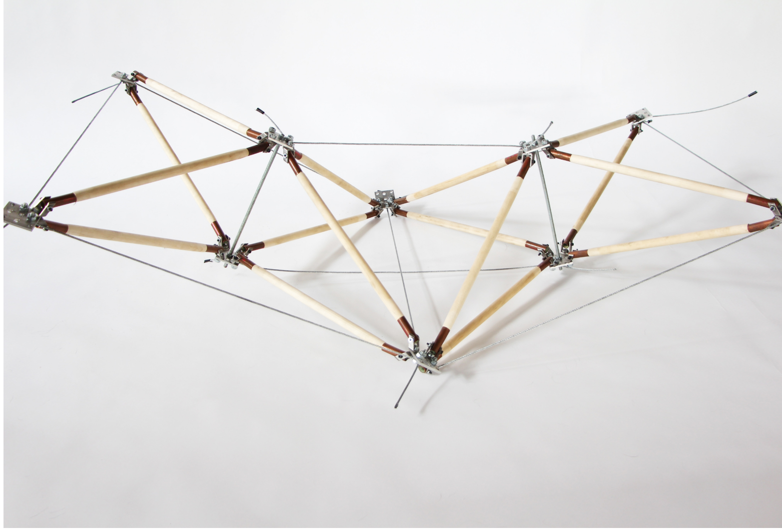

Figure 5.15: Tighten turnbuckles until compression members are tightly compressed. At this point the structure will be standing and cladding can be added.

Figures 5.16-19

Other forms such as the triangle and hexagon were experimented with, resulting in a reduction of components while maintaining a similar volume. Finally, in Figure 5.19 one can see a curved hexagonal form using the reduced pattern to enclose a volume.

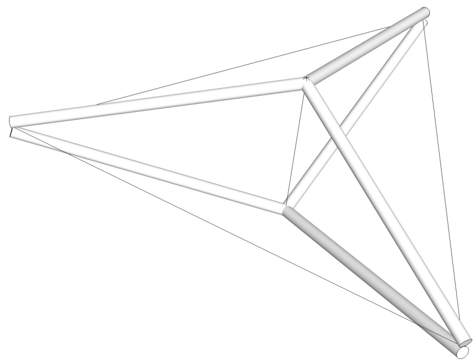

Figure 5.16: Triangular Base Unit. Jensen.

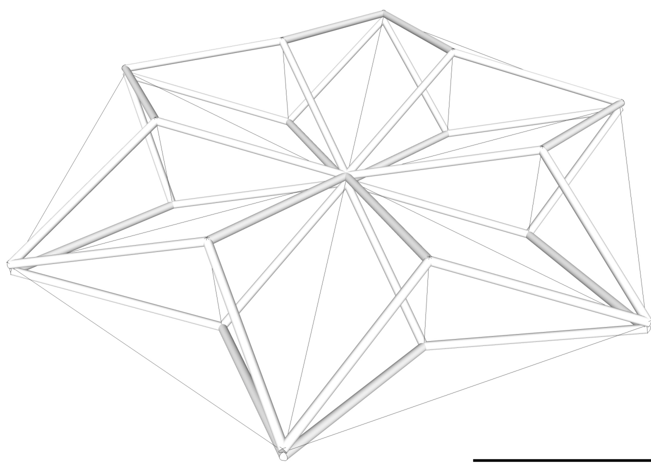

Figure 5.17: Six Unit Assembly. Jensen.

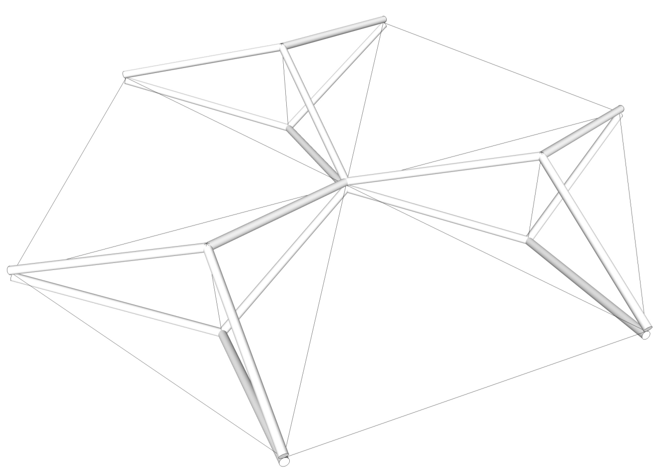

Figure 5.18: Reduced Three Unit Assembly. Jensen.

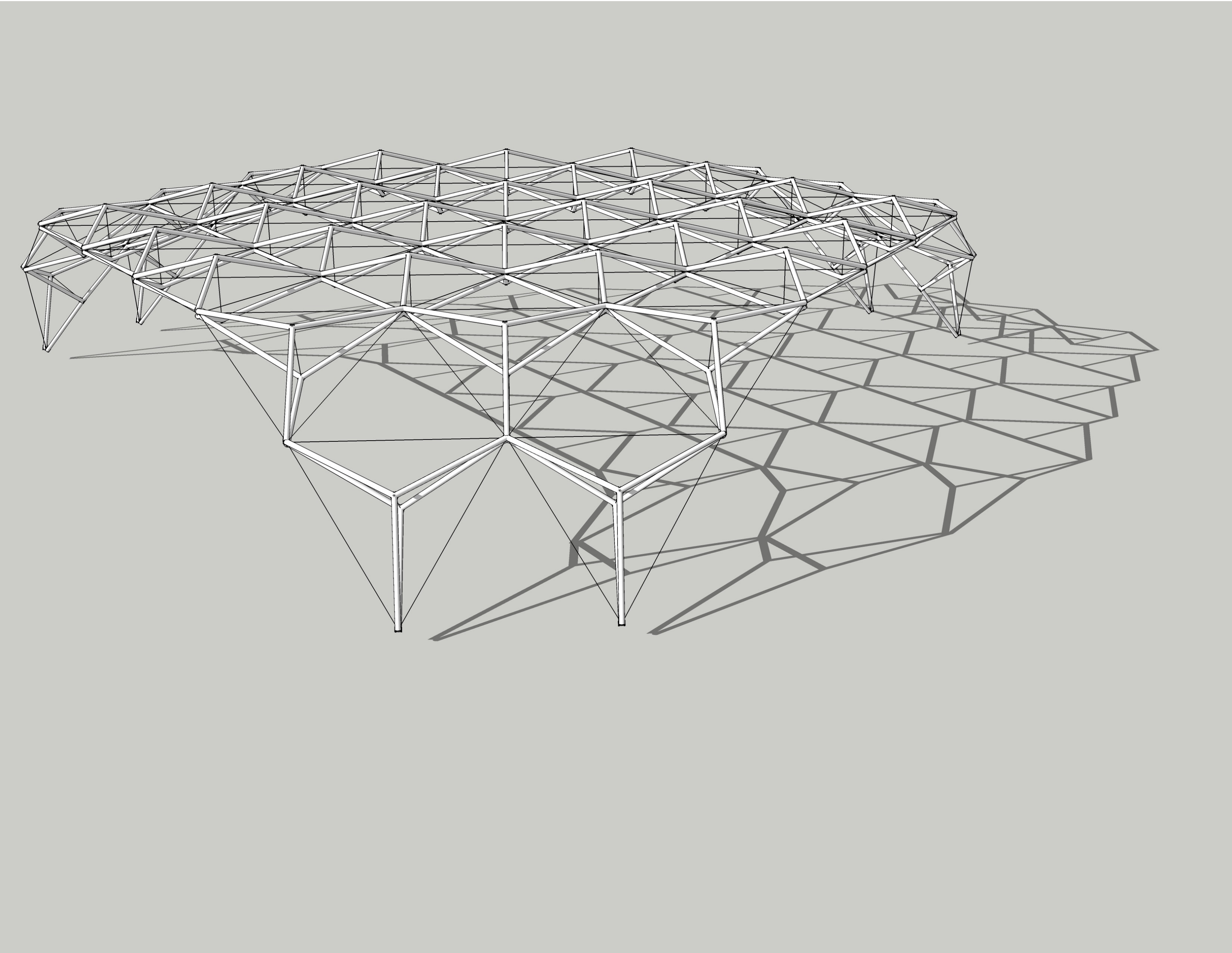

Figure 5.19: Hexagonal Grid Structure. Jensen.

Compression Strut Design

Robert Le Ricolais suggested a research direction to achieve greater efficiency in strut design:

> "I don't mean to suggest that the triangulated element is stronger than the solid, but that through higher degrees of connectivity it could lead to a lighter and more efficient structure."[1]

The objective of this investigation is to establish a strut which is stable on its own but can be assembled with similar struts to form a base unit. In order for the compression member to be effective in a tension structure, a stiffened strut is required, as deflection will lead to an under-tensioned overall structure. The realization of this need in tension structures - as noted earlier in furniture studies (tension bookcase) - redirected my research towards how to stiffen a compression member while keeping it light as well as environmentally sustainable and compact-able.

The proposed members are made up of several smaller pieces of wood spaced to minimize the material weight while at the same time strengthening the member by controlling deformation. A series of designs with this goal in mind were built and tested in this section to find the most suitable option for the task.

[1] LeRicolais, Robert, "Things Themselves are Lying, and So Are Their Images," VIA 2, (University of Pennsylvania: Graduate School of Fine Arts, 1973), p. 25

Bamboo Strut Analysis

Keeping the weight of the structure to a minimum is essential as self weight greatly effects the spans of a system. Less weight means building materials must be optimized down to the individual component. The question then becomes what can be done to an individual strut to lighten it while at the same time keeping resistance to compression forces as well as minimizing bending and deflection. Fuller underscores this issue when he states, “If you load the top center of a thin column, it tends to bend like a banana- its radius of curvature in the bending area gets smaller and smaller.”[2] In order to better understand the relationship of weight to strength of compression members, I designed a series of reinforced members, categorizing their weight compared to their overall resistance to compression forces before failure. The material I selected for the tests was bamboo, one of the most renewable and responsible materials used in the construction industry.

The three members I decided to test differ greatly but all were designed with the idea that by reducing the deflection in the material by adding a stability component, the member itself will become more efficient. By reinforcing the bamboo member, seeing as bamboo is already extremely lightweight and efficient, the resulting resistance found at breaking strength must be significantly stronger in order to compensate for the extra weight. The combinations of bamboo components were selected based on their weight in order to equalize the test components as much as possible. In addition, the natural properties of the members, such as curved nature and location of knuckles, was taken into account to reduce the chances of failure and maximize the unit’s strength. I tested a single bamboo member as well to determine the overall comparison of the units. The results of the tests can be seen in Figure 6.8.

Testing consists of a bar clamp with a pressure sensitive gauge fastened to the fixed plate. As deflection of the member is also important, a height gauge measures the overall deflection through the middle of the segment and the length of the strut deflection is calculated by the number of revolutions that the clamp exerts on the strut. In this way one can compare the overall capability of each strut option (Figures 6.1-2).

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[2] Fuller, R. Buckminster and E.J. Applewhite. “Synergetics 2: Further Exploration into the Geometry of Thinking.” Macmillan Publishing Co. Inc, New york, N.Y., 1979. Print.

Figure 6.1: Weight Measurement Gauge for Testing

Figure 6.2: Bending at the Centre of the Component in Testing

Bound Triple Strut

Length- 72”
Weight- 570 g
Construction time- fast
Complexity of joint- simple
Material - three bamboo members
- reinforced packing tape

The concept in this trial was that the fastest construction method possible in order to reinforce a single slender rod is to sister it with another, as shown in Figure 6.3. In this case the member was sistered twice, resulting in a triangular assembly bound over 10” with reinforced packing tape. Although crude in construction, when together the assembly seemed to fill in any weak or twisted spots that the neighbouring member possessed. For example, the knuckles of the bamboo did not line up perfectly, giving a reinforcement to one another where the largest chance of breakage occurs. Secondly, as the imperfect bamboo was lashed together, a helical pattern of self organization for optimal packing was observed, again filling in the parts of the bamboo where the greatest amount of deflection and therefore threat of fracture could occur.

The tests showed that even though reinforced, the thickness of the component in the centre was not increased enough to stop large amounts of deflection from occurring. The vertical deflection was observed to be 121 mm and the horizontal deflection 92 mm. The test was halted at the point of imminent failure. Much like a single bamboo member, the bending in the middle of the component reduced its ability to resist compression forces and was only able to resist 100 pounds of pressure. Interestingly, the 100 pounds was recorded after the length of the compression member was at 67mm, showing that the compression force exerted was only causing more deflection and not continuing to add value to the compression resistance.

Figure 6.3: Single Bamboo and Bound Triple Member. Jensen.

Tensile Reinforced Single Strut

Length- 72”
Weight- 763 g
Construction time- slow
Complexity- high
Material

- single bamboo member, three small 10” bridging stiffeners
- three turnbuckles
- 432” 1/16 aircraft cable
- two aluminum mounting plates
- five 1/4” bolts and 8 nuts

This design, although very complicated in construction (Figure 6.4), was created in order to reduce the deflection seen in the compression members. Although a similar sized bamboo rod was used in the experiment, the proposed use would be to stiffen a larger single member than was utilized in the test, possibly a different species entirely from bamboo. A triangular bridging component was added in the middle of the member to help reduce the slenderness of the member from buckling due to deflection. Acting as a king post, this bridge adds a point to the middle of the member to help reduce the deflection of the compression component. This makes the overall force it could withstand much larger than just a single non reinforced member as the bending is controlled, keeping the strut in a more aligned axis of resistance.

The drawback of this design is that before the member is even used as a component in the truss assembly, compression forces are already being applied, as the bridging requires some force to hold the cables taut. This force does help to stabilize the member but in this case, when using an extremely thin member, the added weight of the assembly and the time required make its application less effective in the overall construction. Balancing the tensile forces in the member is also important as over tightening one set of cables could actually reduce the component’s resistance to bending and therefore reduce its efficiency. It seems that this solution is overcomplicated in its construction requirements and extra material needs.

The test revealed that at 100 pounds of pressure, the member failed with only having 13mm of deflection at the middle of the component. When compared to a single member with no reinforcing, it showed a far better resistance to compression loads through its resistance to deflection. Therefore the design was successful in that it increased the efficiency significantly but with a weight 4 times that of a single member, these benefits are severely compromised. During the test the bending was observed within the component segments on either side of the bridge, reducing the overall deflection greatly. An S bending pattern could be observed before the member broke (Figure 6.6), and the overall length change was very minimal before the member failed, only 19 mm.

The failure in this case was seen not at the midway fastener but where the bamboo met the end plates. On both ends, compression led to the material splintering along its length, destabilizing the core of the structure. A reinforced base assembly may have alleviated this problem, but more weight would have been added to an already overweight detail. I believe this may be a viable option for members that have greater resistance to compression, possibly a thicker variety of bamboo, but for this application I feel there are better solutions.

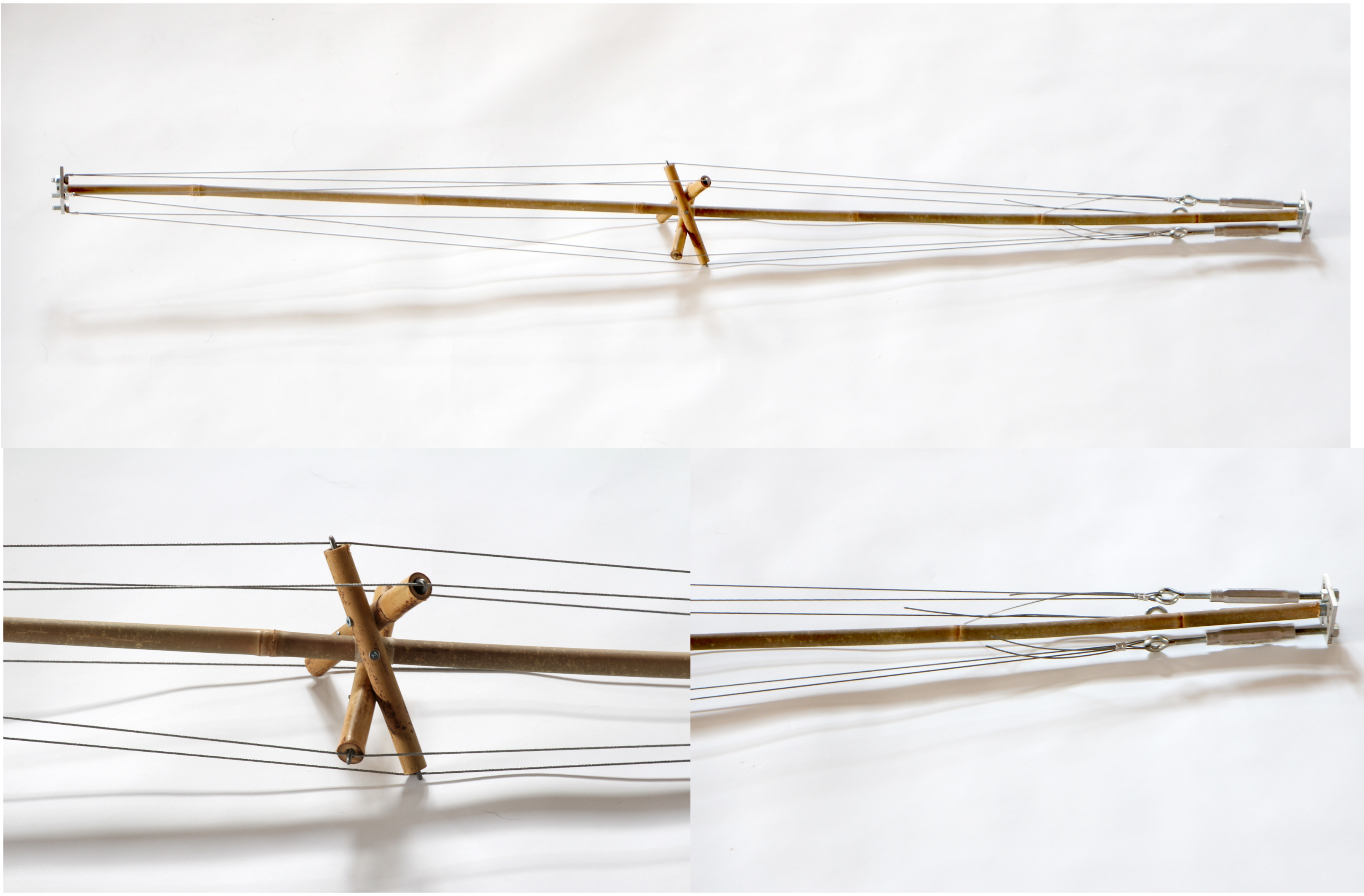

Figure 6.4: Tensile Reinforced Single Compression Member . Jensen.

Three Member Bow Strut

Length- 72”
Weight- 570g
Construction speed- fast
Complexity of joint- intermediate
Material - 3 bamboo members, 3 small 10” bamboo bridging members
- reinforced packing tape and screws

The concept of this truss was to create members loaded with a bending force to counter the bending forces applied during compression (Figure 6.5). By adding the bridging to the centre a truss is formed, breaking the 6’ segment into two 3’ segments, which adds strength to the overall member. The overall increased resistance to bending stiffens the member substantially and allows it to resist far greater compression forces.

The test proved the theory, outperforming the other two designs in all of the categories. The compression load it was capable of resisting before failure was 405 pounds, 4 times greater than the other two options. The deflection of the member in the centre was 15mm and 28mm over its length. The makeup of the members requires minimal materials and the weight increase is very minimal considering the gain in overall performance.

The deflection of the individual rods in the experiment created a curve on each side of the midpoint (an “s” shape again) (Figure 6.7). The failure was seen as a result of the fasteners used to secure the bridge to the rods. Small cracks appeared where the bamboo was screwed together which, as the pressure increased, spread down the length. Only one out of the three failed completely, but stress was showing in the other two as well. With a different fastening detail I feel that this design would take more compression force and that further testing is warranted using this shape as the best example of how to increase a strut’s efficiency.

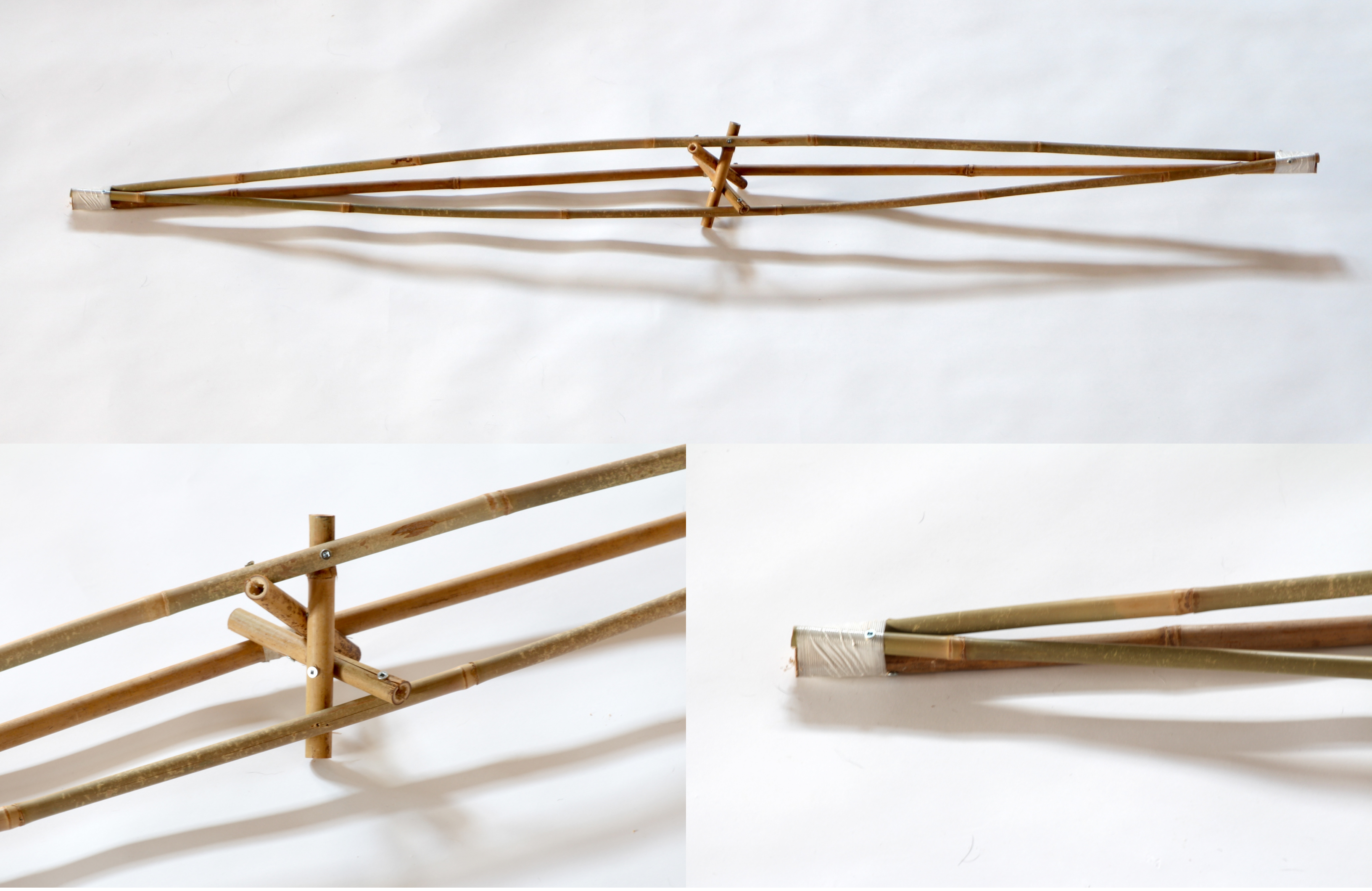

Figure 6.5: Three Member Bow Strut. Jensen.

Figure 6.6: Just before and just after Failure of Tension Reinforced Strut. Jensen.

