Structural Design and Construction of the Solatrium for the Solar Decathlon China Competition

A Major Qualifying Project Report:

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By

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b= base width

b_i= interior width

C_t=thermal coefficient

C_e=exposure coefficient

C_s=slope coefficient

E=young's modulus

FRP = Fiber Reinforced Plastic

G_{eq} = equilvalent total Gravity load

L= Length of member

I= second moment of area

I_x= Second moment of area around the x axis

I_y= Second moment of area around the y axis

I_f=Importance factor

h= height

h_1= height between the flanges

h_i= interior height

M=moment

M_n=nominal max moment

P= axial load

P_e=Euler's load

P_n=nominal max load

P_g=ground snow load

P_f=flat roof snow load

t_w= thickness of the web

Φ= LRFD resistance factor

Ω= ASD Safety Factor

α=horizontal seismic Influence coefficient

V=base shear

Authorship

This report was primarily compiled and written by Gregory Freeman in fulfillment of his Major Qualifying Project requirement for WPI. Gregory Freeman fully wrote the Introduction, Solar Decathlon, Transonite^{tm} panels, Criteria for Structural Design, and Horizontal Loadings sections along with all the sections dealing with construction and the lab report in Appendix A. The rest of the sections contain work by the Belgian students, Tine Lanssens, Charlot Tanghe, Thomas Tassignon, and Tim van Parys as members of the structural team of Team BEMANY. Tine, Charlot, Thomas, Tim, and Gregory worked together on each structural section. Tine provided work in the Walls and Columns, Floor Panels, and Foundation sections. Charlot provided work on the Atrium truss, Walls and Columns, Floor Panels, and Foundation sections. Thomas provided work on the Atrium truss section. Tim provided work on the Atrium section. Gregory Freeman worked as structural coordinator and worked with each team member on their structural sections, and reviewed and edited the written portions of the structural work. In Addition Tine, Charlot, Thomas, Tim, and Gregory all preformed the testing documented by Gregory Freeman in Appendix A.

Abstract

University teams from around the world compete to create net zero energy solar powered houses for the Solar Decathlon competitions. WPI has partnered with two other universities to form Team BEMANY for the Solar Decathlon China 2013 (SD China 2013). This project overviews the structural design and construction considerations for Team BEMANY's entry named the Solatrium into SD China. The Solatrium was designed to conform to the SD China 2013 rules which included Chinese Building codes, and to Massachusetts building codes.

Executive Summary

Introduction

The Solar Decathlon Competition is an award-winning program that challenges university teams to design, build, and operate solar-powered houses that are cost-effective, energy-efficient, and attractive. The winner of the competition is the team that best blends and integrates affordability, consumer appeal, and design excellence with optimal energy production and maximum efficiency.

The U.S. Department of Energy sponsored the first Solar Decathlon competition in 2002 in the US and biannually since 2005. The Solar Decathlon-Europe was held in Europe in 2010 and 2012. The Solar Decathlon China-2013, co-sponsored by the China National Energy Administration and the US DOE will be the first time the competition will be held in Asia. WPI and its two university partners Ghent University-Belgium and NYU Poly (composing team BEMANY) were selected as finalists among 23 international teams to compete in the Solar Decathlon China 2013 competition. (www.solatriumhouse.org)

The three-university team, Worcester Polytechnic Institute, Ghent University-Belgium and NYU Poly, with support from the Worcester Technical High School, designed and constructed a net-zero solar powered house in Worcester, Massachusetts. The solar house will then be transported to Datong China on May 7th and reconstructed and showcased to approximately 300,000 visitors in August 2013. We believe that our team will produce a competitive atrium style solar house with innovative design, modular composite structure, advanced phase changing materials and passive cooling and heating approach.

The main design goal for this project is to accomplish an affordable, attractive, and effective zero energy house that entices Solar Decathlon visitors to become aware of the net zero-energy housing market and sector. This goal will be accomplished by focusing on design principles that simplify and lower the cost of net zero-energy houses. Our atrium house, named 'Solatrium' by our student team, promotes an atmosphere that provides visual continuity between the indoor and outdoor environments. The floor plan is open and flexible and offers visual connections between the various spaces and the outdoors. Large portions of the external walls (40 percent) are covered by floor to ceiling glass doors and windows, and a large atrium that opens the building towards the sky. The design will be optimized to assure that the heating load is reduced during winter time by drawing solar energy directly into the house. When it is warm outside, more shading is provided and air is allowed to pass through the atrium cooling the building directly by means of natural breeze. One of the challenges is to minimize the use of dedicated HVAC system. The photovoltaic system will be integrated into the roof surface. The house is made from lightweight and insulated composite panels that are easy to handle and transport. The finished floor area will be approximately 1500 sq. ft. the house has 2 bedrooms, 1 bathroom, a kitchen and a mechanical room. The bedrooms have sliding partitions for privacy and for allowing light and breeze to circulate through the house when needed.