Figure 6.7: Just before and just after Failure of Three Member Bow Strut. Jensen.

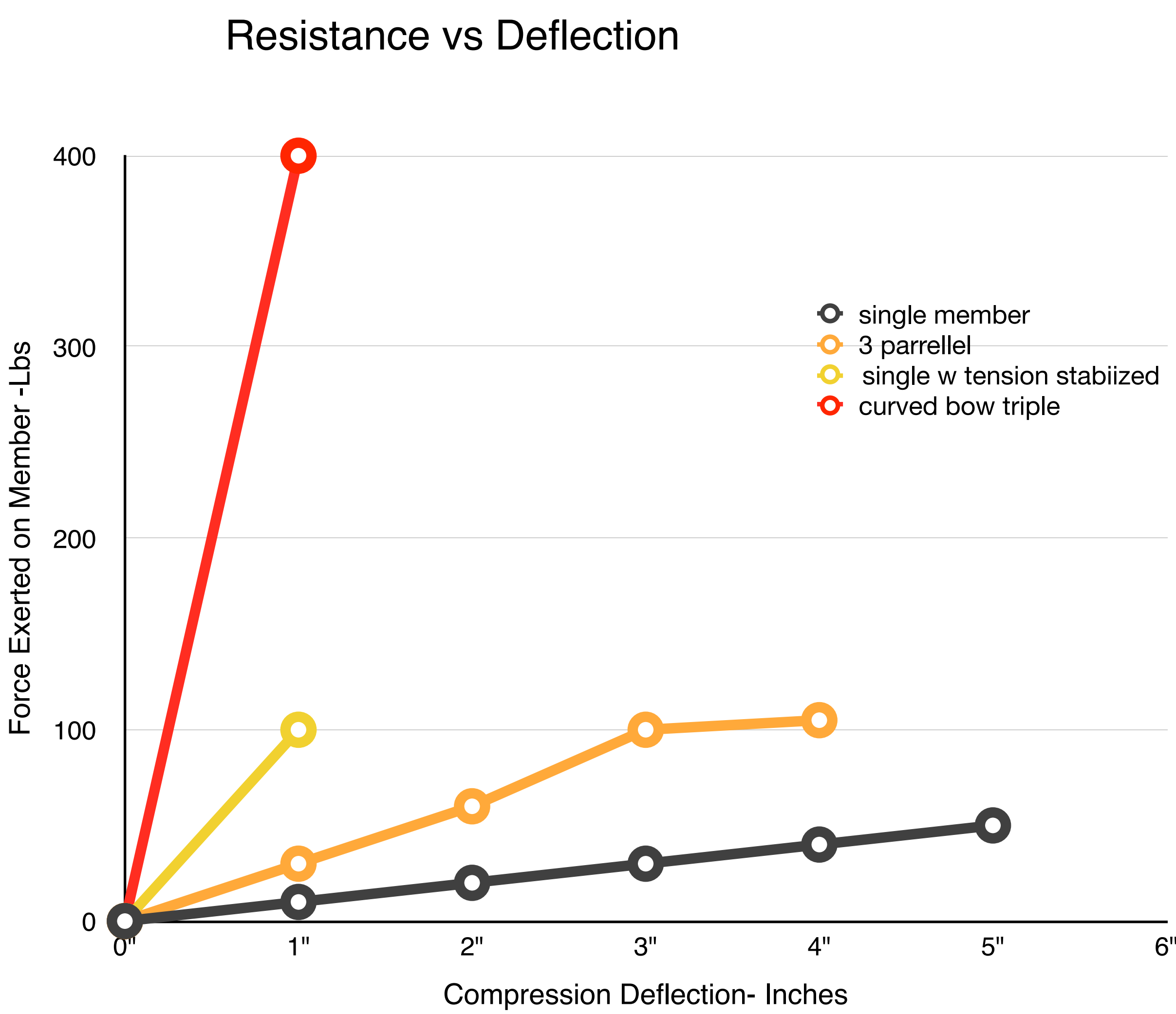

Figure 6.8: Graph of Test Results.

Future Bamboo Testing

That this experiment has showed me the benefits of the three member bow truss over the other designs and for that reason I conducted a new series of tests using this shape as the ideal form. I believe that construction details which do not penetrate the bamboo but instead rest on the outer surface of the bamboo members will increase the overall performance of the member without adding substantial weight. I would also like to experiment with multiple bridging components to break up the overall length of the component into a greater number of segments, as this approach should mathematically decrease deflection even more than has already been observed in the previous experiment.

Pine Strut Experiment

The testing of materials used commonly in construction practices is useful as they are readily available and already accepted. In this case spruce, pine, or fir, similar to the standard dimensioned building material, will be substituted in place of the bamboo. The results of the triple bow truss experiment have shown how this shape is far superior to the other design strut shapes and therefore it will inform my further testing for this new material (Figure 6.9).

SPF is a sustainable building material as it is grown and harvested with care and strategy. In addition, at the end of its life cycle it can be broken down and used as composted matter. It is easily formed/manipulated into shape with low embodied energy processes. Many climates offer specific species which can be easily adapted to the design, creating a local input into the project and reducing associated transportation costs. Wood is the ideal building material as evidenced through its use in common construction for centuries.

Ideally this structure is designed to last a minimum of 50 years before repairs and replacement of components may be required. The components that are made of wood ideally can be replaced at this time and then the structure can be reinstated in much the same position. In addition, because of the minimization of material, waste is kept low and the overall requirements of natural resources can be kept extremely low.

Metal sleeve connectors are used on both ends as well as on a central tensioned band, holding the members in place and minimizing deflection when the strut is put into compression. Metal connections also allow for greater shear resistance and increase ease when assembling the pinned connections in the truss unit. This material is used sparingly as it is less renewable, and weighs and costs more. Its advantage is in its ability to be welded and formed with extremely thin gauge material, allowing for reinforcement at joints where greater stresses are present.

Triangular shaped components increase the overall efficiency of the material as well as minimize waste material. By using spacing blocks, equilateral triangles can be grouped together to form hexagons on the ends, which allows there to be 3 parallel planes on both ends of the member itself. A hexagon is much easier to integrate into a unit as the connections are in line with each other. A second prototype was made using a triangular based section which uses less weight in blocking material, but the triangular shape is much more challenging to link as a pin connection, meaning more steel will be required when compared to the hexagonal assembly.

The majority of the structure is prefabricated and packed in such a way that on site construction time will be significantly reduced. The compression members will be pre-assembled - the only necessary assembly will be inserting the spacing block in the centre of the member. After that is completed the strut can be inserted into the overall assembly. If rapid construction is desired for the project the strut may be 100% prefabricated and assembled before the material arrives on the site. Full scale prototypes were built to better understand the construction process required for such details (Figure 6.10).

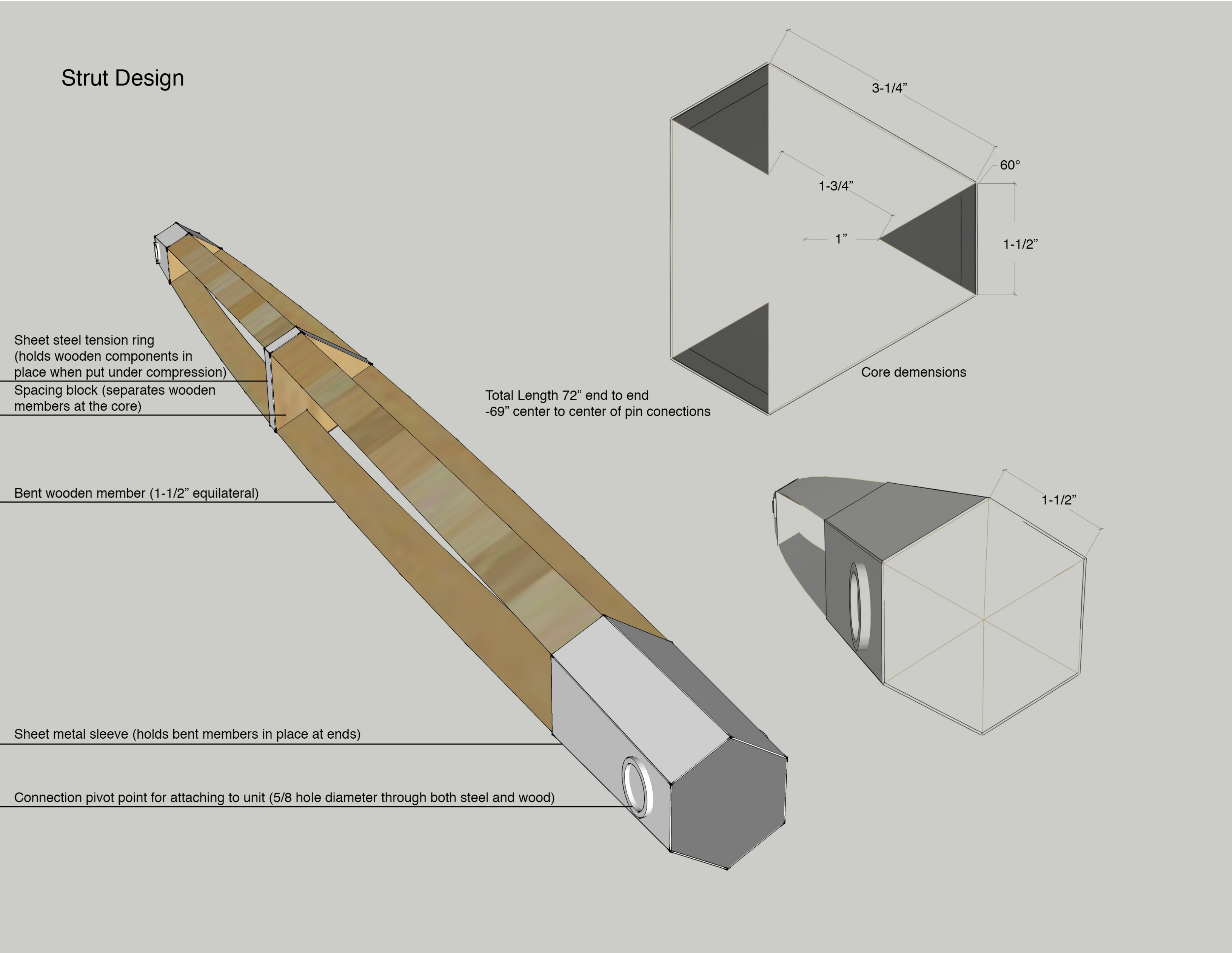

Figure 6.9: Pine Strut Dimensions. Jensen.

Figure 6.10: Pine Strut Prototypes.
Jensen.

Testing of Pine Struts

Since safety, as well as accuracy were a concern, the Civil Engineering Structures lab was used to test the axial force resistance of these struts (Figure 6.13). The controlled setting and accurate testing equipment allowed for a greater understanding of how well these struts function under a simulated compression load.

A pin connection similar to what is proposed in my deployable experiments was required, meaning that the construction of a test yoke which simulated such a connection was needed (Figure 6.11). Its construction was extremely over engineered to ensure that the failure would be seen in the member itself rather than in the testing apparatus (Figure 6.12). This pin connection is not as strong as if a similar such member was attached with a fixed connection but is required for the rapid on site construction that is desired in this application of such a strut.

Modifications to both of the existing strut members were also required to allow them to be connected to the yoke. In this example a bolted connection was used, requiring reinforcement at the point where the pin was inserted to stop the thin sheet metal from shearing when the force was applied (Figures 6.14-15). In addition, the end of both test struts was capped so that the individual triangular components did not slip through the bottom of the assembly. The central tensioning ring was also prefabricated to exactly hold the bridging block in place (Figure 6.10) and therefore reduce the sharp edges which would cause the strut to fail prematurely. This modification also created a much more rigid connection as opposed to the pin connection seen in the bamboo experiments. This design added a small amount of weight to the assembly but as the yoke was custom made to a close tolerance, a minimum amount of bulk was added to each assembly.

Test Jig Set-up

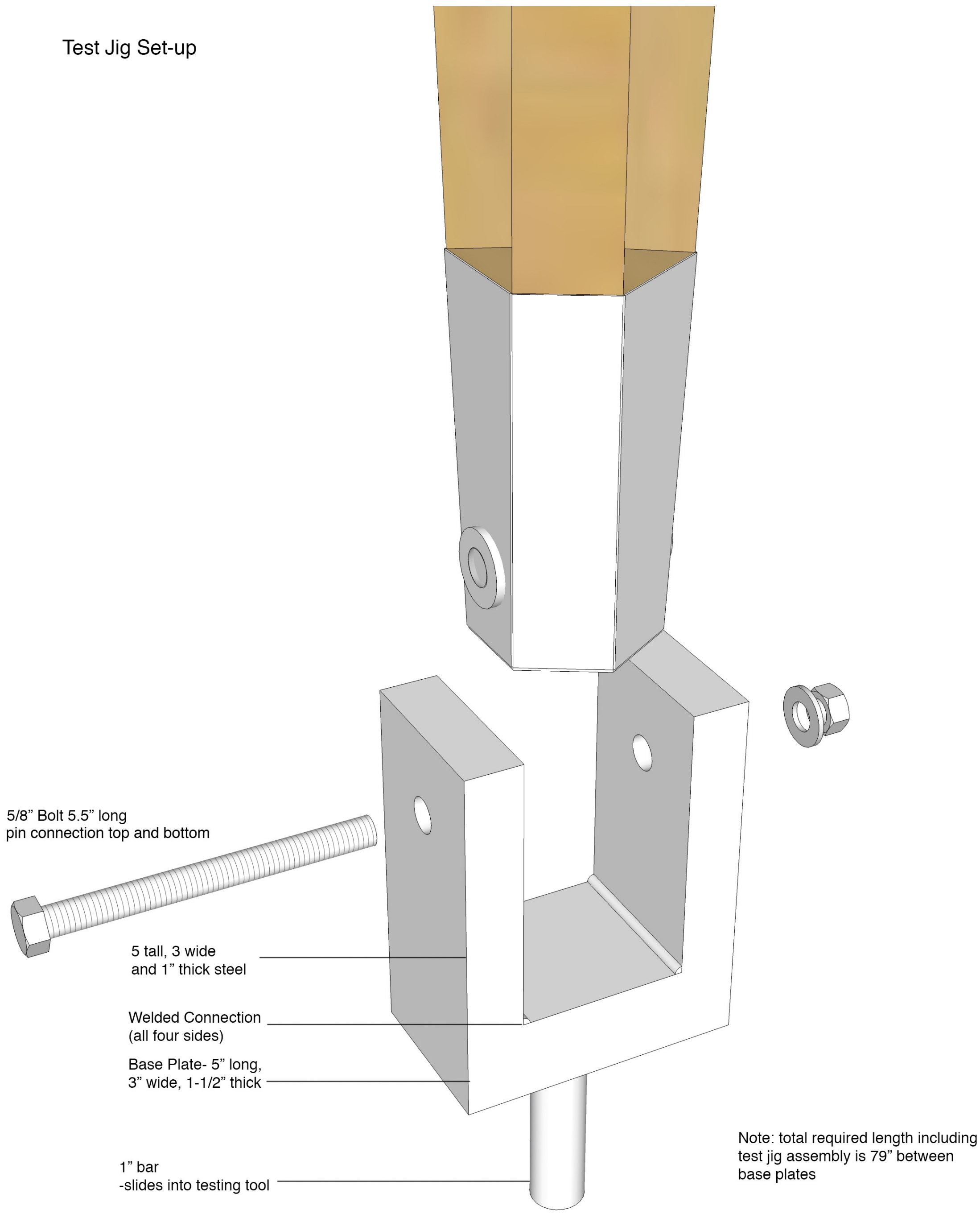

Figure 6.11: Yoke Connection for Testing. Jensen.

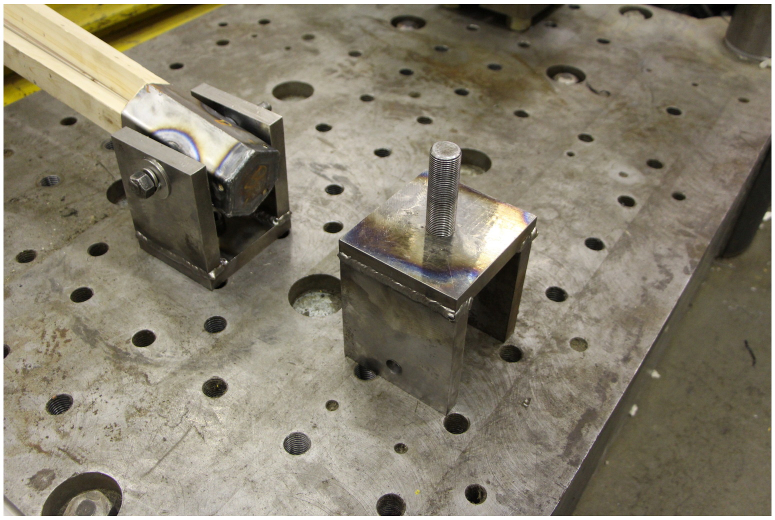

Figure 6.12: Test Yokes. Jensen.

Figure 6.13: Testing Setup.

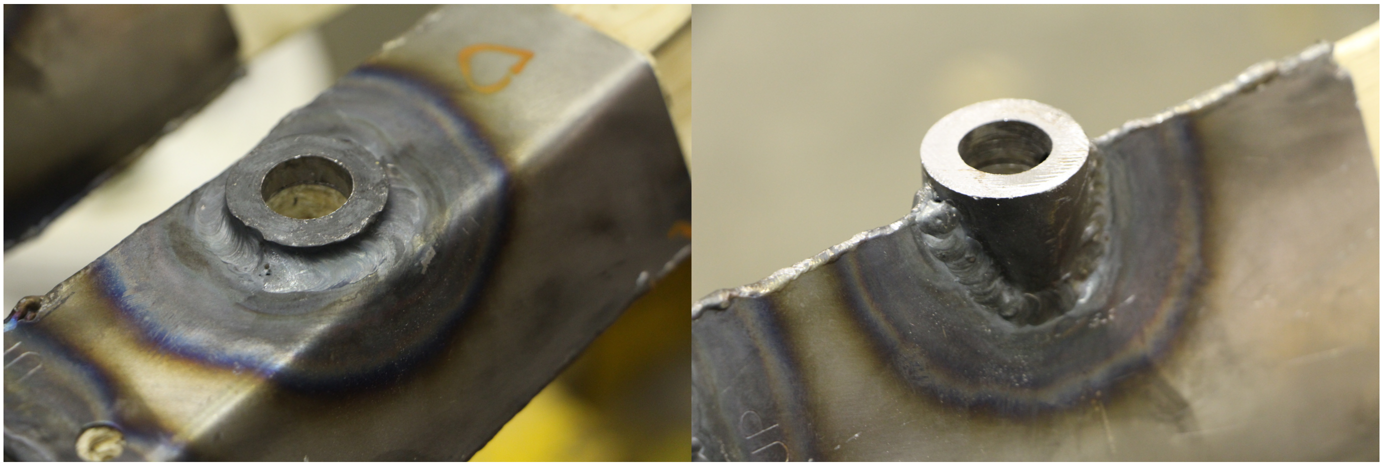

Figure 6.14: Reinforced Bolt Connection. Jensen.

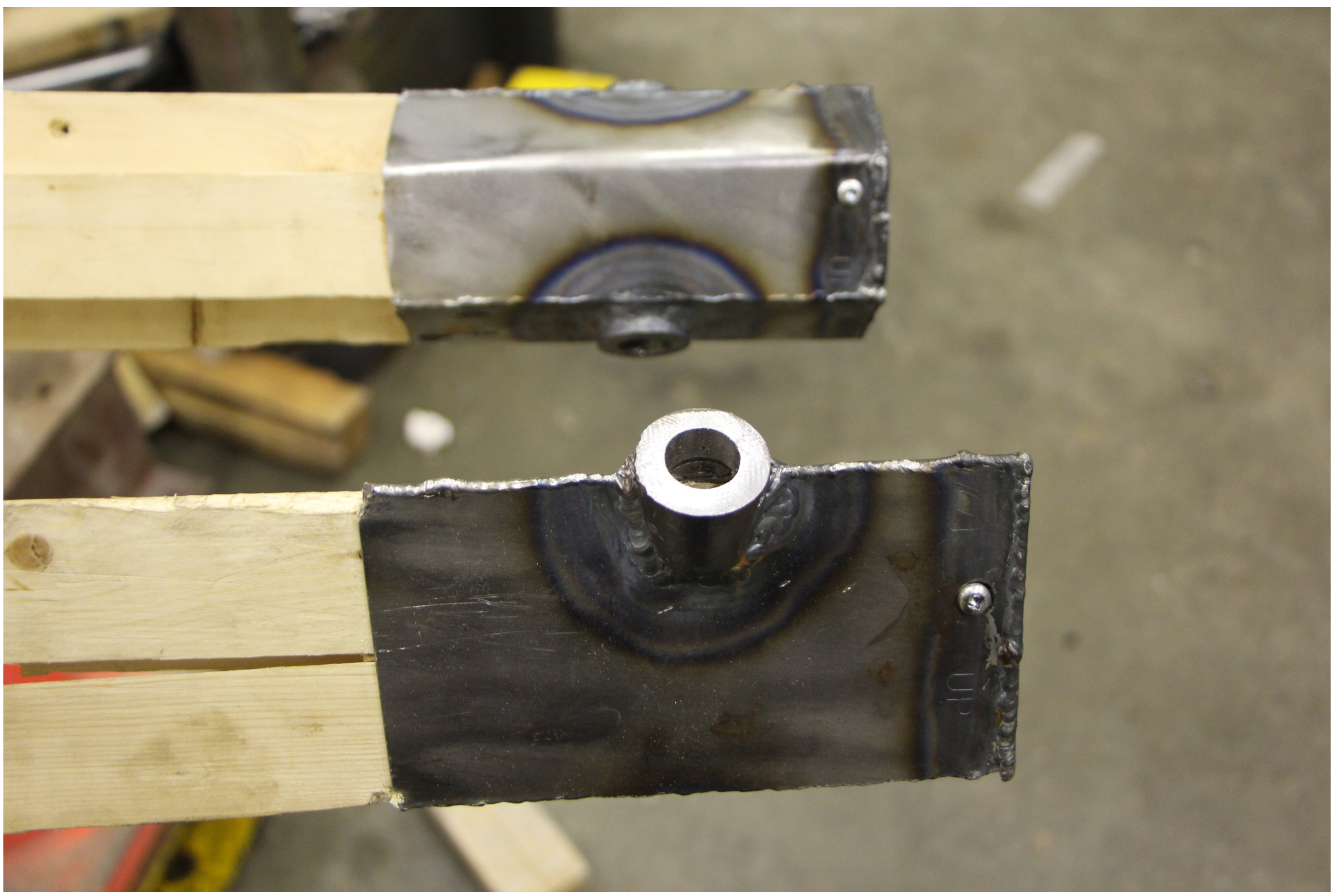

Figure 6.15: Test Struts. Jensen.

The test struts were constructed using equilateral triangular spruce components at 1.5 inches, differing only in the number of small spacing blocks used in the ends. The orientation of the components differed, creating a flat plane on the outside face of the hexagon and a pointed exterior surface on the triangular test strut. The materials used were very similar, with weights of 2987.1 grams (hexagon) and 2962.9 grams (triangular), and having identical heights at point connections. The measure of their splay in the middle was comparable as well, allowing for a similar comparison when put under similar straining conditions.

They both failed in a like manner, bending off of the central axis before the material sheared apart near the tensioning ring in the middle of the strut. I thought that there would be a greater amount of internal twisting in the segments themselves similar to that of the bamboo; however, I believe the triangle shape of the parts in contrast to the tube/rod of the bamboo stabilized the parts and caused the entire strut to bow out of centre. Also, the stiffer centre tension ring held the components much tighter than the screw detail seen in the bamboo. They both bent perpendicular to the pin connection in different directions which is typical of such a connection. Figures 6.18-19 show the deflection of the failed struts.