Team BEMANY consists of approximately 40 students and faculty across the three partner universities and across many disciplines including Architecture and Architectural Engineering, Civil Engineering, Electrical Engineering, Mechanical Engineering, Fire Protection and Communications and Arts Majors. Our three university team will partner with the Worcester Technical High School during the construction of the house in Worcester. Students from the WTHS will assist with areas related to carpentry, plumbing, electrical and HVAC installation. The solar decathlon project challenges students to solve real problems that help societal needs, promote collaborative learning and develop skills that are required for a technological and innovation based economy.

Our power will be generated through a 12 Kilo watt peak photovoltaic system. Forty panels of 300 watts each will be placed directly on the flat roof. Two 6 Kilowatt inverters will be used to convert DC power to the China electrical needs of 208 V, 50 Hz, 3 phase. However, the house will be connected to a mini grid and will draw US standard power, since our house is designed to operate in the US during the post competition time.

Structural Design

The post-competition purpose for the solar house could be a residential home in Massachusetts so in addition to the loading from the site in Datong, China, loads from Worcester Massachusetts were also considered. Load and Resistance Factor Design was used for the design of the house for loads expected to occur in Datong, China and Worcester, Massachusetts. The governing loads were snow and wind loads for Worcester and seismic loads for Datong, China. The major design constraint was the deflection of the Fiber-Reinforced Polymer (FRP) panels that composed the roof, walls, and floor.

The structural design was done by a group of students from Ghent University, Belgium and WPI. The structural calculations were done both manually and with the Finite Element Modeling (FEM) software. Design of the columns and cable stayed truss were done manually, but the FEM software was used to design the roof, steel truss, floor, and foundation grid.

The house will need to be shipped to China; therefore the entire dissembled house is designed to be fit within 3 shipping 40 ft. high containers for ease of transport.

Atrium

The atrium of the house is a 6.25m x 6.25m steel truss angled at 45^{o} on all four sides with a 5.13m x 5.13m FRP roof panel covering the center. In addition to supporting the atrium roof, the steel trusses are lined with windows to let in natural light. The window glazing is a double pane acrylic plastic that will endure deflections during transport and shipping. Because of the excessive deflection of the roof panels, a cable stayed truss was designed underneath the roof panel. The cables are connected to the four top corners of the steel truss and to four struts placed at each third of the diagonal. This cable system reduces the deflection under loading to acceptable levels. The 2800 lb. atrium steel truss was welded together by students from WTHS, and the entire atrium truss is to be placed using a crane during the construction phase in China.

Columns and Walls

In addition to the standalone columns, every wall panel in the Solatrium has a column inserted into each end. The skin of the wall panels and columns are made up of FRP materials. The FRP makes the columns and walls lightweight compared to traditional building materials, therefore larger elements can be maneuvered and placed without mechanical assistance. After preforming a buckling check on every column, it was determined that some columns were critically loaded. A secondary steel column was inserted into the FRP columns in these locations to strengthen the FRP columns against buckling.

Floor Panels and Foundation Grid

The floor of the Solatrium is composed of concrete tiles that incorporate phase changing materials that rest on top of FRP panels. The panels are placed on a foundation consisting of FRP beams and girders that are placed in a 2.25m x 2.25m grid pattern. In order to comply with the competition regulations that require an adjustable foundation of 10 inch vertical height, a 1" diameter adjustable screw supports each foundation beam intersection and underneath columns that carry large loads.

Construction

During the SD China 2013 competition, each team is given two weeks to assemble their house. Because of this time constraint, a practice build was held in Worcester, MA. The practice build's objectives were two fold, to give the students experience with the Solatrium's construction, and to prefabricate some of the necessary structural elements. This prefabrication included

- The welding the steel trusses
- The detailing of the roof, wall, and floor panels
- Pre-drilling
- Inserting the wiring into the wall panels
- Inserting the plumbing
- Completely assembling the kitchen module

All these tasks were designed to reduce the construction time during the decathlon competition period. The kitchen and bathroom modules are being shipped completely assembled to the competition site to further reduce construction time.

In addition to the prefabrication, the choice of materials was designed and selected to further reduce construction time. The FRP panels that make up the roof, walls, and the floor are lightweight, modular, and came predimensioned by the manufacturer.