The results of the test showed the hexagonal configuration as able to hold a greater amount of axial force, peeking at 15.38 kN with an axial displacement of 6.6mm. Figure 6.16 shows a graph of the test results. The triangular member's axial force peeked at 14.31 kN with an axial displacement of 8.7mm. Figure 6.17 shows a graph of the test results.

It would be interesting to consider how much a change in the size of the core bridging would influence the overall performance of the struts. My concern would then be adding too much bending strain on the wood before it is loaded in compression. In this sense a type of wood that is more stable under bending stresses such as ash may be a better choice for future testing. I feel the spruce would fail during the assembly process if subjected to much greater forces than were applied in these examples.

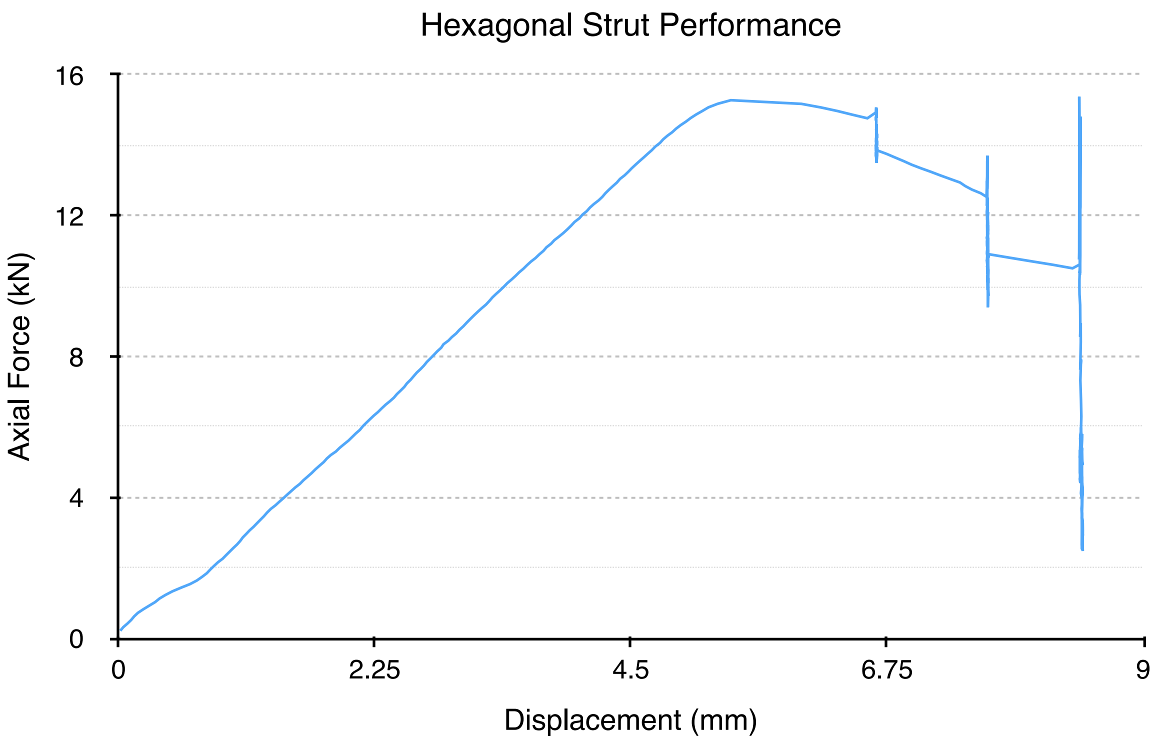

Figure 6.16: Hexagonal Strut Performance. Jensen.

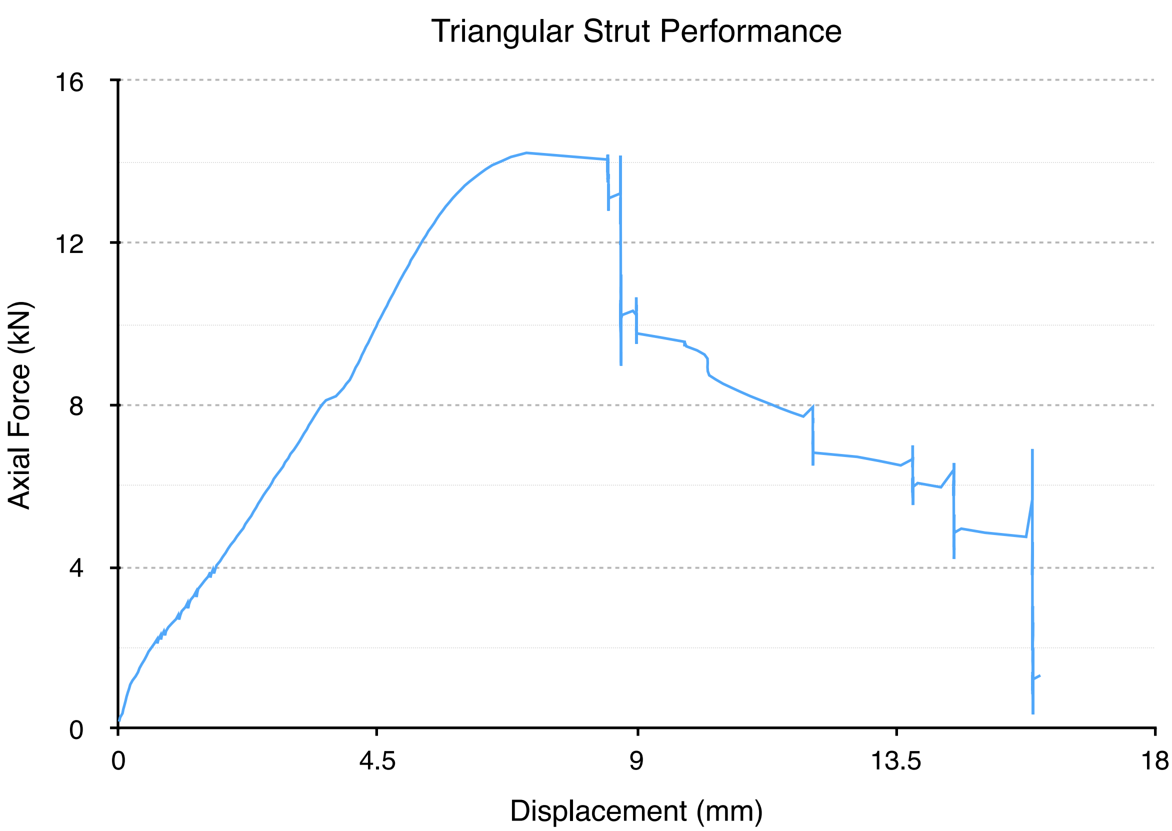

Figure 6.17: Triangular Strut Performance. Jensen.

Figure 6.18: Failure of Hexagonal Strut. Jensen.

Figure 6.19: Failure of Triangular Strut. Jensen.

The Arch

Transferring the knowledge gained in scale modelling to the scale of building proportion poses a significant challenge for complex structures. A simplified shape, the arch, was chosen as it is desirable for the first calculated form before more complex shapes are attempted at building scale (Figure 7.1). Common segment sizes and angles between components create building structures which could be easier to understand and assemble quickly. This relative simplicity of the arch shape is in fact its greatest asset, as it reduces the potential points of failure to their minimum and is one of the earliest forms of structural ingenuity known for its strength.

The stable octahedron unit that was studied in the preceding investigation on shapes was chosen for the arch structure, as it possesses the greatest potential for modification, both on a unit scale as well as an overall assembly. The unit is linked along its cable axis to similar sized units (Figure 7.2). These individual units are linked in a grid that is 10x12 or 120 units (Figure 7.1). A grid tension cable network is attached to the top and bottom of the units, creating a network of cabling needed to cover the desired area. While one can change the footprint by flattening the curve or rendering it steeper, such modifications do not constitute the ideal configuration analyzed in the following pages.[1] The dimensions of the arch under investigation here are: 23m x 17.3m, for a total footprint of 397 m2.

The following includes load calculations on the structure as a whole, a breakdown of the component parts in an energy analysis, details of individual components, followed by an example of instructions illustrating how the entire structure could be assembled in a deployable situation.

[1] Variations on the arch structure will be considered in the following section.

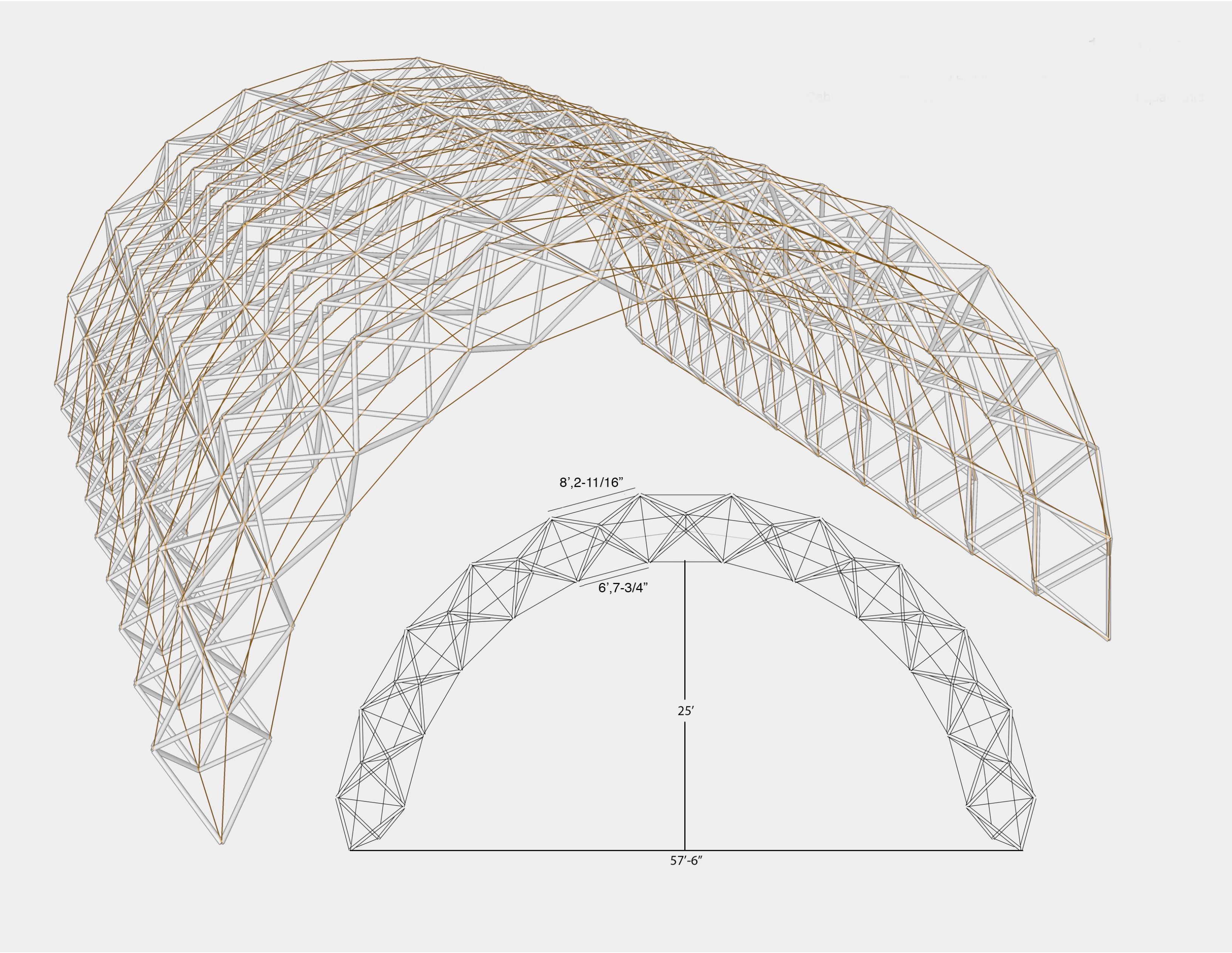

Figure 7.1: 12 Unit Barrel Arch. Jensen.

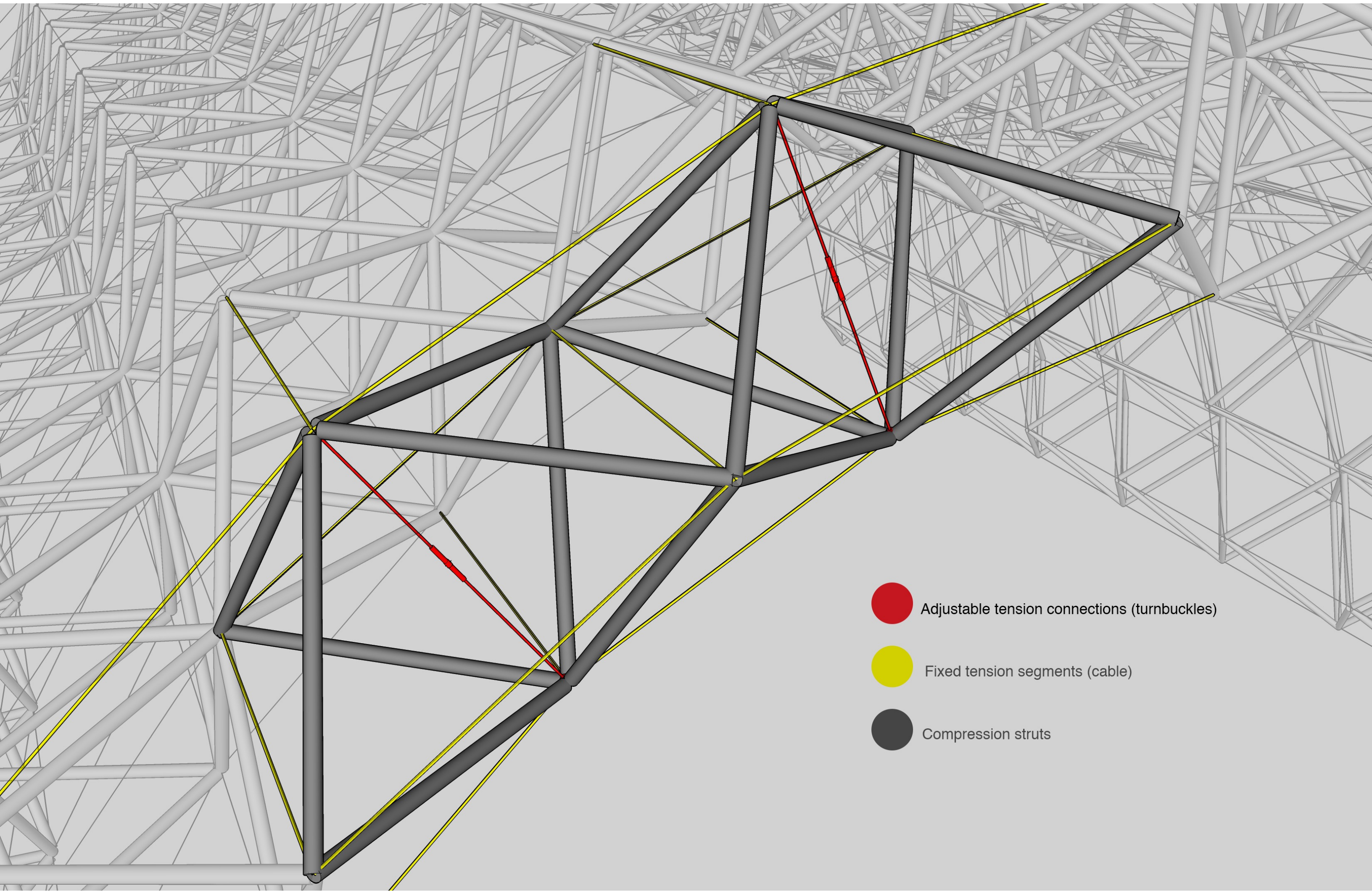

Figure 7.2: Two Units Connected Within the Grid. Jensen.

Arch Structural Testing

Calculating the forces acting on the arch can show its value as a structural system. In Figures 7.3-6, it can be seen that the distribution of forces is fairly even, with the greatest increase showing at the highest point of the arch, directly below the loading location. One can extrapolate, through knowledge of the arch shape, that the more you flatten out the shape, the greater the strain on the centre would be. Further studies may include increasing the depth of the top units to better handle the added stress.

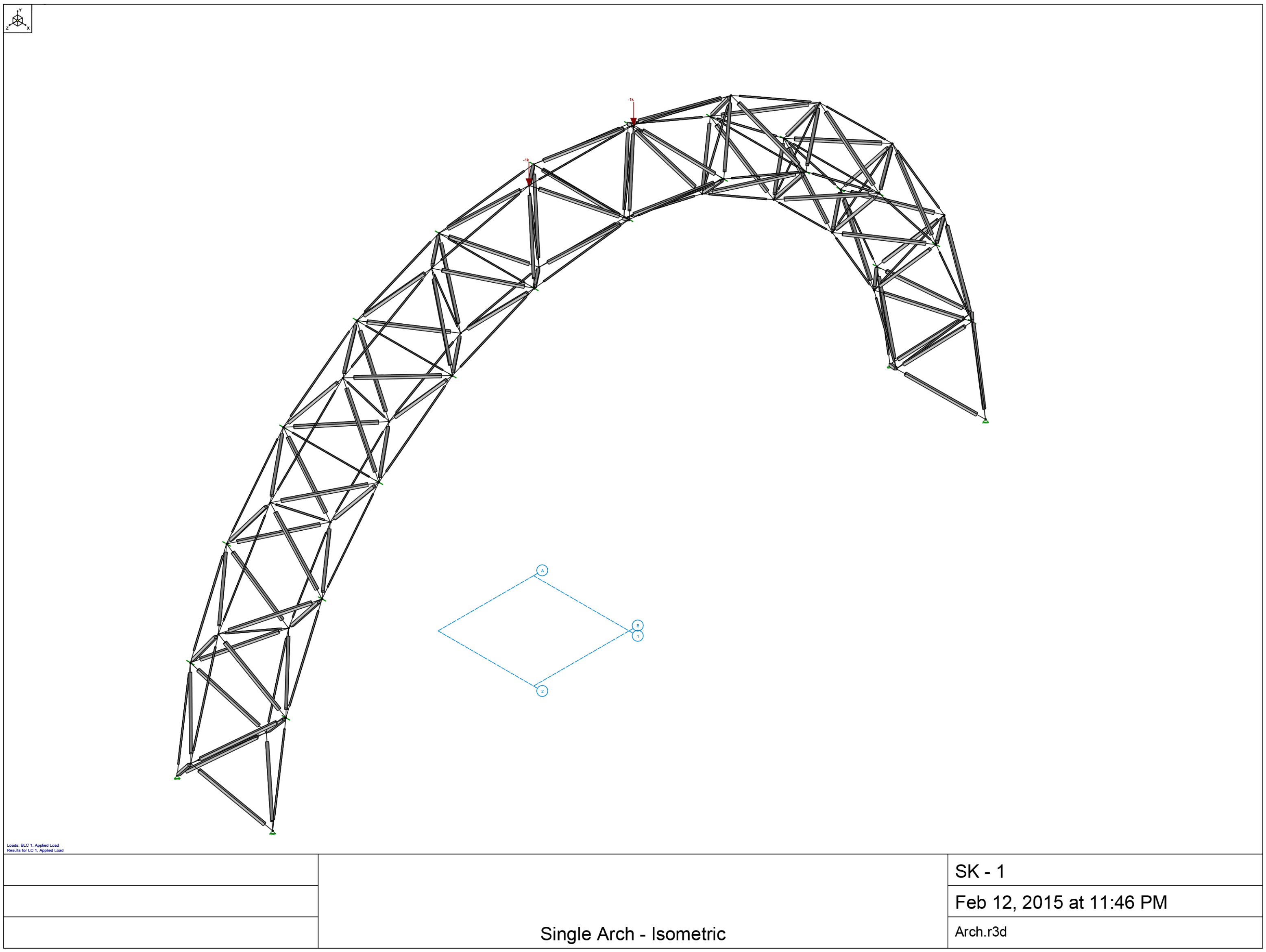

Figure 7.3: Arch Model Testing.

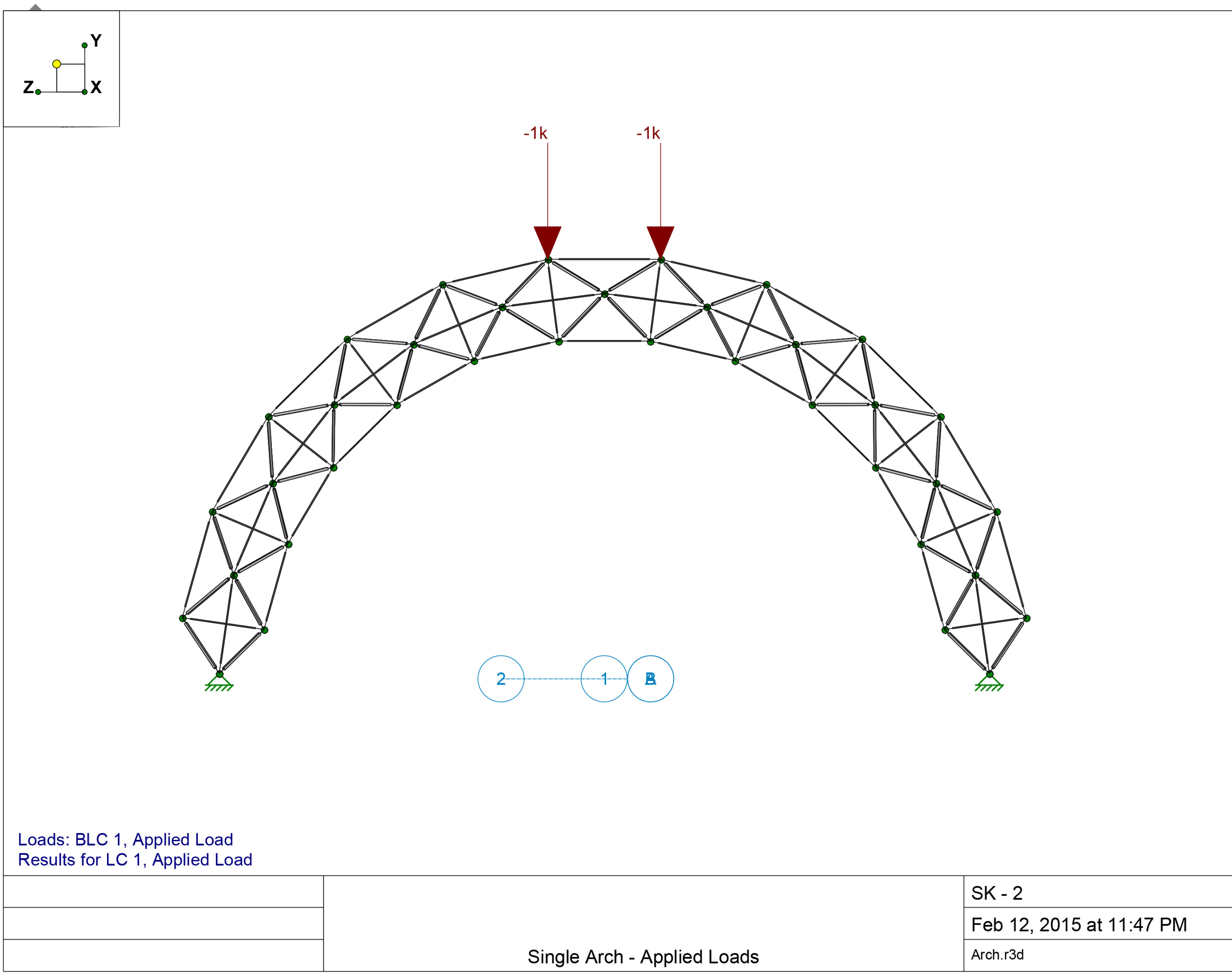

Figure 7.4: Model Testing - Front View

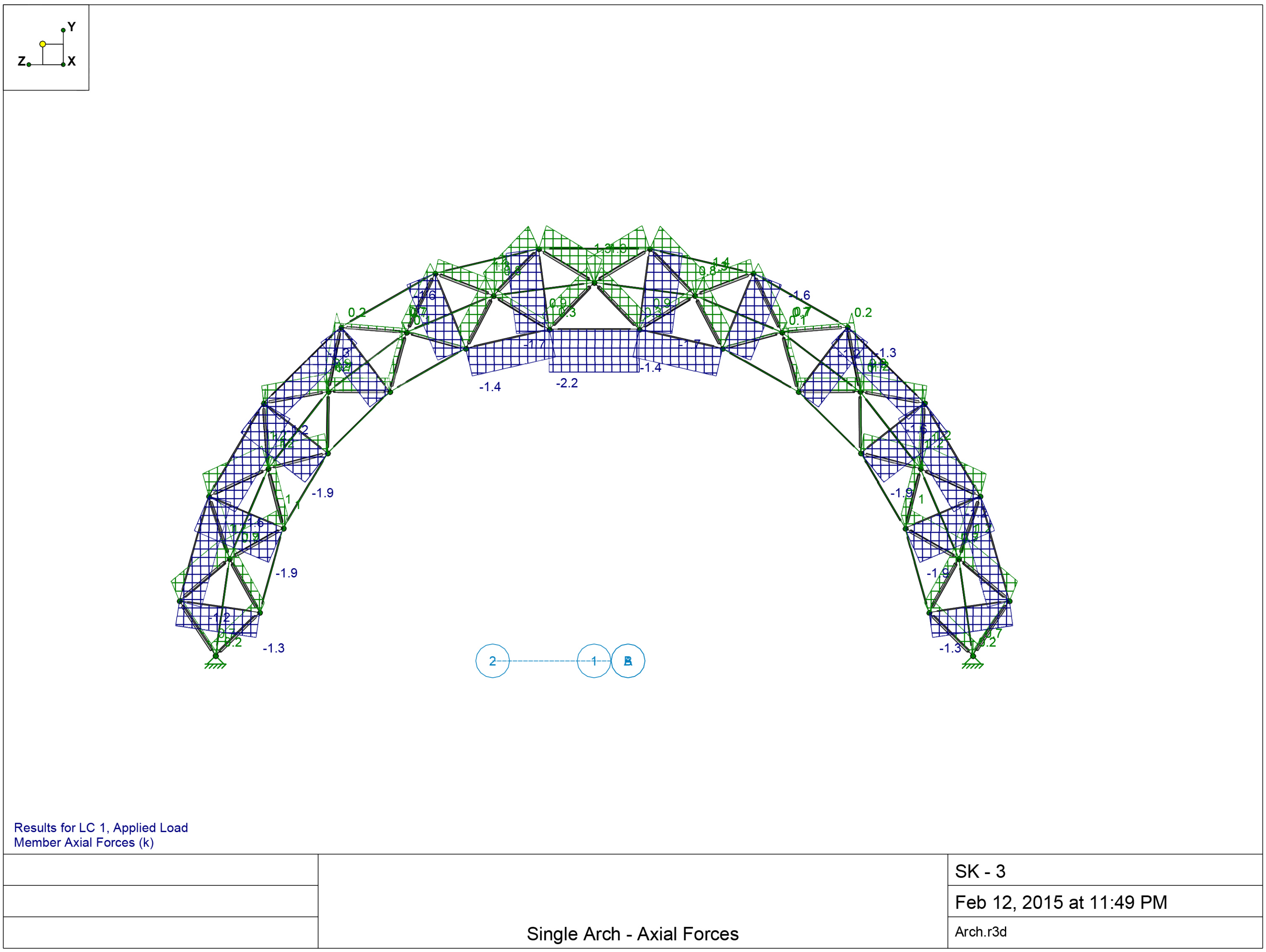

Figure 7.5: Arch Model Testing - Results

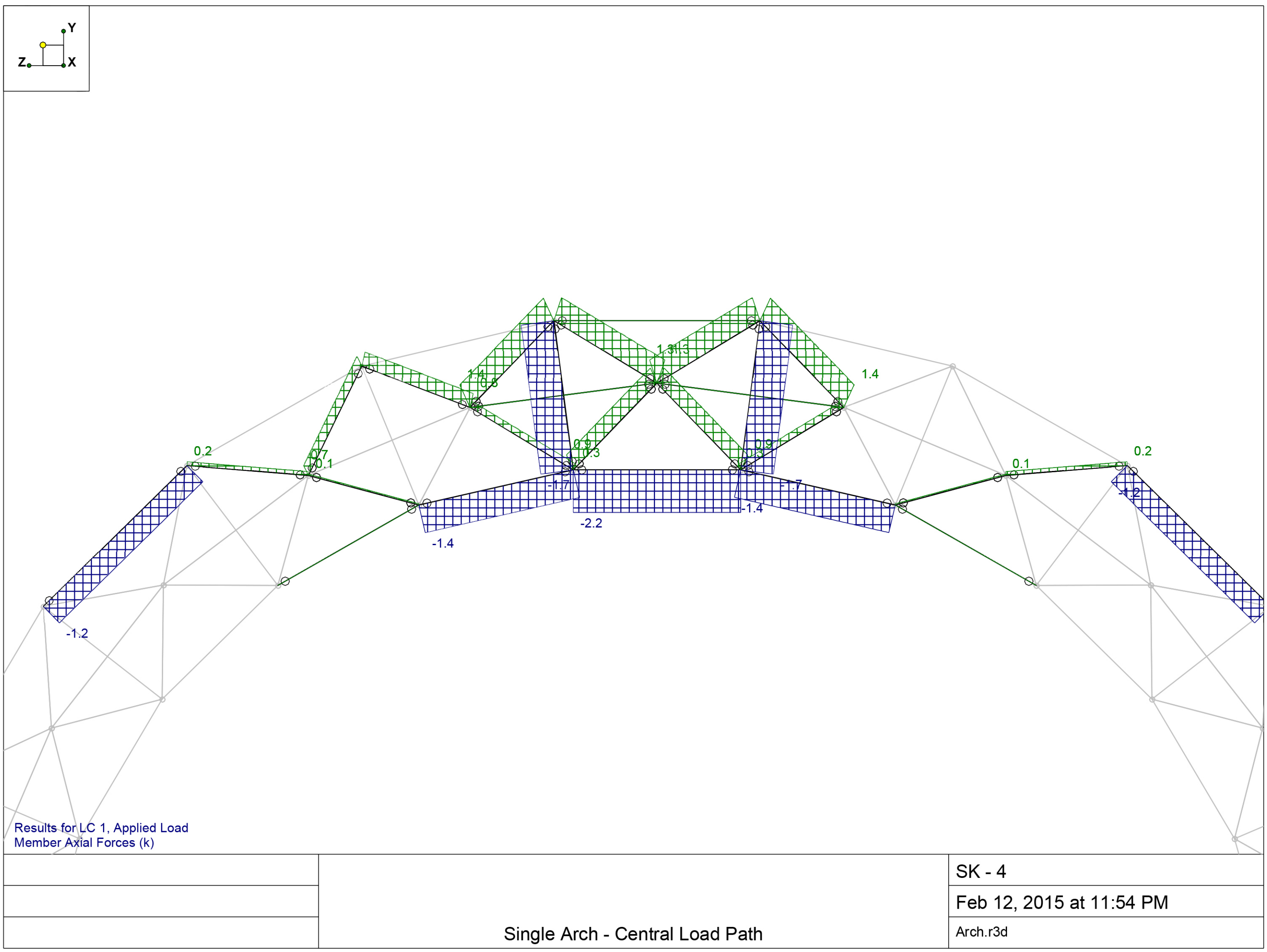

Figure 7.6: Arch Model Testing - Detail

Energy of Components within a Structure:

To be viable, the arch structure described should afford an appreciable savings in embodied energy over conventional structures. Using the material energy constants found in Figure 3.7, the following calculations were undertaken to test the proposal. Detailed representations of the elements discussed can be found in Figures 7.7-10.

Contents:

1. Strut Component
2. Connection Components
3. Cable with Connector and Turnbuckle System
4. Fabric Enclosure
5. Footing Solutions
6. Calculations for the Number of Component Parts in the Structure
7. Final Tally of Energy in Components Parts

1. Strut Component

Made up of lumber segments attached at the ends with steel connections.

Wooden components (Energy constant of lumber= 1380 MJ/m cubed)

-triangular profiles, 1-1/2" equilateral

$$A=\frac{BxH}{2} \quad A= \frac{0.0381m \times 0.033m}{2} \quad A= 0.000622865m \text{ square}$$

Lengths of component parts:

3@6'

6@6"

1@1"

=21.5' =6.55m 6.55m x 0.000622865m squared= 0.0041m cubed

1380 x 0.0041= 5.6 MJ of energy, and a weight of 2.05kg

Steel Components

-hexagon in shape with pin connection

16 gauge sheet steel- thickness= 0.0598" = 0.00151892 m

Volume= Length x Width x Thickness x Number

sides

= 0.0381 x 0.15224 x 0.00151892 x 6

=0.00005292m cubed

end cap

= 6 x area of 1.5" equilateral x thickness

=6 x 0.000622865m x 0.00151892m

=0.000005676m cubed

tensioning centre tie

8 gauge streel- 0.1644" = 0.00417576 m thick

Volume= Length x Width x Thickness x Number

= 0.0889 x 0.0254 x 0.00417576 x 6

= 0.000056575m cubed

reinforcement ring

volume of a cylinder = pi(r squared)(hight)

= pi (0.012700 x 0.012700m) (0.012700m)

=0.000006435m cubed

Total volume of steel components: 0.000121606m cubed

Steel @ 251200/ meter squared X 0.000121606m

=30.55 MJ/ strut

Wood and steel combined = 30.55 MJ + 5.6 MJ = **36.15 MJ** per strut

2. Connection Components

Fabricated out of 3/16” recycled aluminum plate (21870MJ per meter squared) -quadrilateral shape including one rectangle and two similar triangles

- assumed cut out components are either scrap or components for attaching fabric, and therefore are calculated in the overall energy sum of the components

=0.000030687 m cubed + 0.00004944m cubed

=0.000080124 m cubed

each connection plate is made up of 4 of such parts giving a total volume of:

0.000325 m cubed

21870 x 0.000325= 7MJ per 4 point connection weighing only 0.884 kg compared to 2.6kg if it were to be constructed out of steel. Twice this amount can be expected for an 8 point connection.

Bolt for connection, call for- 1/2 steel bolt @ 4” long with nut and washer= 0.3 lb =0.136 kg

@ 32 MJ/KG (steel) = 4.352 MJ times the number of point connections present.

3. **Cable with Connector and Turnbuckle System**

Proposed 1/4” cable for entire system (7x19) with a breaking strength of 7000 lbs

-There are three common sized cable segments in this simple arch orientation: mid unit connectors, top vertical, and bottom vertical

V = pi RxR (length)

Mid unit connections:

7.5’ = 2.286m with a volume of 0.000075095 m cubed

= 18.86 MJ

Top connection:

8' = 2.4384m with a volume of 0.000082164 m cubed

= 20 MJ

Bottom connection:

6.5'= 1.9812m with a volume of 0.000066759m cubed

= 16.77 MJ

In addition, each of these cable segment requires a swage connection on either end. The weight of a single 1/4" swage jaw connection is 0.33 lbs., equivalent to 150 grams, making 1.355 MJ of energy per connection.

Turnbuckles:

3/4" size 6' long = 1.818m with a volume of 0.00052125 m cubed

= 130.93MJ

4. Fabric Enclosure

Similar to glazing in energy cost but 10 times more efficient due to its thickness. The chosen material is an ETFE fabric capable of being inflated to increase its insulation value.[2] I am proposing that this material be used in two distinct layers on the outside as well as the inside of the structure to further its usability for many climates. This material comes in multiple thicknesses but since I am opting for a shelter to last as long as 50 years, I have selected the heaviest possible thickness - 0.25mm.

Outside layer - 8' by 7.5'

v= 2.4384 x 2.286 x 0.00025

=0.001393546 m cubed @ 37550 MJ/m cubed

[2] ETFE (Ethylene Tetrafluoroethylene) film- Product carried by Birdair, Inc. http://www.birdair.com/tensile-architecture/membrane/etfe.

=52.327 MJ

Inside layer- 6.5' by 7.5'

v= 1.9812 x 2.286 x 0.00025

=0.001132256 m cubed @ 37550 MJ/ m cubed

=42.516 MJ

Bottom triangular sections

v = BxH/2 x thickness

=1.143 x 1.43 x 0.00025

= 0.000408623m cubed @ 37550MJ/ m cubed

= 15.34 MJ

End panels

v= pi R_2 (thickness)

= pi 8.685 x 8.8685 (0.00025)

=0.05924m cubed @37550KJ/ m cubed

=2224.536 MJ

5. Footing Solutions

Depending on the need for rapid construction, there are a few different alternatives as far as anchoring the structure. For the most rapid construction, a product known as diamond pier would allow for extremely fast installation as well as easy transportability but would not have a finished floor.[3] The other more standard method is a concrete pier and/or slab on grade configuration.

Diamond pier :

Concrete triangular portion- 54 lb (precast concrete 2.0 MJ/ Kg)

54lb = 24.5 kg,   24.5x 2.0= 49MJ

Steel rods- 4 @ 4' = 16' of galvanized pipe (32MJ/kg)

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[3] Diamond Pier © DP-50 Product of Pin Foundations, Inc. http://pinfoundations.com/

1.64 lb/ foot weight of 0.133" thickness wall thickness = 26.24 lb

26.24lb = 11.8 kg, 11.8 x 32 = 377.6MJ

Total of 426.6 MJ per footing

Standard sono tube footing :

6" tube using case on site concrete (@3180 MJ/m)

v=pi R_2 (height)

=pi (0.0762 x 0.0762) (1.2192)

=0.0222 m cubed

0.0222 x 3180

total = 70 MJ

Slab on grade:

-more permanent condition also could allow radiant heat source piping to create a heated enclosure 6" thick slab with 4' foundation on all sides

slab concrete (@3180 MJ/M)

V= L x W x D

= 22.68 x 17.37 x 0.1524

=60.03 m cubed

60.03 x 3180

=190921.55 MJ

foundation concrete (@3180 MJ/M)

V (length) =1.22 x 0.305 x 22.68 (2)

=16.878 m cubed

V (width) = 1.22 x 0.305 x 17.98 (2)

= 13.381 m cubed

30.2387 x 3180

= 96222.7 MJ

Total energy= 287144.267 MJ

6. Calculations for the Number of Component Parts in the Structure

1) Wooden Compression Struts: 36.15 MJ

8 required in each unit, 10 x 12 = 120 units

8 x 120 x 36.15 = 34704MJ

2) Connection Components

top and bottom:

(4 point connections)= 10 x 12 x 2 = 240

middle connectors:

(8 point connections)= 11 x 13 = 143

bolted hardware required 1 per point connection:

240(4) + 143 (8)= 2104

total 240 (7) + 143 (14) + 4.352 (2104)

= 1680 + 2002 + 9156.6

= 12838.61 MJ

3) Cable with Connector and Turnbuckle System

Unit cabling (4 per unit):

(18.86 + (2 x 1.355)) x 4 x120

= 10353.6 MJ

Top cables:

12 x 9 x (18.86 + (2 x 1.355))

= 2329.56 MJ

10 x 11 x (20 + (2 x 1.355))

= 2498.1MJ

top total = 4827.66 MJ

Bottom cables:

12 x 9 x (18.86 + (2 x 1.355))

= 2329.56 MJ

10 x 11 x (16.7 + (2 x 1.355))

= 2135.1 MJ

bottom total = 4464.66

Total of all cables = 4464.66 + 4827.66 + 10353.6 = 19645.92 MJ

Turnbuckles:

130 x 120

= 15600MJ

4) Fabric Enclosure

Outside Layer:

square parts: 9 x 11 x 43.11

= 4267.89 MJ

triangular parts: (19 x 2) + (12 x 2) (12.6)

= 781.2 MJ

Inside Covering:

square parts: 9 x 11 x 35.03

= 3467.97 MJ

triangular parts: (19 x 2) + (12 x 2) (12.6)

= 781.2 MJ

End coverings:

2 x 2224.536MJ

= 4449.072 MJ

Total fabric energy usage 13747.33 MJ

5) Footing Solutions

- comparison to typical building calls for slab on grade with footings

(alternative option 1)Diamond piers:

426.6 x 11 x 2

= 9385.2 MJ

(alternative option 2) 6” sono tubes 4’ deep:

70 x 11 x 2

= 1540 MJ

slab on grade (used in total)

Footings + Slab (calculated above)

190921.55 + 96222.7 = 200544.25 MJ

7. **Final Tally of Energy in Component Parts**

34704MJ (struts)

12838.61 (connectors)

19645.92 (cables) + 15600 (turnbuckles)

13747.33 (fabric)

200544.25 (slab on grade)

total = 297080.11 MJ

total floor area of 397m squared

In conclusion, the energy within this building equals 748.31 MJ/meter squared. This focuses strictly on construction materials for structure and envelope which total 50% of a building’s energy consumption, as indicated in Figure 3.5.

In contrast, the average on a typical construction is 4820 MJ/m squared, with 2410 MJ/m squared being the energy figure for the envelope and structure only (Figure 3.5). This shows an improvement factor of 322% over standard construction methodology for envelope and structure.

Details

The details are crucial elements in the execution of the arch structure, allowing for mass fabrication, quick assembly and maximum efficiency. The individual assembled unit can be seen in Figure 7.7, illustrating where each of the following joints appear in the greater structure. Light weight, recycled aluminum plate is used for the joints. In the arch under consideration, all of the compression segments join at either 4 or 8 point connections.

4 point joint connection (Figure 7.8)

Capable of holding 4 members, this joint is rigid as well as light weight. The detail includes large connection points to ensure no shearing course at the pivot point. A ring at the top of the joint allows cables to fasten in order to link sequential units together. Weight reduction is achieved from cut plate stock, creating a series of holes within the plate section. In this way the part is reinforced or reduced according to the strain that will be applied in each location. The plate material is then welded together, forming triangulated grid structures.

8 point joint connection (Figure 7.9)

The 8 point joint is essentially two 4 point joints mirrored and assembled together. The major addition is the presence of 4 connection hooks which protrude from the centre of the component on all four sides. These hooks are positioned in line with the pin connection of the compression members in order to stabilize the overall connection. The torsion in each joining component is greatly reduce by allowing each unit to have its own stabilized tension segments.

Modified 4 point joint for connection to ground (Figure 7.10)

Where the components meet the ground, a modified 4 point joint is required. The grid meets the ground with four compression segments at an offset angle, requiring a rotation of the pin connection by 45 degrees to that of the segments. An appropriate footing connection, dependant on the footing selection is required as well, in order to affix the units with a pinned connection. A diamond pier is shown as the footing here.

Figure 7.11 illustrates a typical assembly of struts to the joint connections, showing the ease with which the elements fit together.

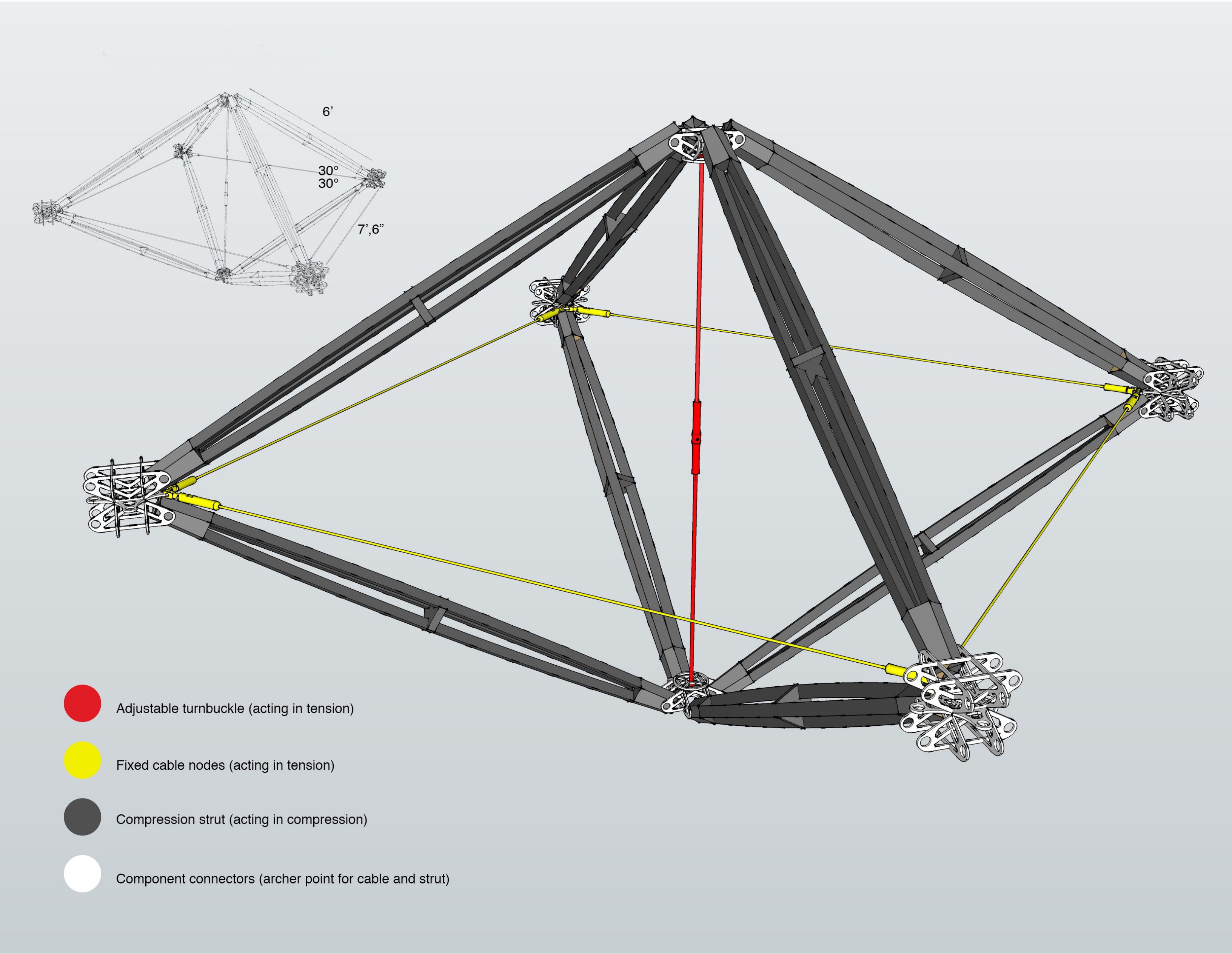


Figure 7.7: Single Unit with Connectors. Jensen.

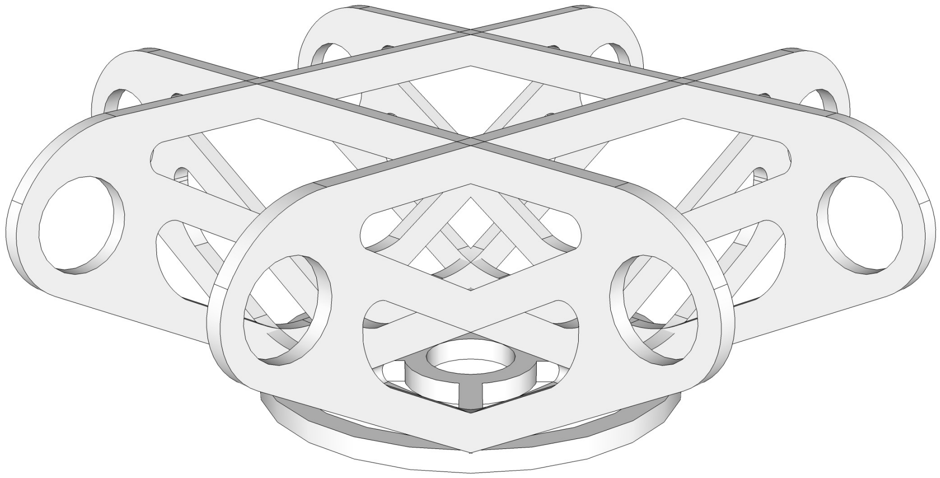


Figure 7.8: Four Point Component. Jensen.