Conclusion

The Solar Decathlon project has brought three institutes of higher learning and over 40 students and faculty to compete with 22 other universities from around the world. The ultimate goal is promoting construction design and technology application to produce net zero-energy houses that are appealing and affordable. The team members involved in this project have a broad multi-disciplinary background including architectural, civil, electrical and computing, fire protection mechanical, lighting and acoustical engineering

The use of the FRP elements in the Solatrium presented some interesting challenges during the design process due to the lack of code guidance for the relatively new material and the low stiffness of the material compared to traditional construction materials. Column placement and a cable stayed truss were used to overcome the low stiffness and industry standards were used in lieu of code requirements for composite materials.

The construction phase of the Solar Decathlon China is only 2 weeks long and the construction will be completed by students, faculty and other volunteers. And therefore, the decision to use a prefabricated house that would facilitate the quick construction time constraints during the competition in Datong China.

Sustainability was a major focus in the Solatrium design. The Solatrium is a net zero energy house designed to create a feeling of connection with the outdoors, through the large windowed surfaces and the open central atrium.

Engineering Capstone Design Statement

The Solatrium house is primarily designed with of Fiber-reinforced polymer (FRP) materials; these materials are lightweight but have low stiffness. The Solatrium house needs to comply with the code regulations for both Worcester, Massachusetts and the SD China competition. The architectural design of the home is supposed to have open areas, so all design decisions have to be made without compromising that openness but still delivering a code compliant house. Also the design cannot be overly complex to construction as the SD China competition only allows for 10 days of construction.

This design issue will be approached by determining the loading that's each code requires the building to endure. Then material testing on the FRP panels will be done. Then the design will follow the loadings paths through the structure.

Environmental: As part of an international design competition The Solatrium project promotes the use of sustainable energy buildings by attempting to create an affordable design that will use emissions-free solar energy. The extensive use of solar energy in this project creates an alternative to non-sustainable electricity generation.

Health & Safety: The Solatrium is designed to be structural sound under the conditions expected in the SD China rules and the building codes of the state of Massachusetts. These codes are enforced to protect the occupants of buildings. Using methods learned in structural classes as an undergraduate at WPI, the Solatrium is designed to be safe for its occupants.

Manufacturability: One of the design constraints of the Solatrium is that is must be constructed in 10 days and that it must be shipped to China in three shipping containers. This created a need for modular design, and for lightweight material

Social: As a competition, the solar decathlon creates a public discussion about various solar home designs. The Solatrium will be open, along with all the other competitions, to the public of Datong, China. By opening the home to the public, it is disseminating knowledge about solar home design and creating a social interest in sustainable design.

Sustainability: The design focus on solar power allows the Solatrium to operate sustainably and environmentally friendly. The home combines a sustainable energy space with modern living in a way that is designed to be appealing to both the contest judges and the general public.

1 Introduction

In 1997, The Kyoto Protocol (United Nations 1998) was signed in an effort to reduce the emissions of greenhouse gases as to mitigate the effects of global climate change. The greenhouse gases enumerated in the Kyoto Protocol are carbon dioxide (CO_2) water vapor (H_20), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). These gases allow the heat from the sun to pass through to strike the Earth but trap the reflected heat off the Earth

One of the major sources of these greenhouse gases, CO_2 in particular, is the burning of fossil fuels. Fossil fuels, like petroleum, natural gas, and coal, are used to power cars, electrical plants, and used to generate heat. The production of electricity alone represents about 38% of CO2 emissions due to fossil fuels (US Environmental Protection Agency 2013). While fossil fuels have many benefits, there many initiatives to replace fossil fuels or reduce the emissions produced by burning them because of the emissions they produce.

As the levels of greenhouse gases are continuing to increase, many groups are looking to greatly decrease global reliance on fossil fuels by replacing them with alternative sources of energy. Hydropower, wind power, nuclear power, and solar power are some of those alternative power sources. These power sources do not produce CO_2 emissions at all, and if alternative power sources were fully adopted in the US power generation sector, 38% of fossil fuel based CO_2 emissions would be eliminated.

The US Department of Energy created a competition to promote use of solar energy in housing design (US Department of Energy 2013a). This competition is the Solar Decathlon and has been running biennially since 2002. . Solar Decathlon has “collegiate teams design and build energy-efficient houses powered by the sun,” (US Department of Energy 2013a). These houses completely replace the fossil fuel provided heat and energy with solar power. The Department of Energy has since expanded the Solar Decathlon to have separate European and Chinese competitions.

Worcester Polytechnic Institute in Worcester Massachusetts, Polytechnic Institute of New York in New York, New York, and Ghent University of Ghent, Belgium make up one of the twenty three teams that have come together to design and build a house for the Solar Decathlon China 2013. The team is called the BE-MA-NY which represents the three locations of the colleges, **BE**lguim, **MA**ssachusetts, and **N**ew **Y**ork. The students of those three universities are working in teams to develop the design of the competition structure. This report is for the structural and construction design of the BE-MA-NY house.