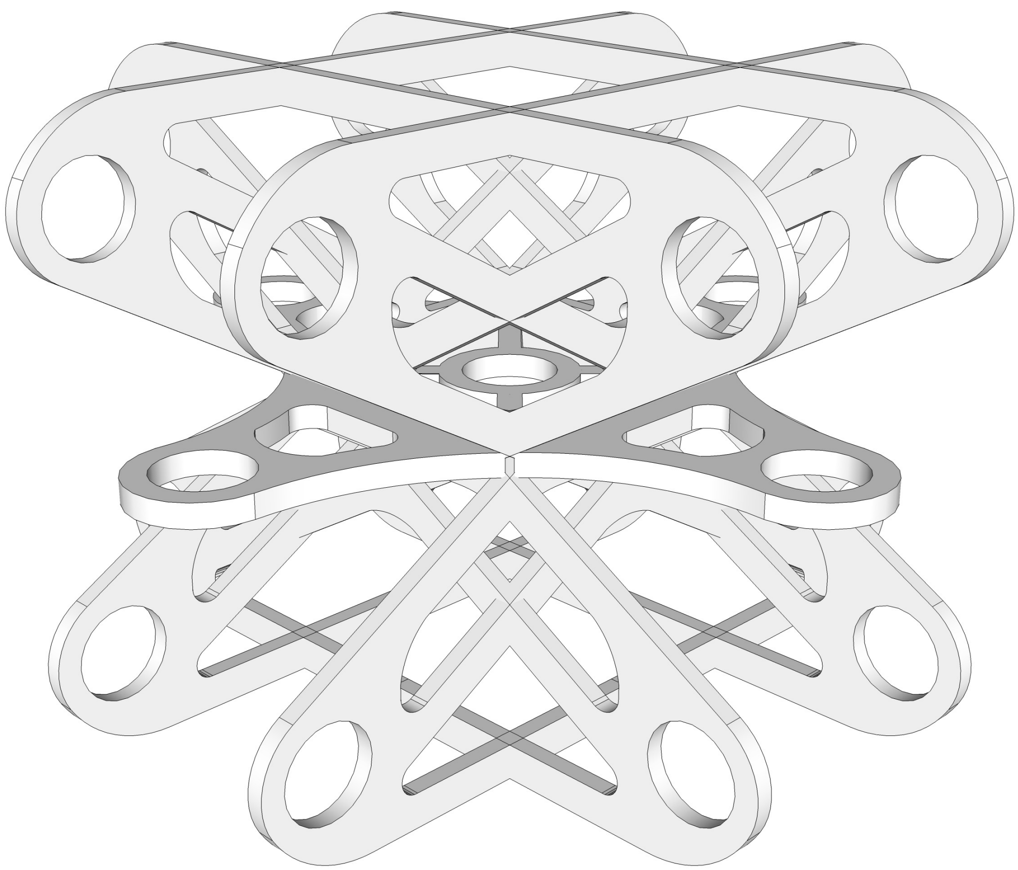


Figure 7.9: Eight Point Component. Jensen.

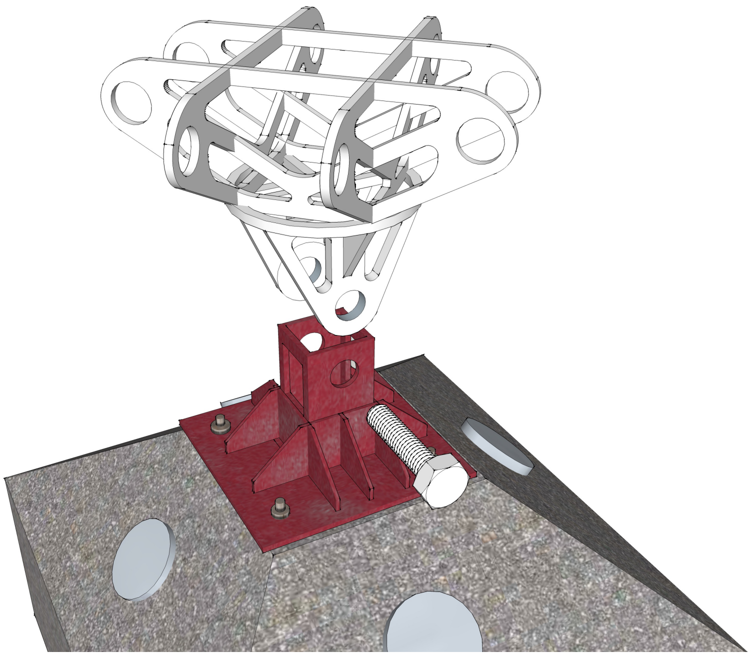


Figure 7.10: Modified 4 Point Joint for Diamond Pier. Jensen.

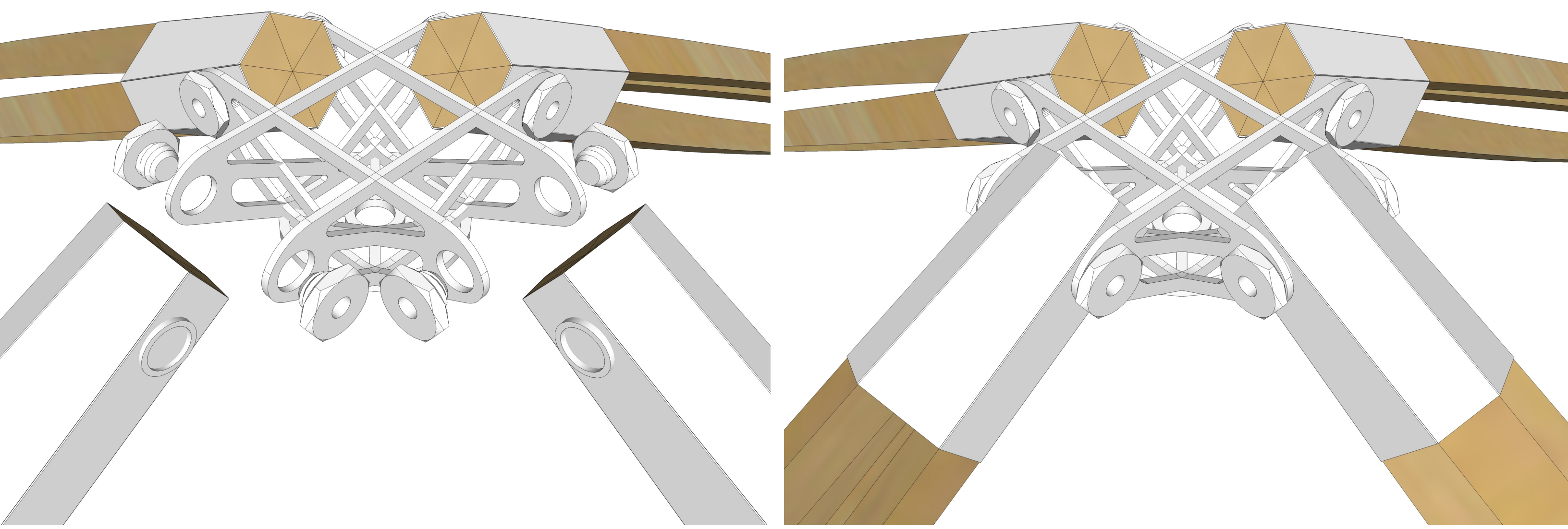
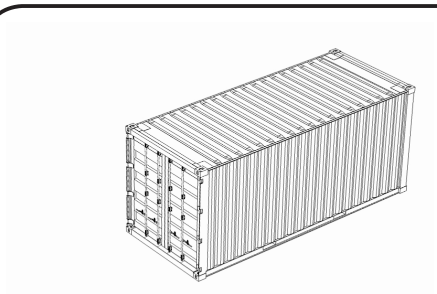


Figure 7.11: Typical Assembly. Jensen.

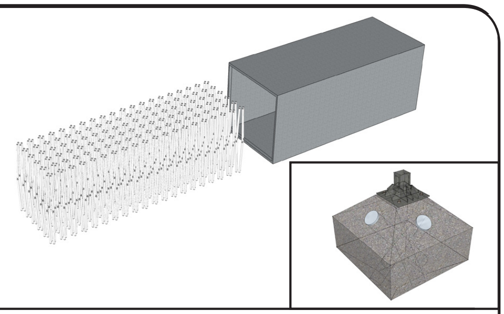
Assembly

In most cases, the struts and joints would be shipped pre-assembled, with only a few key connections left to be completed. Each unit is stabilized on its own and can be packed virtually flat - similar to the design of an umbrella - by simply disconnecting the centre tensioned turnbuckle. When all of the turnbuckles are tightened, the desired shape is generated based on the length of the tension segments. In this way an entire grid structure can be packed and shipped to a site largely pre-assembled, and then expanded and tightened. It is this easy-to-assemble structure that reflects the goals suggested by the disaster relief scenario described in the introduction to this thesis. The following assembly instructions illustrate a detailed example of how the arch structure would be packed and deployed on site.

SHELTER ASSEMBLY



1 Move the container near to, but not covering, the desired location.

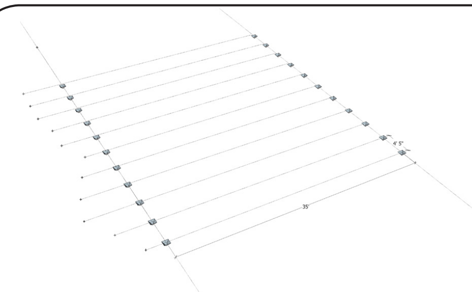


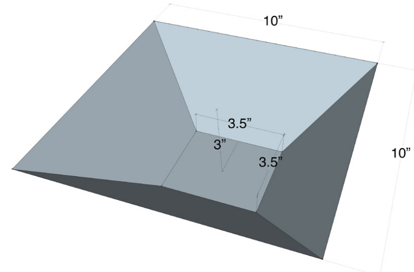
2 Remove all contents from container including Diamond Piers.

1

SHELTER ASSEMBLY

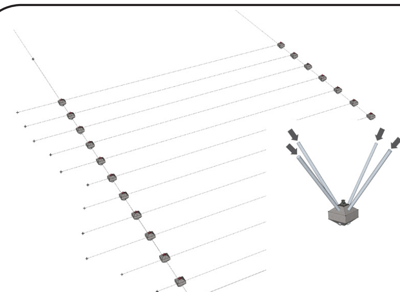
2

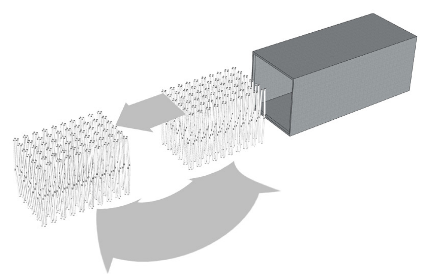




3 Mark out desired location of shelter on the ground.

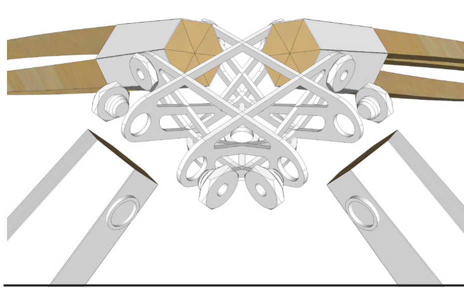
4 Dig pyramid shaped holes in the ground at the locations of all the footings using the measurements above.

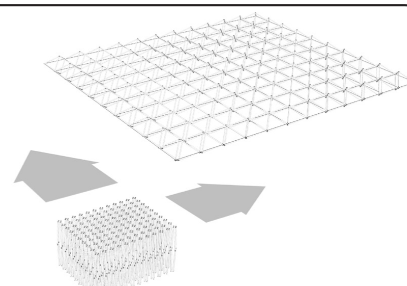




5 Place a single footing in all of the holes and use a pile driver to drive steel rods into the ground to hold the footing in place.

6 Separate the grid sections and rotate one to meet the other in the center as shown.



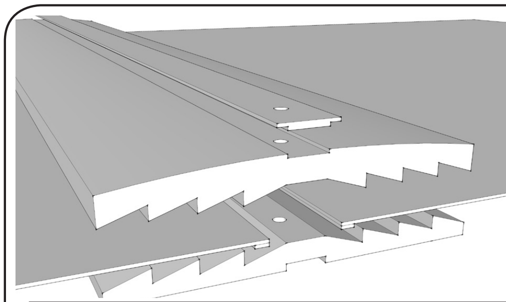


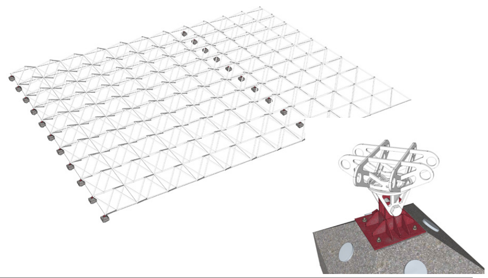
7 Fasten the two halves by attaching the remaining joint details to the compression members and tension cables, as marked.

8 Pull grid section in both directions to create a large flattened sheet.

SHELTER ASSEMBLY

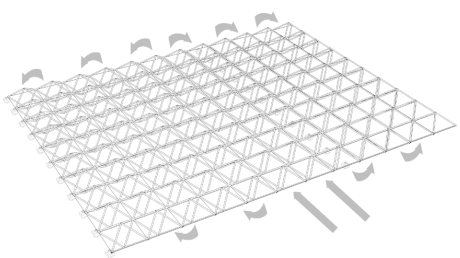
3

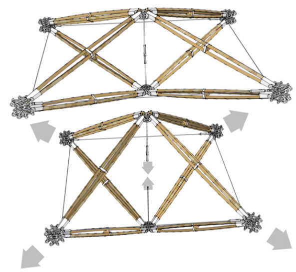




9 Attach the centre ridge seam of the enclosure's fabric, ensuring a water-tight seal.

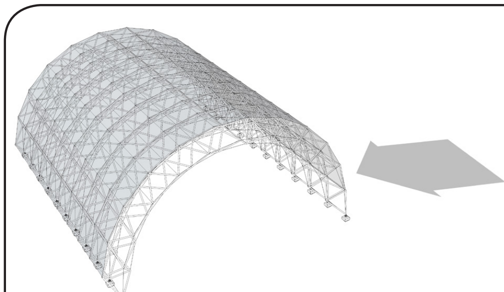
10 Attach one side of the grid to the corresponding footing.

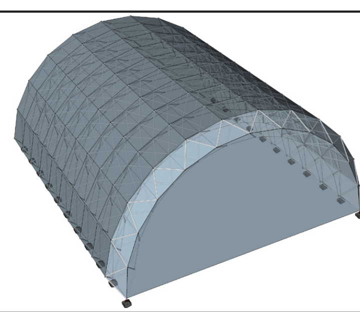




11 Starting from the centre of the grid, attach and tighten the centre turnbuckle segments. The arch structure will raise itself as the turnbuckles are tightened.

12 Detail of tightening the turnbuckle from step 11.





13 Pull the bottom connections into the corresponding footings on the opposite side of the structure.

14 Install end caps on to the open edges of the structure, closing the internal space.

Practical Applications

In this section the concepts and forms examined previously will be shown in possible real world applications. All of the examples present similar advantages, being easily transportable, compact-able, versatile and economical.

For the most part, the structures illustrated constitute modifications of the arch adapted to different locations and demographics. Although these modifications sometimes deviate from the optimal configuration of the structure as discussed in the previous section, the technology can benefit people on a global level depending on their needs and access to resources. Gradual integration of such technology into the public consciousness may be the only way that it becomes a common building alternative.

Airplane Hangar

Figures 8.1-3 illustrate how the technology is being implemented to replace the typical steel construction of an airplane hanger. As its purpose is to store planes having extremely long wingspans, a clear useable span is a requirement. The structure proposed would be ideal for such a purpose as it has the potential to have spans great enough to allow a plane to be stored within it.

The structure also has the potential to be altered depending on the type of plane that is being stored within the space. As heating of a hangar is often not required, the structure could easily accommodate a fabric shell enclosure. In this case two Cessna 182's with a wingspan of 11m are housed in the structure.[1] Both ends of the shelter in this design can be removed in order for a plane to enter from either side.

[1] Cessna Aircraft Company. http://cessna.txtav.com/

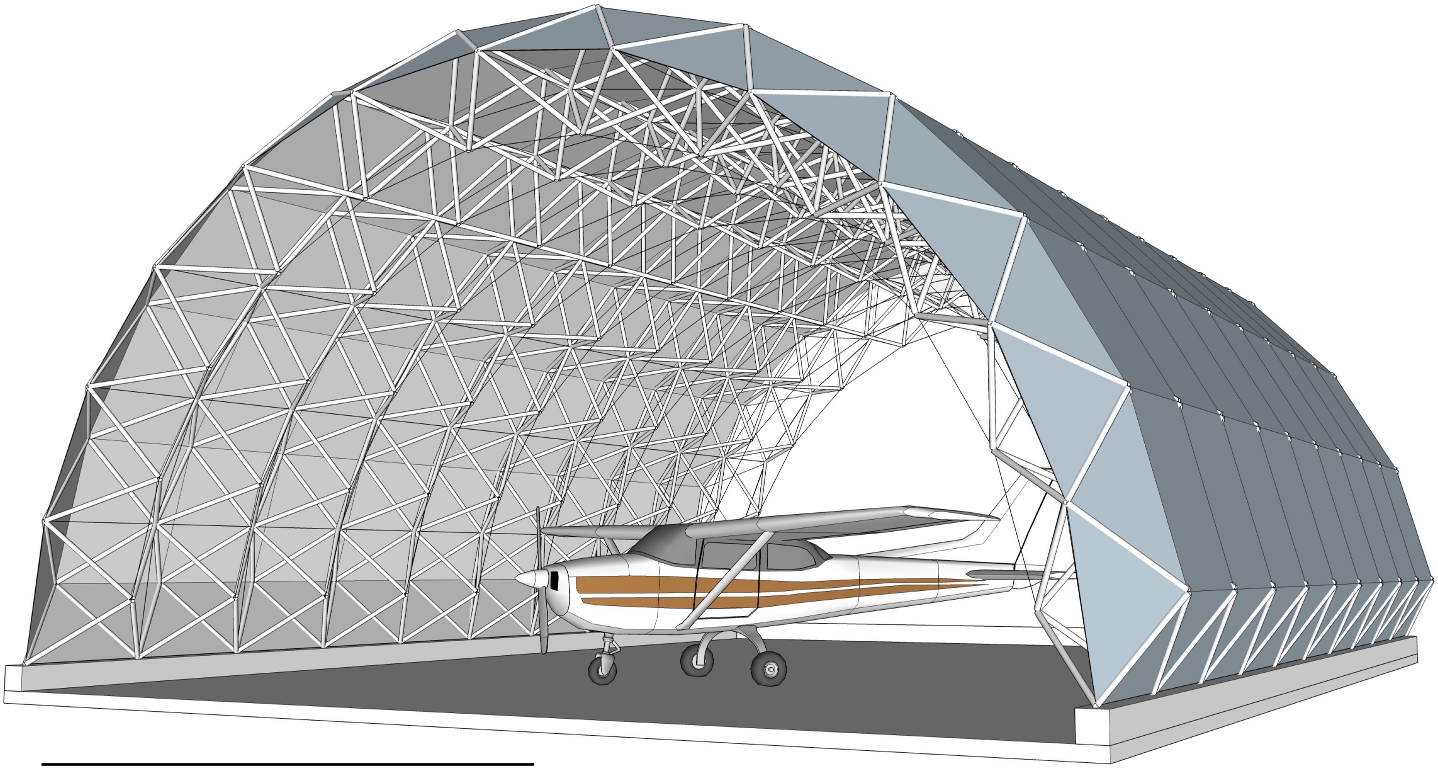


Figure 8.1: Perspective of Airplane Hangar Solution. Jensen.

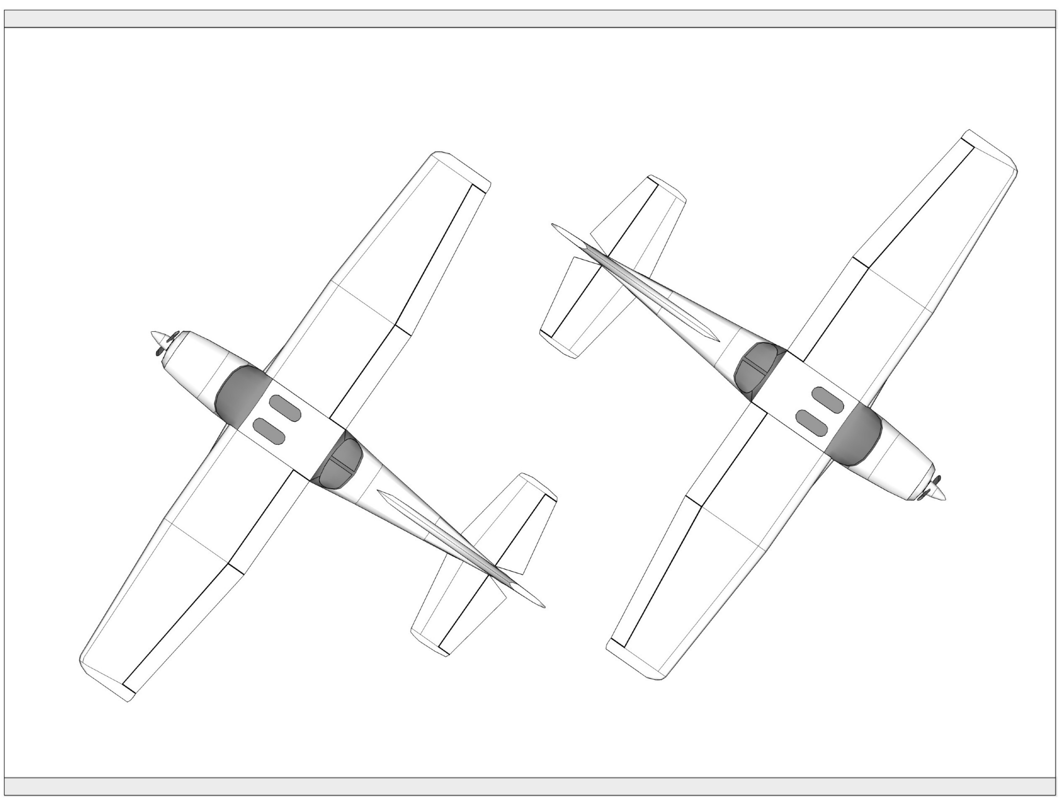


Figure 8.2: Plan of Airplane Hangar.Jensen.

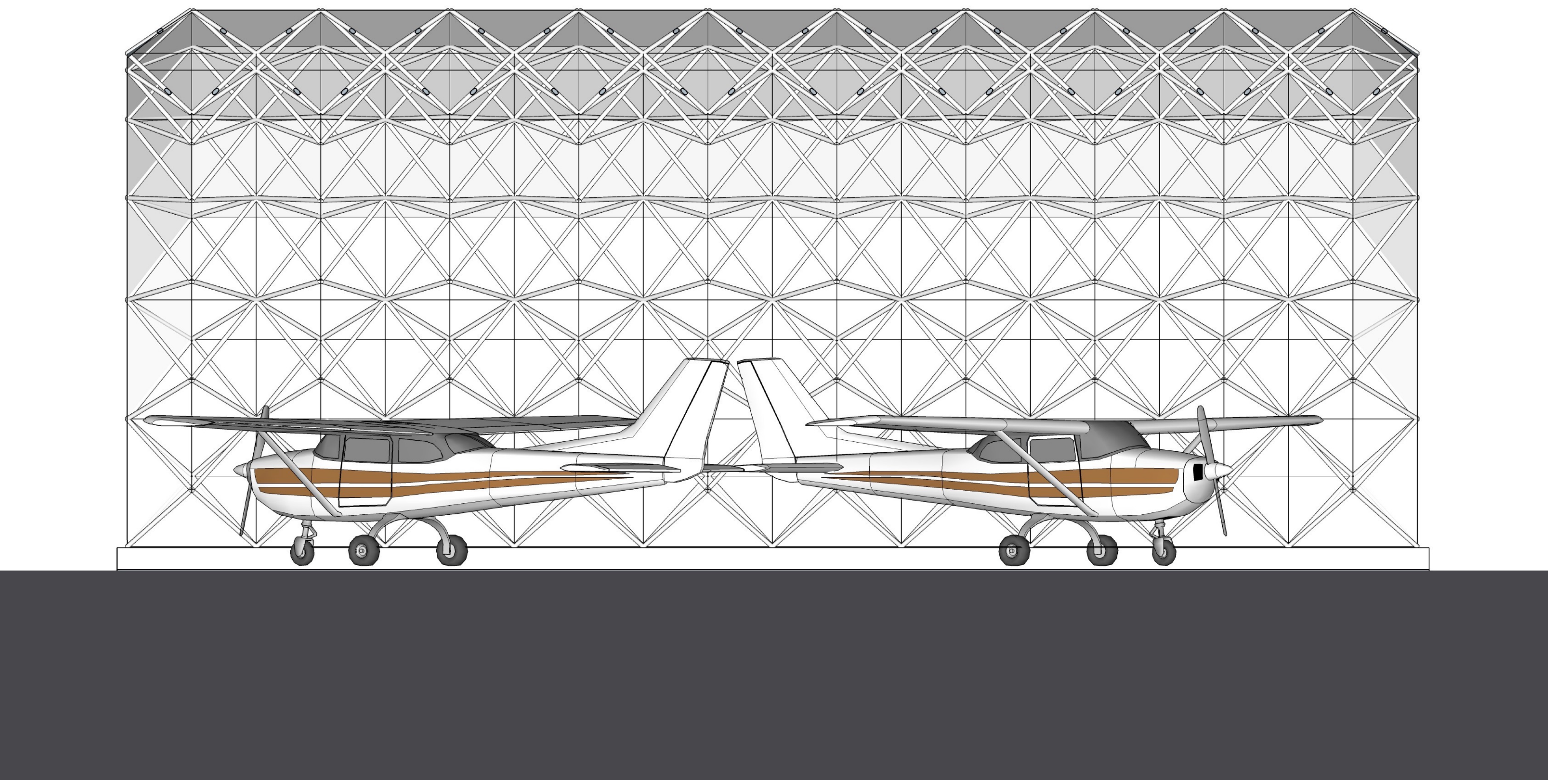


Figure 8.3: Sections Airplane Hangar. Jensen.

Relief Hospital

The need for relief hospitals after a disaster makes them critical life and death facilities. The rapid construction capabilities of such a structure would mean it could be erected in a matter of hours after its arrival on the site. (Figure 8.4)

As a response to changing conditions the design of the structure can be altered to accommodate its purpose. A wall through the enter of the building will not only provide privacy and another space within but can reinforce the overall structure in the process (Figures 8.5-6). These tension shear walls help the structure to maintain its shape in harsh conditions. By having a series of rooms it is possible to have operating facilities and care based on the severity of the injuries as seen in Figure 8.7. Also as the need for medical facilities changes into a need for short term housing, the structure is able to accommodate the transfer (Figure 8.8).

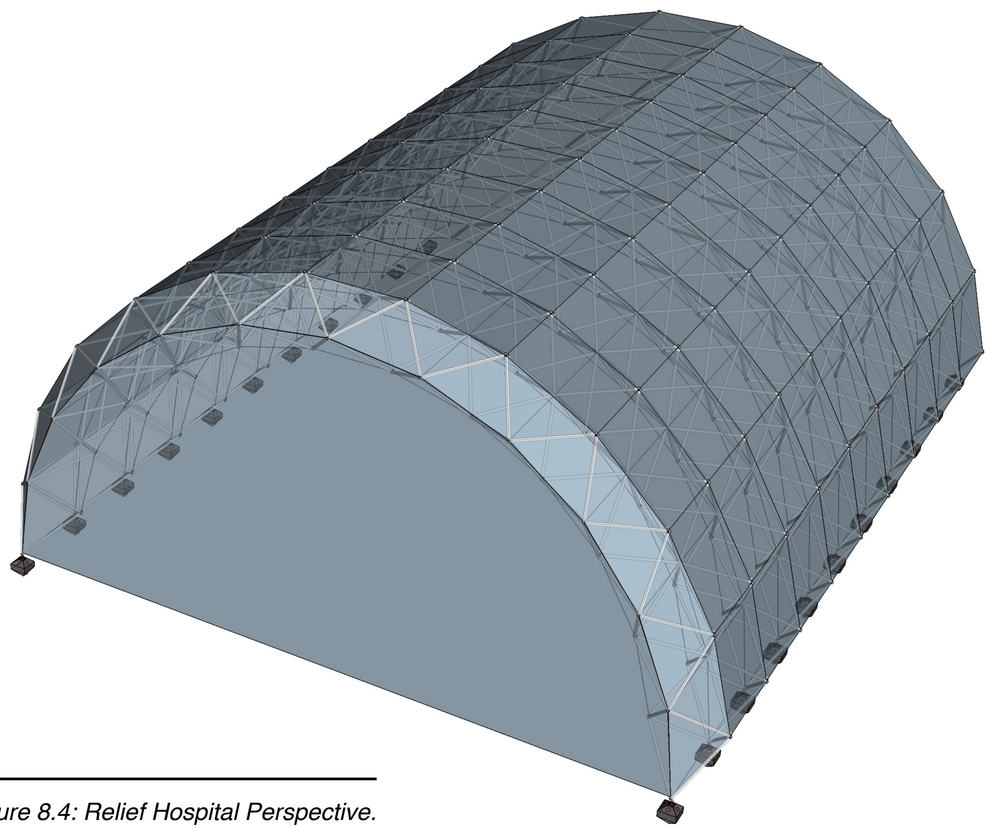


Figure 8.4: Relief Hospital Perspective. Jensen.

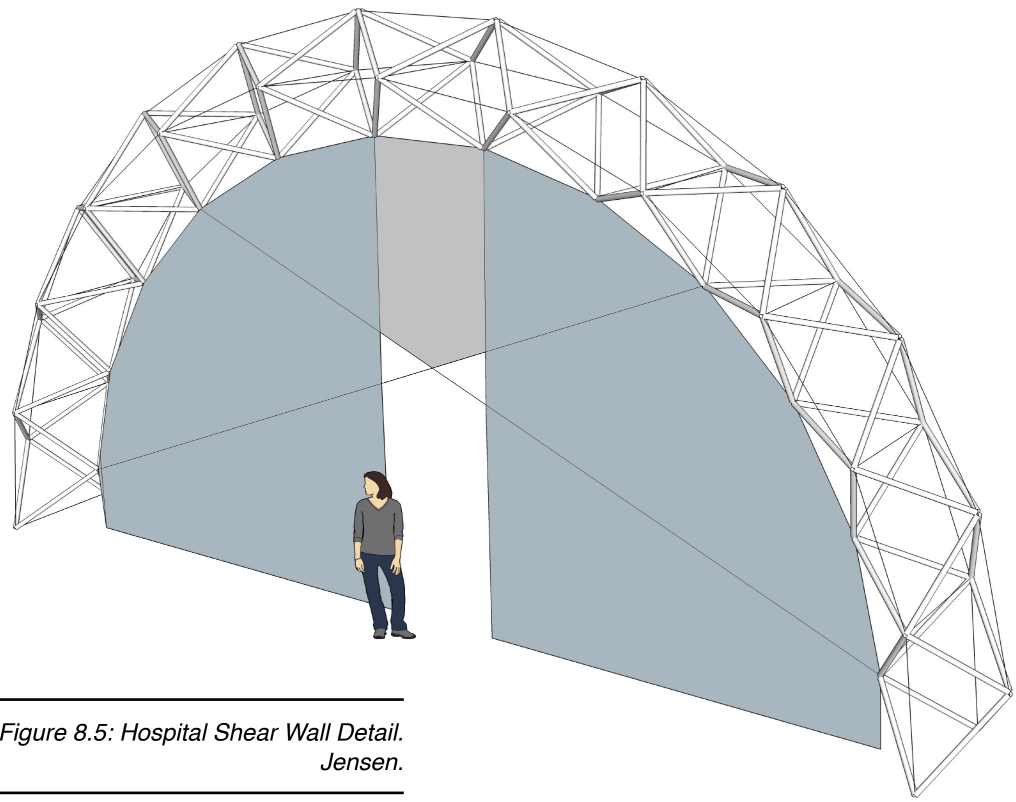


Figure 8.5: Hospital Shear Wall Detail. Jensen.

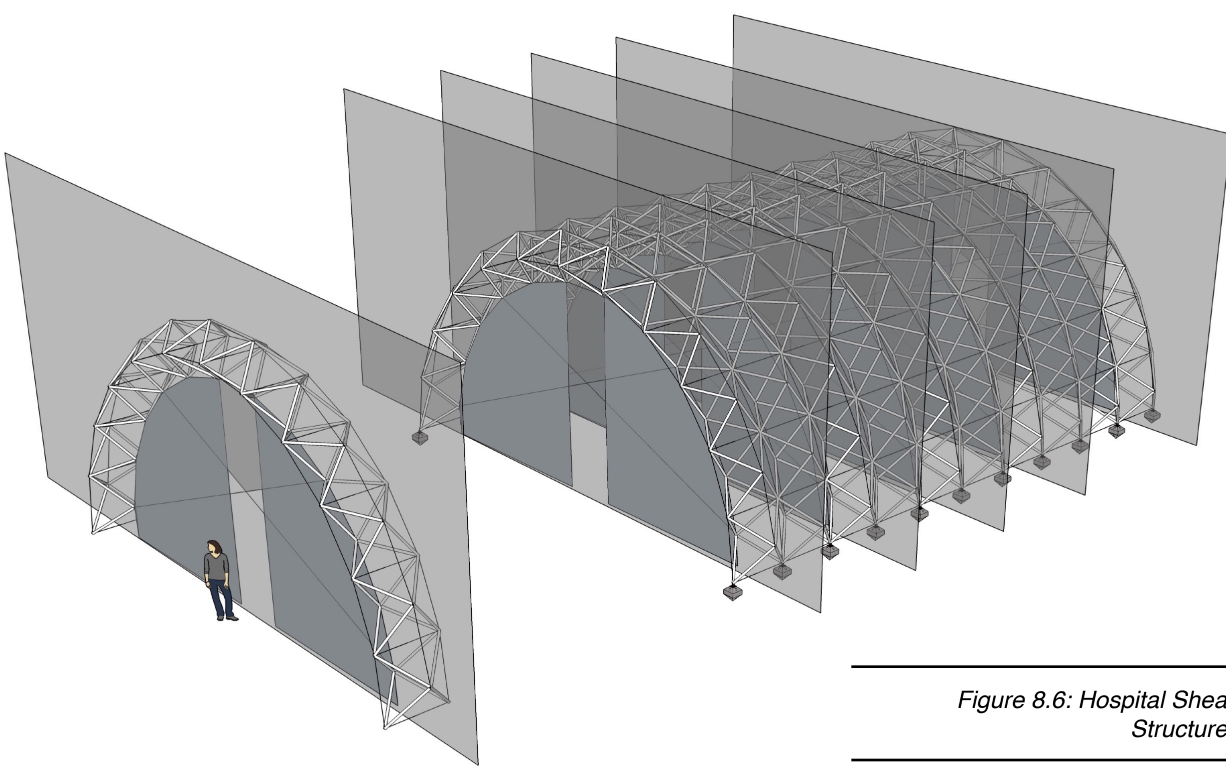


Figure 8.6: Hospital Shear Walls in Structure. Jensen.

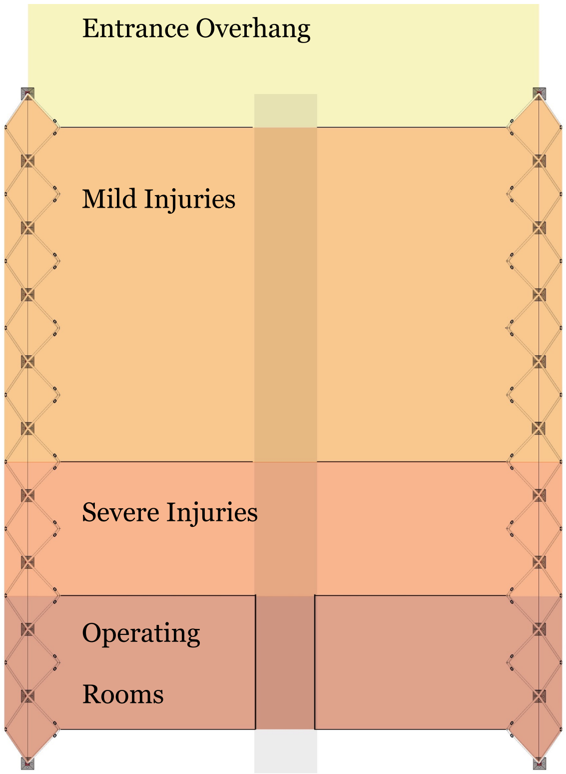


Figure 8.7: Hospital Plan. Possible Division Layout. Jensen.

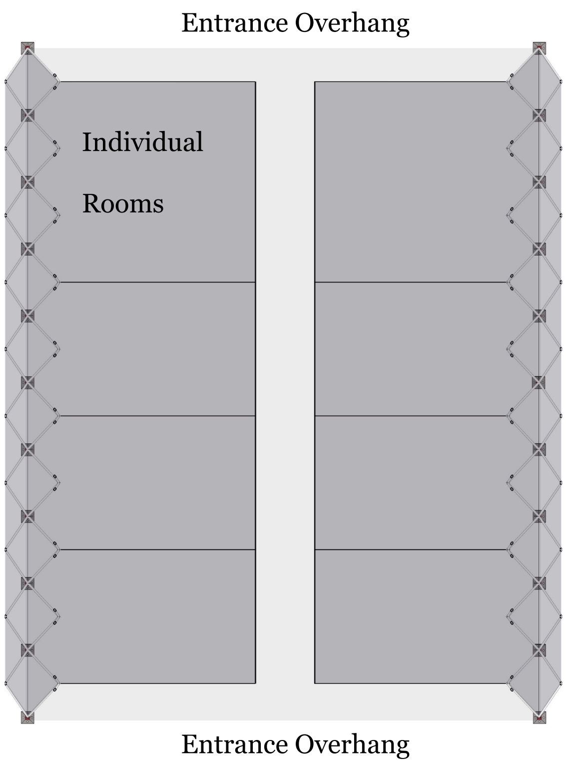


Figure 8.8: Short Term Housing Plan. Jensen.

Temporary Event and Canopy Applications

Large enclosures are in high demand for temporary events. Weddings, festivals and markets are only some of the places where such structures could be used. These structures can be erected and collapsed extremely easy and quickly. Height requirements, wind loading and overall coverage capacity are all things which could be adjusted using similar components while changing only minor details. Most times such structure do not require insulation, allowing them to be more playful and interesting (Figure 8.9).

Canopies or enclosing entrances are another significant adaptation that can easily be accomplished by using elements of the structure developed in this study, responding to the demand for multiple configurations and installation options (Figure 8.10). This could include seasonal shelters needing canopies to keep snow, rain and wind away from the threshold, ambulance bays, or more aesthetic functions such as a restaurant entrance. These light structures are an ideal solution as the canopies can be either fully dismantled or partially left in place by removing only the the fabric component.

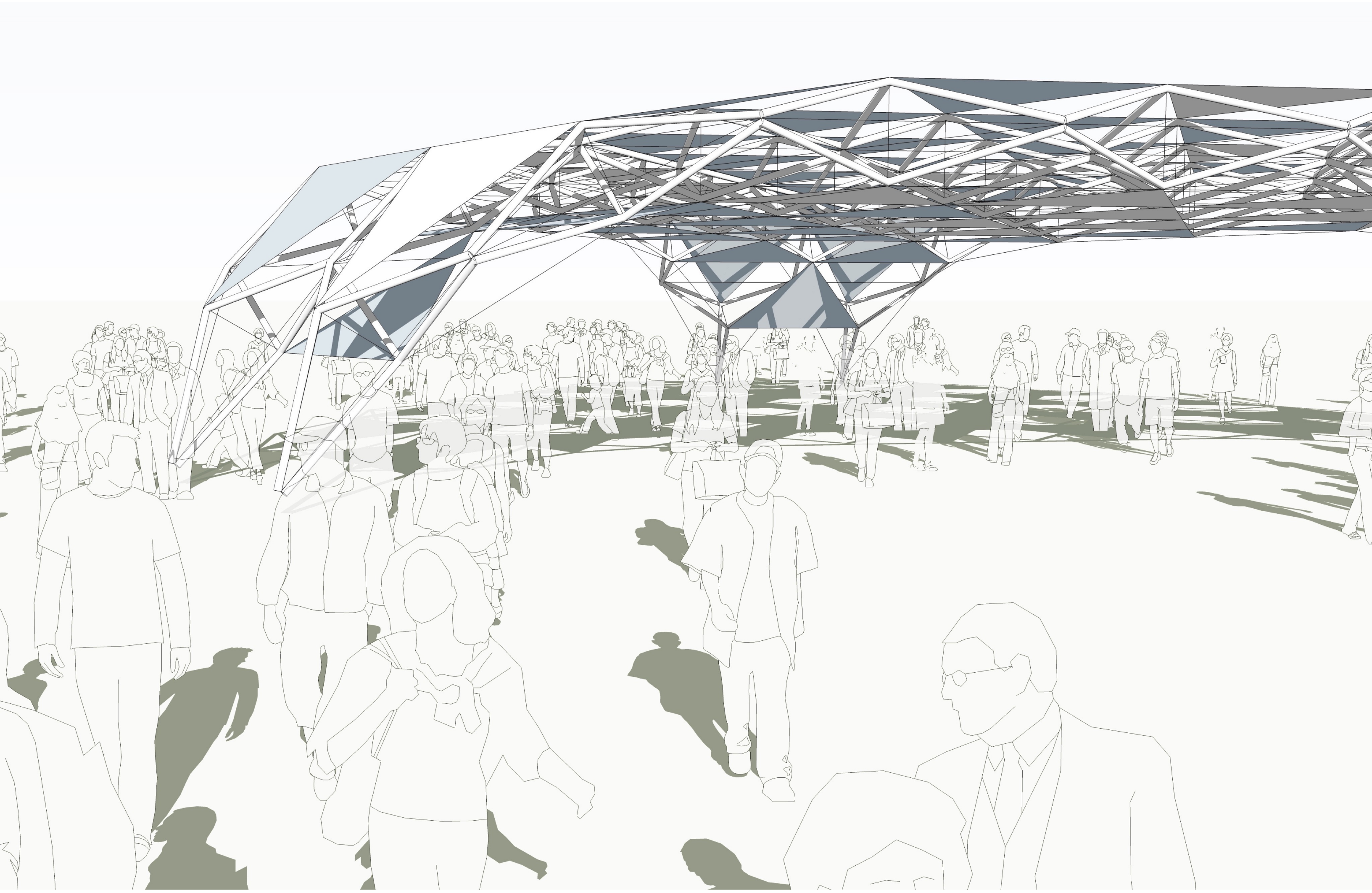


Figure 8.9: Shade Structure for a Park Setting. Jensen.

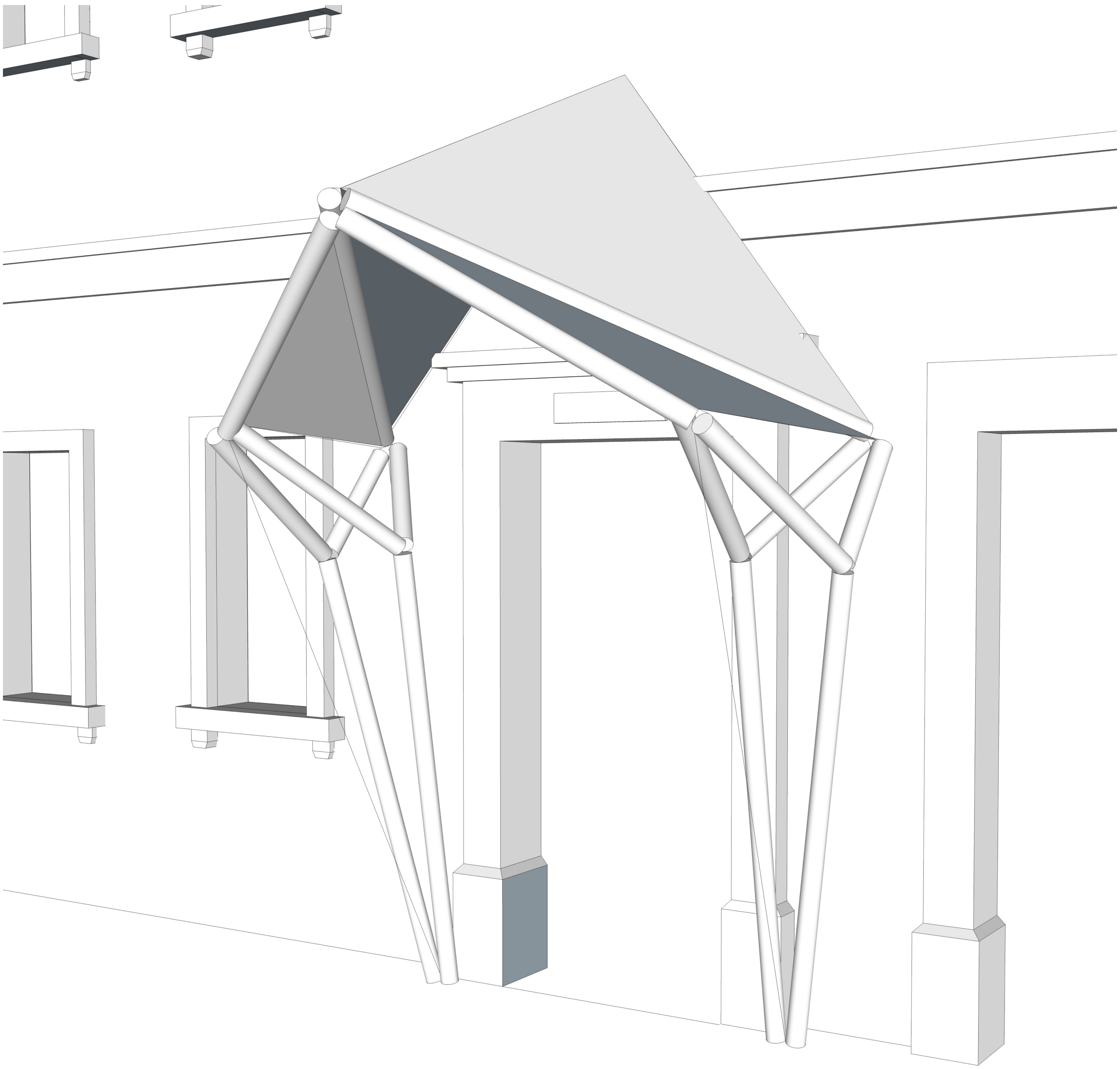


Figure 8.10: Threshold Canopy. Jensen.

Dwellings

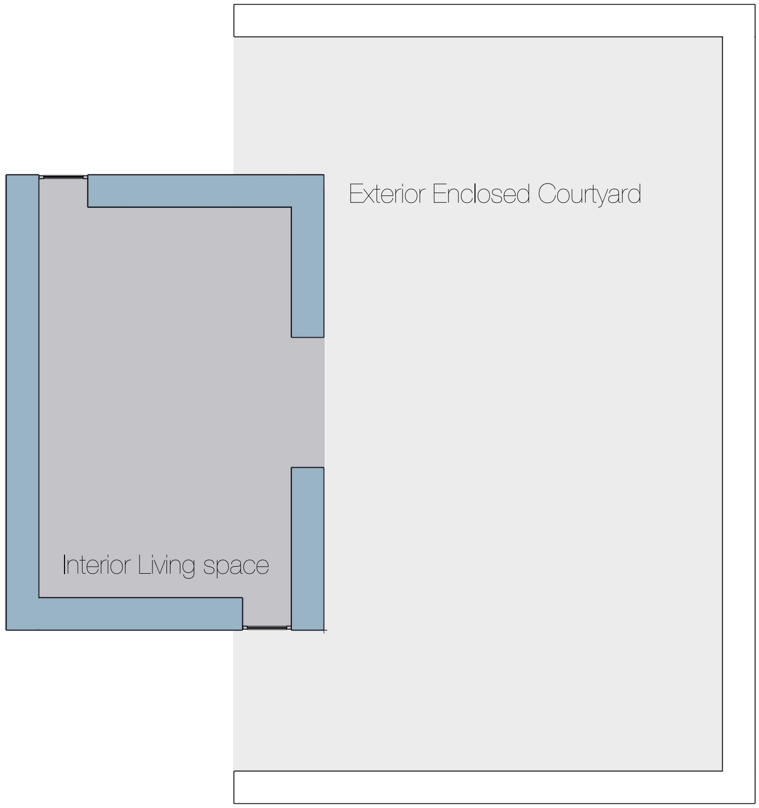
Enclosures for human habitation represent one of the most interesting and useful applications of the arch structure. As illustrated below, these dwellings can range from simple, temporary or permanent one room shelters to more elaborate and complex constructions. The adaptability of the structure allows it to respond to housing needs on a global level.

Refuge shelter

This single room dwelling is large enough for an entire family to live in. Designed with a large external covered area to allow for breakout space and a small garden, this shelter affords a family a safe and contained area with both inside and outside occupation. For additional safety and privacy, a fortified exterior wall is all that is seen from the street, and the entrance to the home is only accessible by walking around this wall and through the open space. (Figures 8.11-12).

The dwelling is arranged in such a way that it can be linked to a similar neighbouring house by linking garden walls and roof canopies (Figure 8.13). Local materials can be substituted for the heavy masonry walls and the compression struts in the roof, making the dwelling fit into a community both terms of availability and tactility of materials. The building can be built quickly and inexpensively in this way, using local labourers and techniques.

It is a modest dwelling but fully capable of sheltering a family from the elements, and it can be converted to a permanent residence if desired.



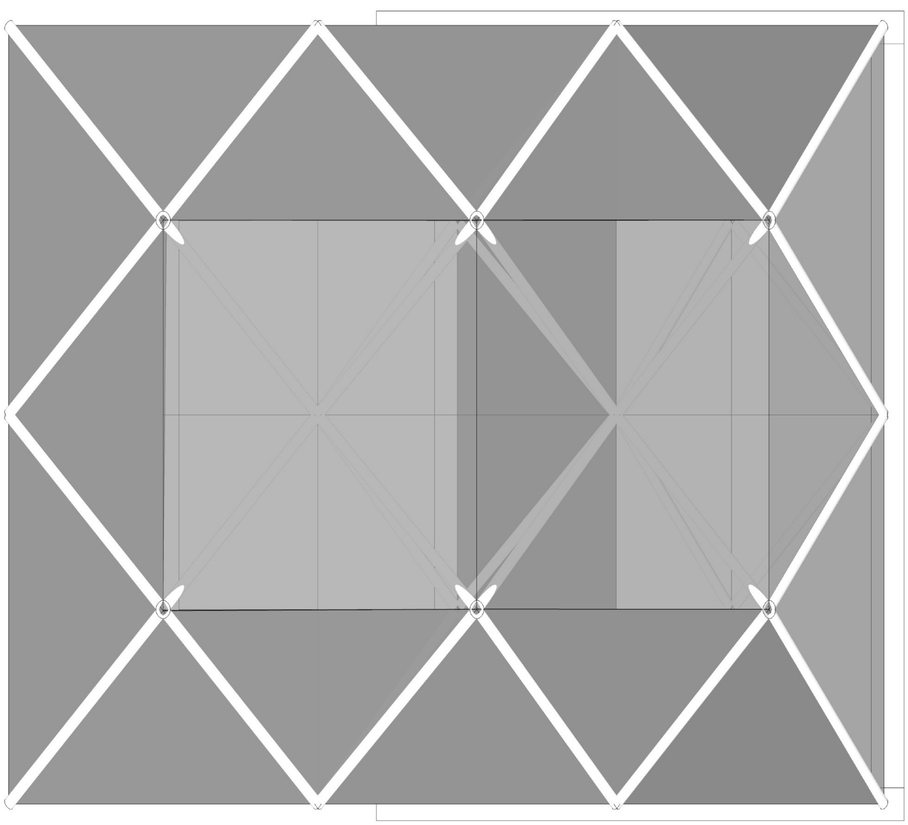
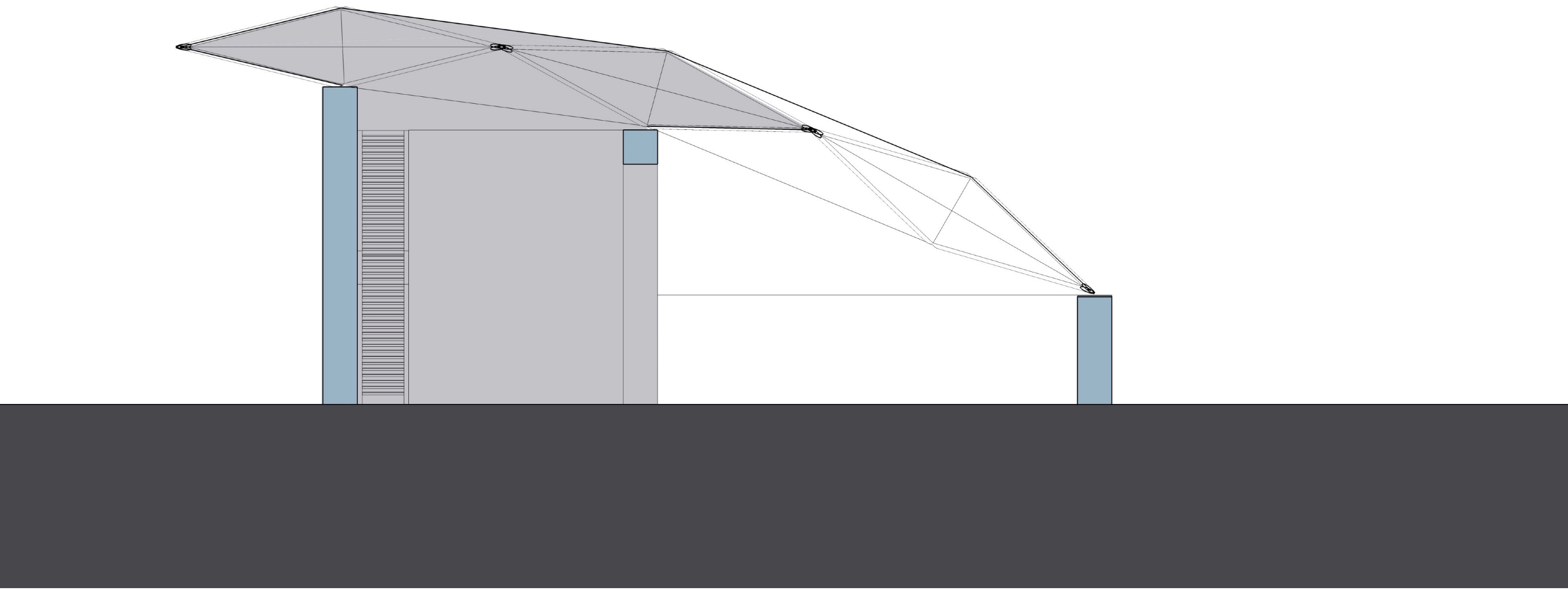


Figure 8.11: Refuge Floor and Roof Plan . Jensen.



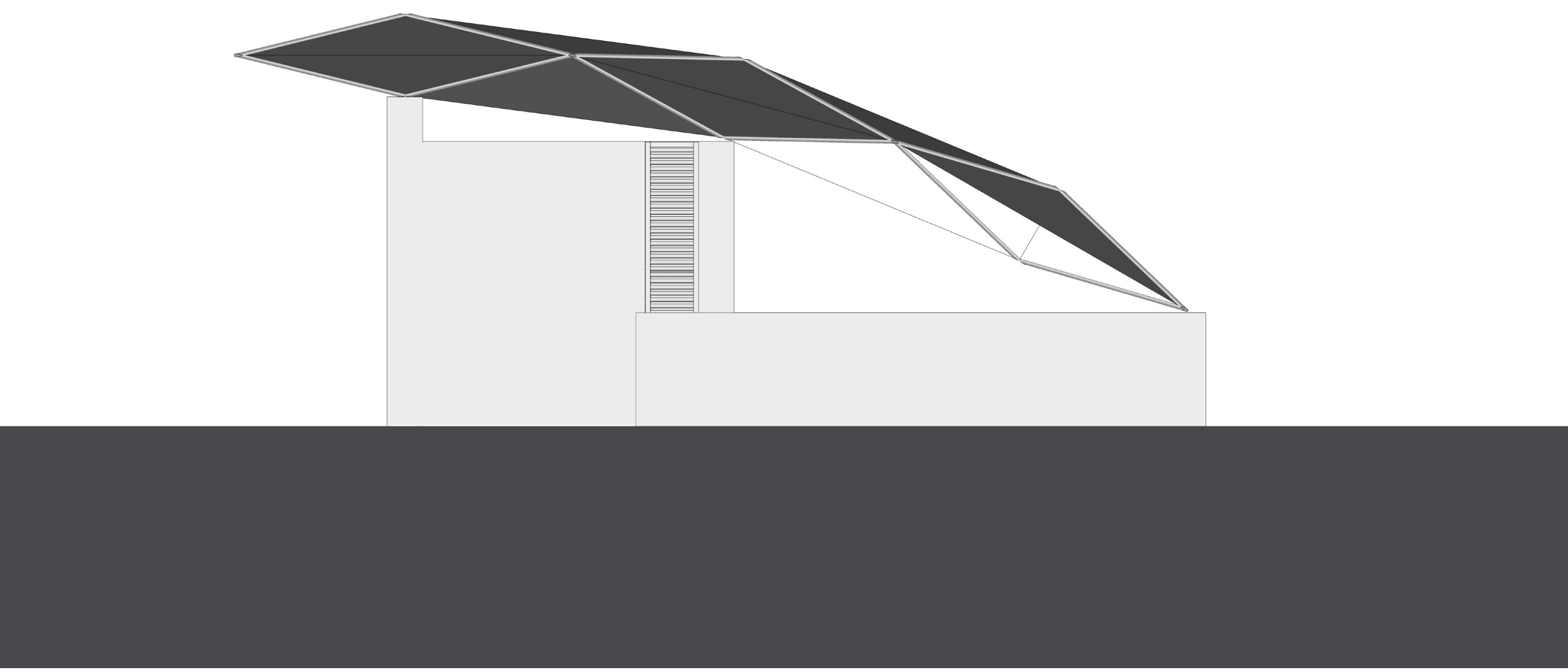


Figure 8.12: Refuge Section and Elevation. Jensen.

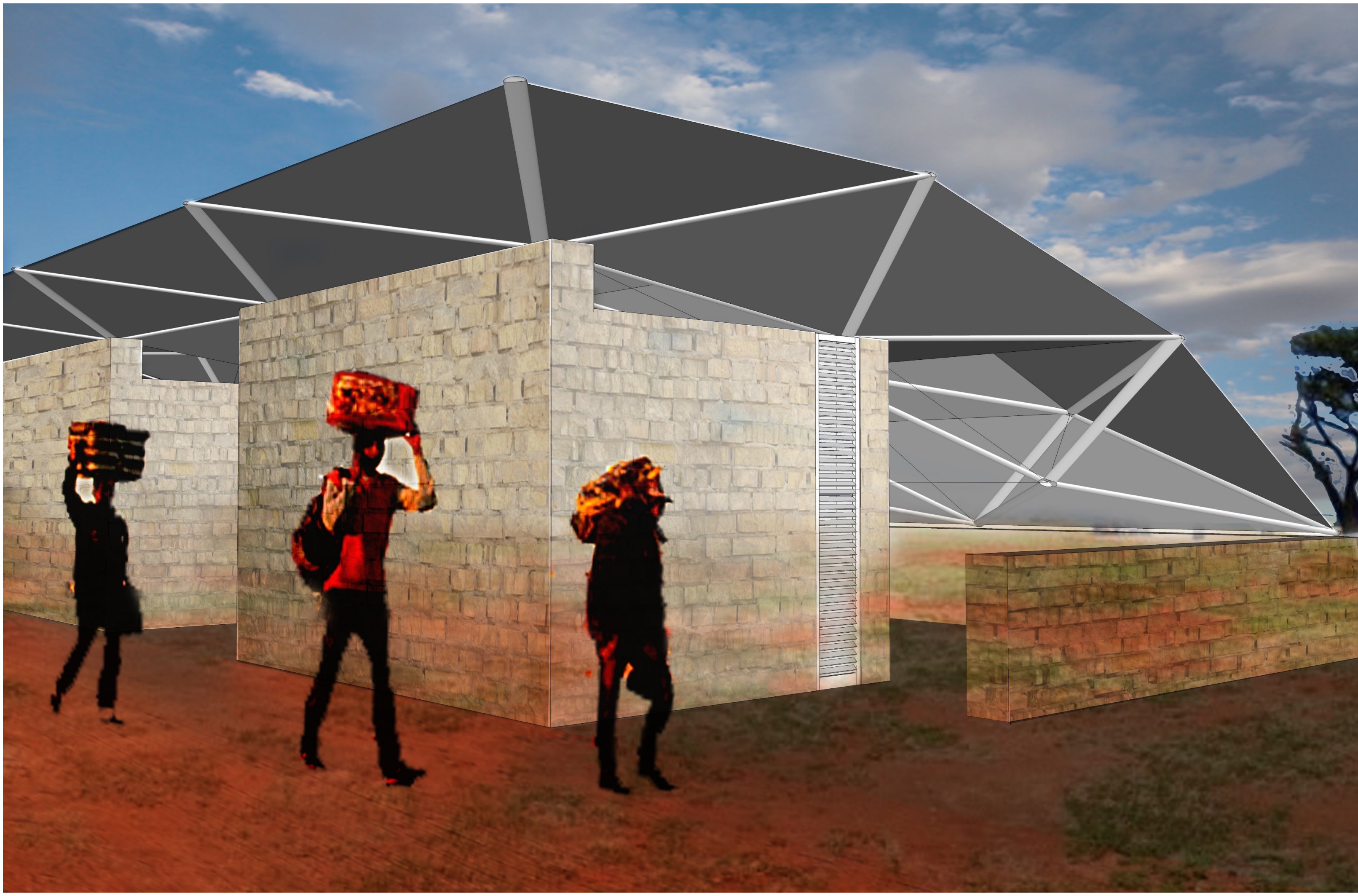


Figure 8.13: Perspective Refuge in its Natural Environment Connected to its Neighbours. Jensen.

Hill House

This example uses natural typography to integrate an arch type shape into the landscape (Figures 8.14-20). By cutting into a hill, a flat wall on one side of the dwelling is possible allowing for common installation of stock furniture and finishings. The advantage of an earth sheltered wall would also reduce the required building materials as the hill foundation wall itself could take the load of the vaulted roof. Depending on its function and scale, I envision a solarium space on the downward facing slope creating an interior/exterior threshold space and seasonally changeable area.

The scale and overall dimensions of such a dwelling are very dependent on the client's needs and desires. This example illustrates my vision of how a North American residential project might use this technology. The interior of the dwelling contains three bedrooms, two bathrooms and large living space, while the exterior enclosures include space for a seasonal green house and a car park area.

While this dwelling does not take full advantage of the potential of the structural system and possibilities within, it was created more as a transition piece for the acceptance of a new technology. To be widely adopted, I propose that we start by giving people what they expect, and today that is flat walls and square rooms in which they can use their current furniture.

In the future, the advantage of a clear span will give great flexibility to the overall plan and allow for multiple orientations of the space while allowing the footprint of the house to remain small. These features allow the house to reduce the materials used in its construction while providing a comfortable dwelling.

I see this house as a first step. If the technology is accepted, I believe it could lead to a new way of building. In the future, curved, angled, or oblique walls may gain favour and if that is the case this construction system would be ideal as it is capable of forming to the desires of the occupants. The more the system is used, the more the efficiency of the dwelling can be increased.

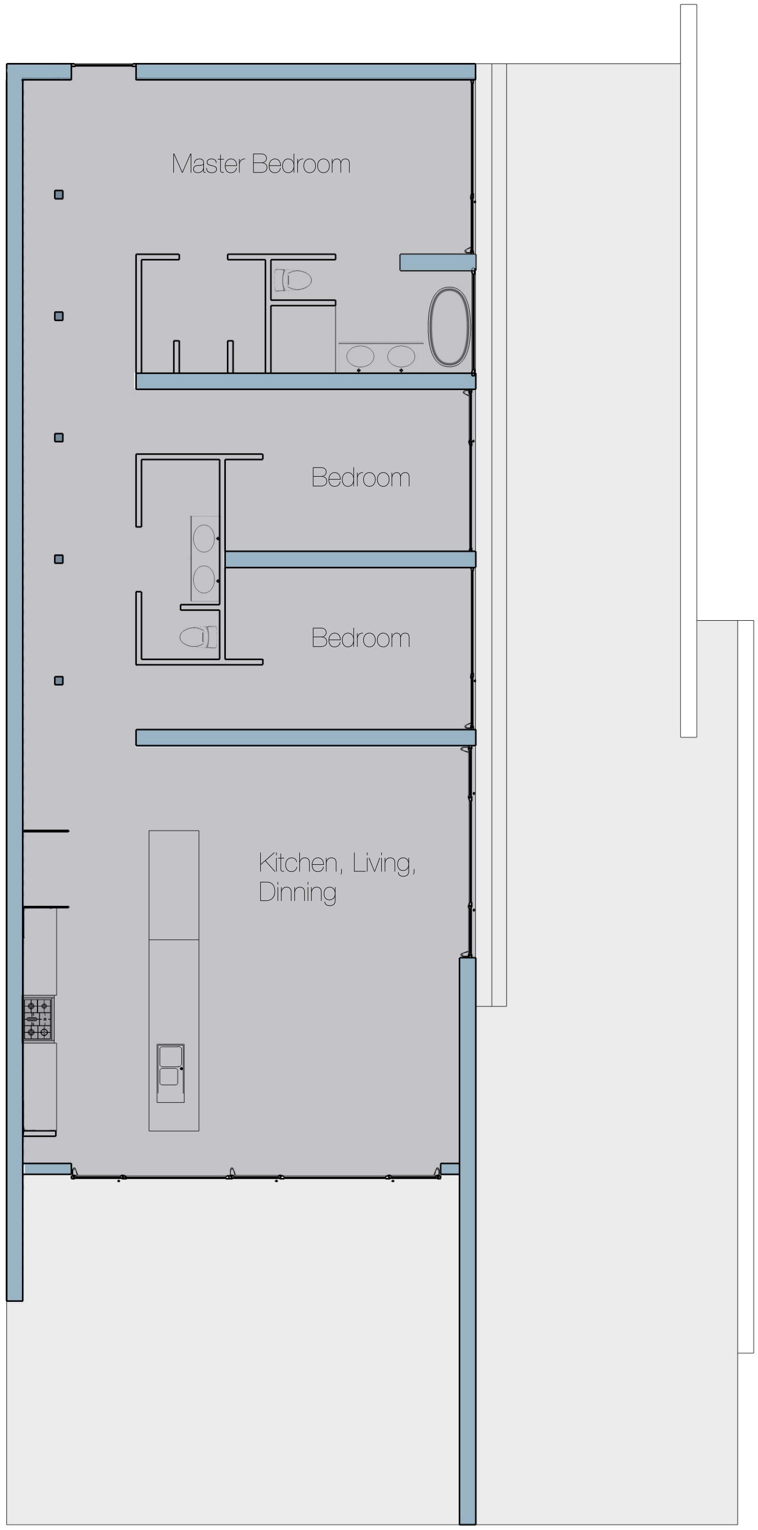


Figure 8.14: Hill House, Plan. Jensen.

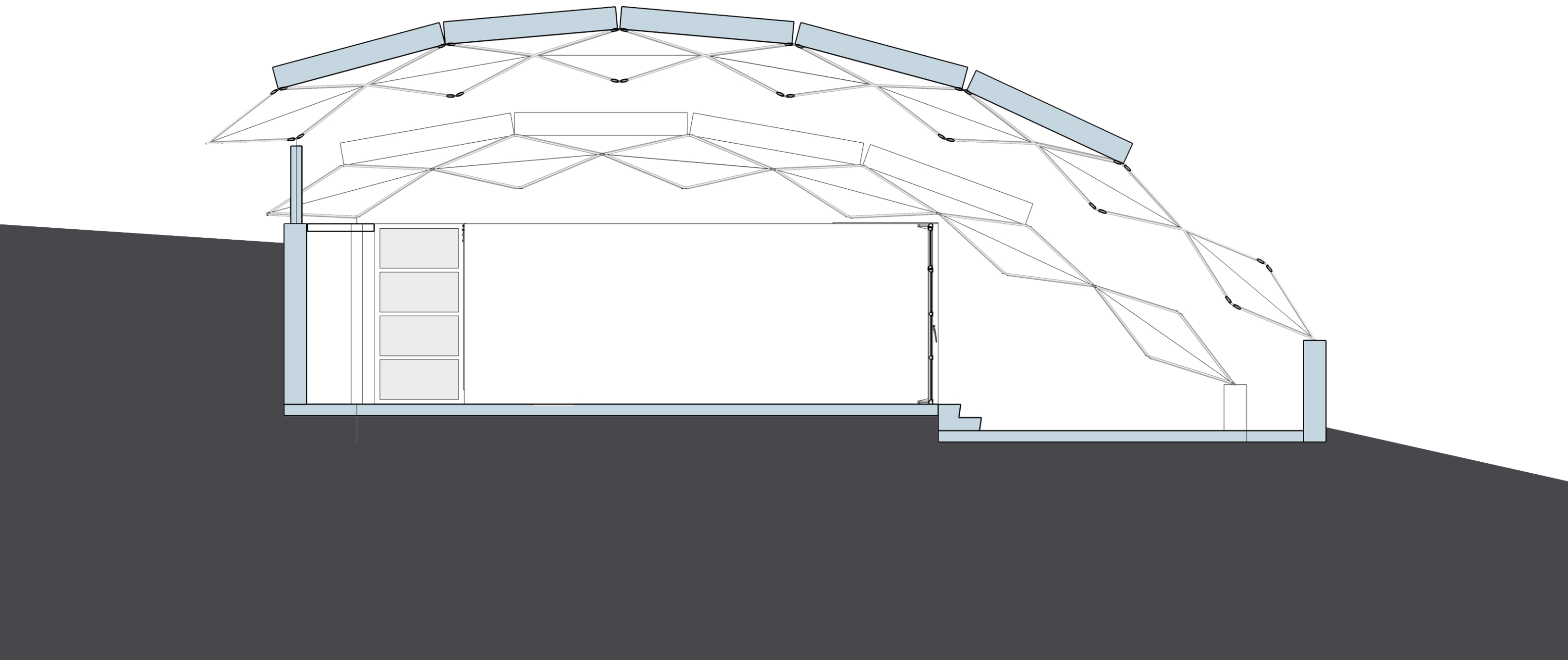


Figure 8.15: Section through Main Living Space. Jensen.

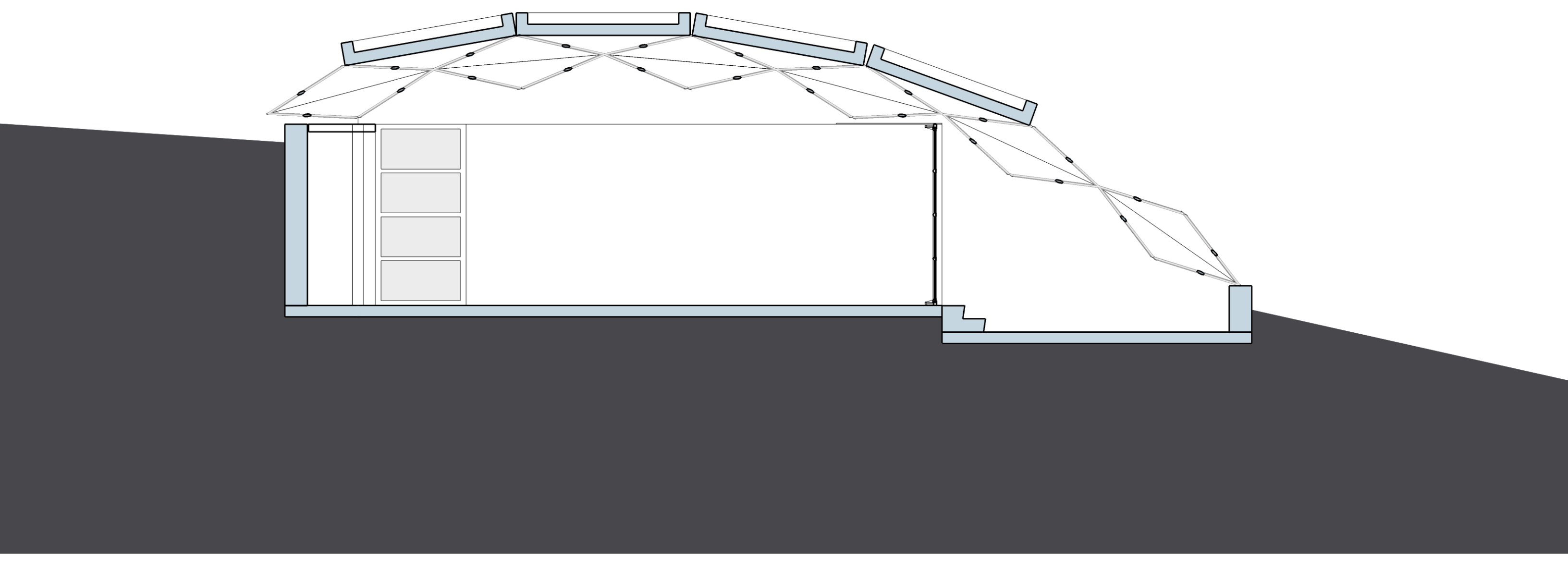


Figure 8.16: Section through Bedroom Space. Jensen.

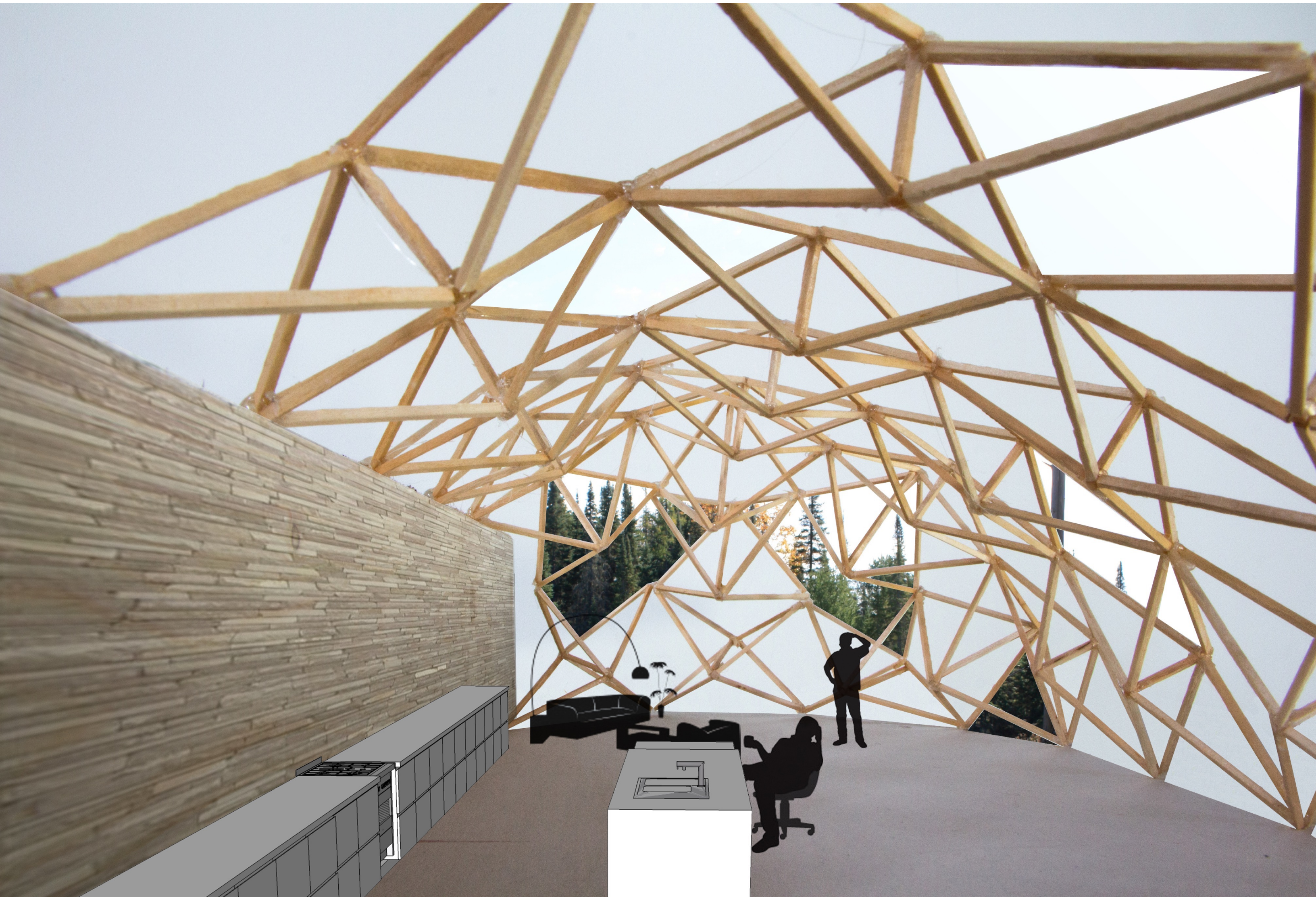


Figure 8.17: Interior Spatial Quality. Jensen.

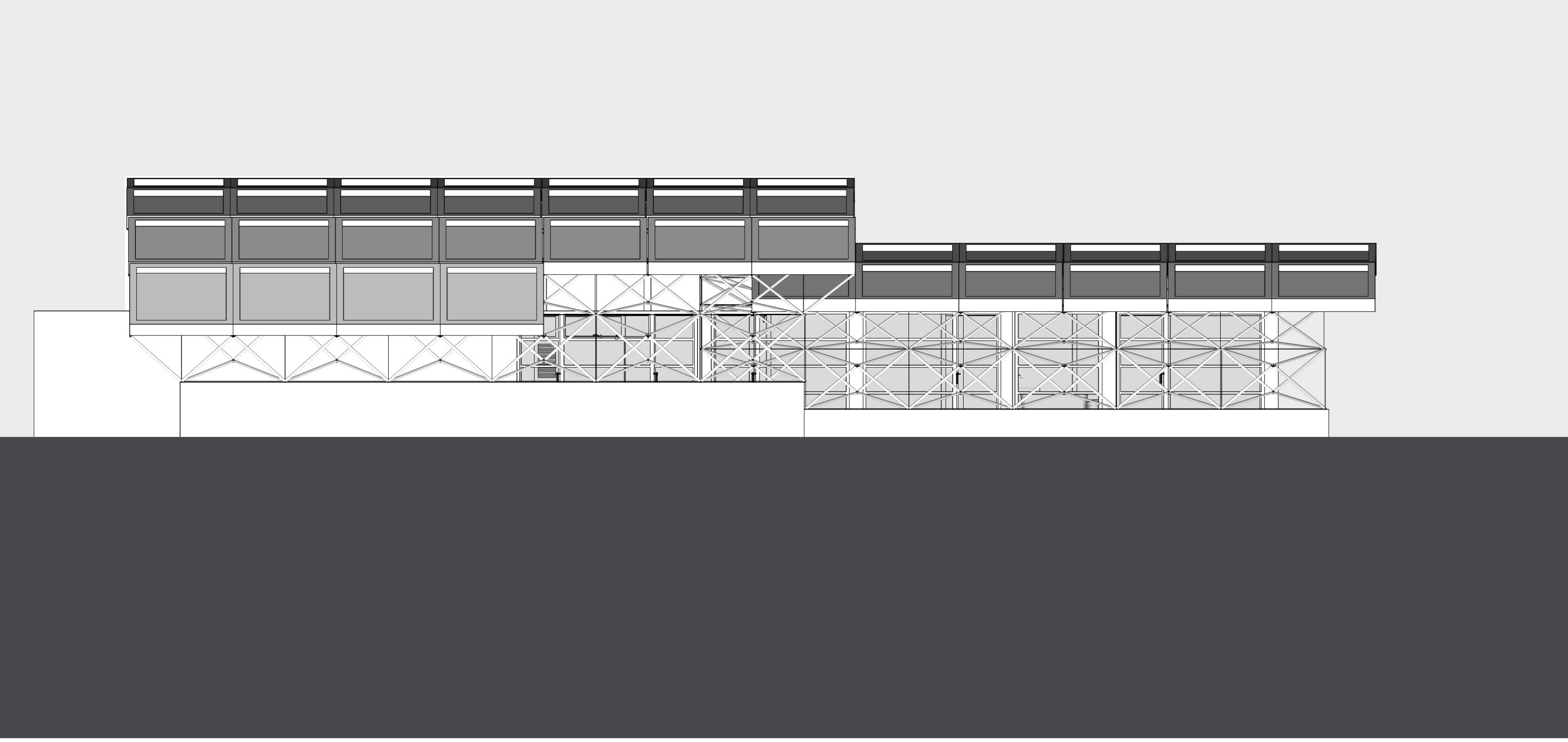


Figure 8.18: South Elevation. Jensen.

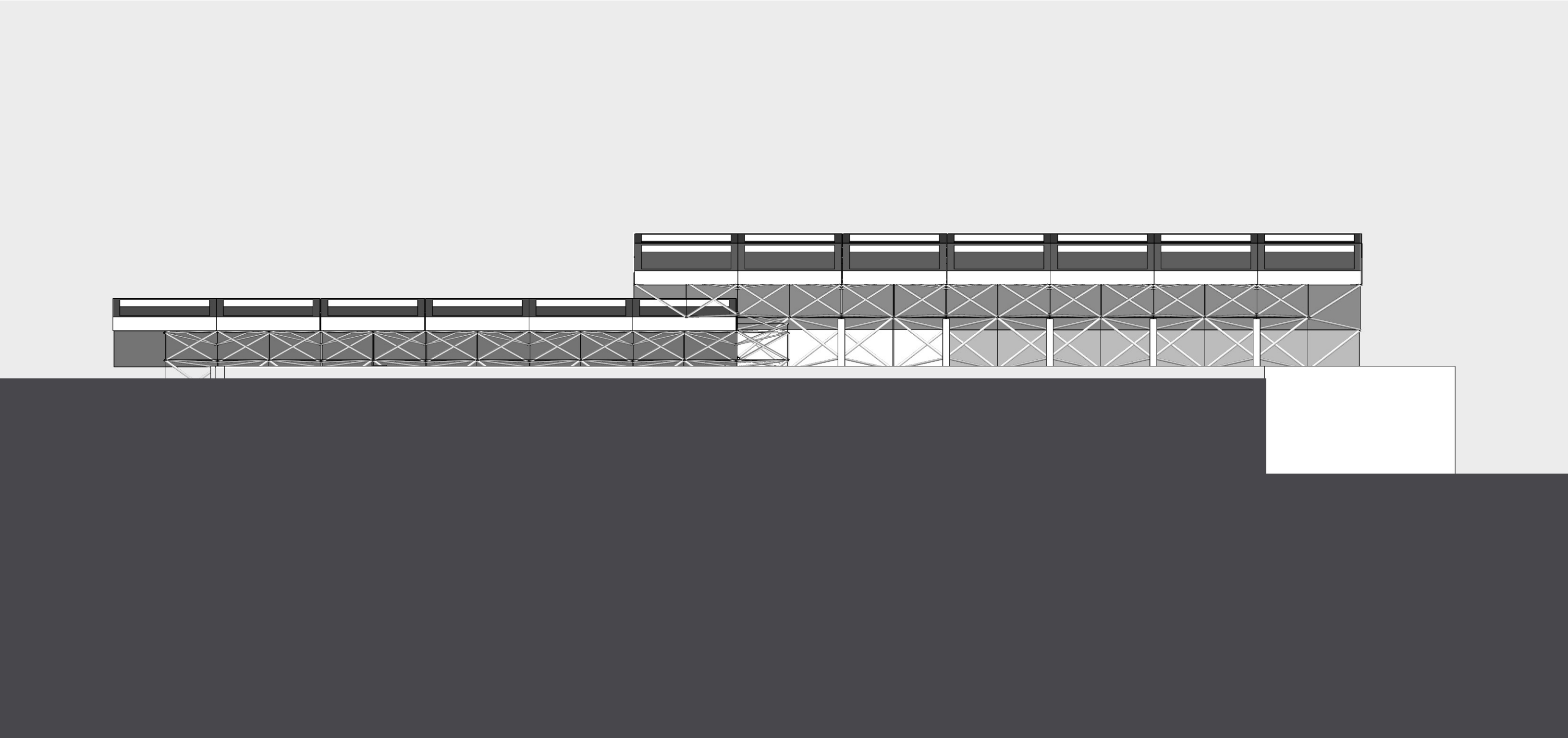


Figure 8.19: North Elevation.

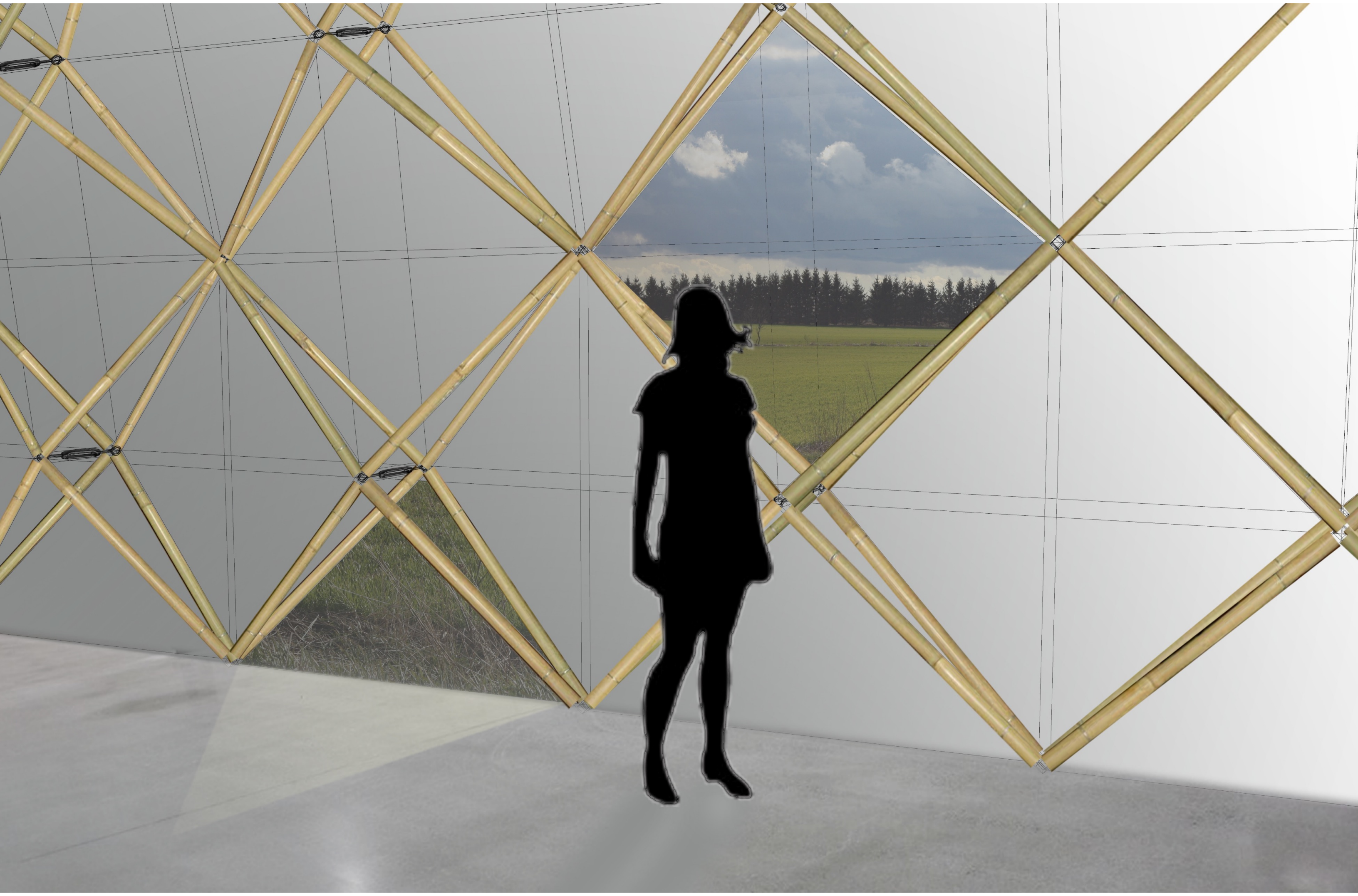


Figure 8.20: Exterior/Interior Relationship. Jensen.

Conclusion

In his book Cradle to Cradle, William McDonough makes the following assertion regarding the need to rethink the way humans "make things":

> "Negligence is described as doing the same thing over and over even though you know it is dangerous, stupid, or wrong. Now that we know, it's time for a change. Negligence starts tomorrow."[1]

The research presented in this thesis demonstrates beyond a doubt that we "know" we are on a path to destruction. Studies taken from environmental organizations such as the Global Footprint Network have clearly indicated untenable circumstances. These include inefficient use and waste of natural resources and loss of biodiversity, to cite only two examples.

The development of more efficient building technology is crucial to the global outlook of humanity's future. The days of short term gain are now quickly leading us to realize the imminent reality of our long term loss. We must institute changes now before the devastating effects of humanity's consuming nature causes irreparable damage to the natural systems we depend upon.

The literature has shown that over the course of the last century, a number of architects and engineers have begun to predicate their work on the ideals of innovation and sustainability, several even taking their cue from the shapes and systems found in the natural environment. Prominent among these innovators are people like Vladimir Shukhov, Buckminster Fuller, Peter Rice, and Robert Le Ricolais.

Shukhov's innovative work with truss structures led to successful efforts in creating aesthetically pleasing buildings such as the Shukhov Tower and his Machine Hall. Fuller's concern with humanity's tendency to over-consume translated into exciting solutions for optimizing the material to space ratio, as evidenced by one of his defining creations - the American Pavilion at Expo '67 in Montreal. Le Ricolais' research resulted in the concept of the Sky Rail to revolutionize an urban transportation system.

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[1] McDonough, William and Michael Braungart. "Cradle to Cradle: Remaking the way we Make Things." North Point Press, New York, N.Y., 2002. Print .p. 117.

While extremely innovative and inspirational, the majority of the project techniques highlighted in my research have not been adopted into mainstream construction practices. Some were simply too far ahead of their time, as with Le Ricolais' Sky Rail and Fuller's Dymaxion house and car; others were unique creations often made possible through government or special funding, such as Rice's collaboration on the Louvre pyramids and Fuller's U.S. Pavilion dome.

Drawing from the inspiration of the above precedents and from my personal projects, I explored and developed building components aimed at creating structures that articulate purposefully with the mandate of sustainability, specifically through achieving reduction of embodied energy in buildings.

The embodied energy in building material as well as the reduction in the amount of materials required in a structural system will dramatically reduce our demands on environmental systems. Through methods such as optimizing tension components in a building it is possible to greatly reduce the upfront energy that a building requires.

Early projects like furniture design and creation enabled me to acquire knowledge about the tension/compression relationship; developing a compact and transportable living space like the trailer gave me insight into the spatial challenges of lightweight, transportable structures.

By studying tension, it become clear very quickly that the compression members required to hold such an extreme force were a concern. The automatic reaction was to make the members larger to resist the tension, but that would negate all of the lightweighting principles that were put in place to begin with. Through further experimentation, I was able to arrive at a compression strut that could resist a load of 1538kg while only weighing 2.9kg. This compression member became an integral part of the unit designs for practical applications.

Compression members were focused on here as a way to use tension, but it led to the conclusion that the joints and construction details created a new direction for study. Further research on the simplification and rapid construction of connection details as well as maintaining a high strength to weight ratio are avenues for the future. Specifically one could investigate the joint's ability to be quickly manufactured and accurately duplicated with computer based technology like 3D printing or CNC routers.

While investigations here were primarily experimental, a mathematical understanding of the proposed components in this thesis would be a useful tool in realizing a structure that is outside of the conventional building code yet offers great promise for the future. A full scale prototype could then be used to verify and refine the design.

The arch structure that evolved out of my investigations is the purest form of the optimized structure I am seeking. In the case of the hospital and the refuge shelter/small scale habitation, advantages can be seen through using local materials and rapid construction, making lightweight structures a great equalizer for countries plagued with natural disasters and poverty.

In the case of a larger habitation, developed nations can utilize the advantages of a new building technology to reduce their impact on overconsumption.

Embodied energy values were used in this thesis as a way of understanding the potential impact of each individual material. It should be recognized that it is a complicated value, as it would vary significantly depending on the location and processes involved. It is, however, a global value, and while perhaps flawed, it is a nonetheless a useful benchmark.

The comparison of embodied energy in the arch structure versus a comparable standard structure was calculated to be a 322% improvement. It can be argued that this is an unfair comparison in a northern climate such as Canada because of the decreased insulation value and increased running costs due to heating and cooling requirements. While this a valid point, one could also consider that this construction method would allow for clear spanning spaces, so a smaller, more efficient dwelling could provide the same standard of living as a currently larger dwelling would. So while running costs would go up with less insulation, they would go down with a smaller footprint. Further investigation into building envelope technologies that address running costs associated with insulation is warranted.

The ability for this technology to take on existing building languages - straight walls and tall ceilings - could be the starting point of its acceptance into common practice. The inherent characteristic of this structural system to take on multiple shapes may eventually spawn a new accepted language in architecture and new ways to occupy space. Further design studies can be done to determine the optimal shapes, orientations and use of the technology with a view to creating a more permanent aesthetic.

Lightweight buildings could be a catalyst for change in the built world humanity creates. The potential to reduce our impact through new, responsible building strategies can translate into a global system which could help house the world's population and play a significant role in equalizing the share of the world's precious resources.

A solution to our problems will require a significant re-alignment of our value system, as we need to consider the longterm ramifications of our current decisions. Our intellect and ability to construct incredible structural feats now needs to be directed towards the intertwined goals of preservation of self and of the natural environment.

What I have explored here is a possible way to move forward. There is of course much work left to be done to make a new approach more acceptable and mainstream, but I am confident that we as a society - architects, consumers, producers, governments - will embrace the notion of change that will allow humanity to embrace the future, responsibly.

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