2 Solar Decathlon

The United States Department of Energy (DOE) has sponsored the Solar Decathlon (SD) competitions biennially since 2005, after a first Solar Decathlon in 2002 (US Department of Energy, 2013). The Solar Decathlon pits net zero energy solar powered houses designed by collegiate teams against each other. The designs are built by each team in a public space, like the National Mall in Washington D.C. and then judged in 10 different contests the competition stated purposes are

- To educate students and the public about money-saving opportunities and environmental benefits presented by clean-energy products and design solutions.
- To demonstrate to the public the comfort and affordability of homes that combine energy efficient construction and appliances with renewable energy systems available today.
- To provide participating students with unique training that prepares them to enter out nation's clean energy workforce

Since its inception, 112 teams have designed solar powered homes for Solar Decathlon competitions and the competition has expanded into an international competition with competitions on 3 continents.

2.1 History

In 2002 the DOE created a competition and had teams create a "Solar Village" on the National Mall in Washington D.C. (US Department of Energy 2010). In 2002, 14 teams designed 14 solar powered houses that were judged in 10 contests. Because of the focus on solar energy and the 10 contests, the competition is called the Solar Decathlon. The 14 teams were all from the United States and were all single university teams. After the 2002 competition, Eastment stated that "Based on the success of this first event, there will be subsequent Solar Decathlons. The next Solar Decathlon will be held in 2005, and another in 2007," (Eastment 2002). After the 2002 competition, some of the houses are now part of solar energy research, inspirations from eco-friendly housing initiatives, office buildings and administrative centers, university solar villages, powering non-profit offices, houses for rent, integrated into larger houses. The buildings are continuing to benefit the public long after the competitions have ended. This is a testament to the quality of the designs.

Later competitions continued this trend of continued benefit after each completion and the locations and used of all the houses can be found on the DOE's Solar Decathlon website. By the second competition in 2005, the Solar Decathlon had become an international competition with the inclusion of three teams with schools from Canada and Spain designing the solar houses (US Department of Energy 2010). The 2005 Solar decathlon also was the first have more than one school per team. The Canadian Solar Decathlon team had two universities working together and the Pittsburgh Synergy team had three. Both teams consisted of schools within the same localities, Montreal, Canada and Pittsburgh, PA respectively.

In between the 2007 and 2009 competitions, the United States government and the Spanish government signed an agreement that expanded the Solar Decathlon program into Europe. A branch of the competition called Solar Decathlon Europe was created from that agreement. What started as a program that only involved American schools was expanded into a truly international program. The first two SD Europe competitions were each held in Spain and in 2014 the program will be held in the historic Versailles, France.

In the 2011 Solar Decathlon, more international teams came to the US, from Belgium, Canada, New Zealand, and China. Also in 2011, the Governments of the United States and the People's Republic of China signed an agreement similar to one between Spain and the US in 2007 which stated

> … the Governments of the United States of America and the People's Republic of China have a common goal in fostering sustainable economic and social development while encouraging the use of renewable energy sources and recognize that solar energy development and use is an important part of their collaboration …

This agreement created the SD China competition. SD China's first competition will take place in Datong, China and will host 23 teams from 13 countries.

2.2 SD China contests

SD China has ten different contests that each team competes in. Each contest is worth 100 points, and the team with the highest combined point value is the winner of the competition. The SD China rules state that points are awarded in three ways; Task Completion, Monitored or Measured Performance, and Jury evaluation. The ten contests, their point values, how points are awarded and a brief description are found in Table 1 below. Of the ten contests listed and described, this report directly relates to two contests: Architecture and Market Appeal.

Table 1 List of contests in SD China with available points, subsections, contest types, and a short description (SD China 2012b)

Contest Number	Subcontest Number	Contest Name	Available Points	Subcontest Name	Available Points	Subcontest Type	Brief Description
1	n/a	Architecture[2]	100	n/a	n/a	Juried	Architecture Jury reviews and evaluates the drawings, construction specifications, audiovisual architecture presentation, and final constructed project
2	n/a	Market Appeal[2]	100	n/a	n/a	Juried	Market Appeal Jury reviews and evaluates the drawings, construction specifications, audiovisual sales presentation, and final constructed project
3	n/a	Engineering[2]	100	n/a	n/a	Juried	Engineering Jury reviews and evaluates the drawings, construction specs, energy analysis results and discussion, audiovisual engineering presentation, and final constructed project
4	n/a	Communications	100	n/a	n/a	Juried	Communications Jury reviews and evaluates the Web site, video walkthrough, onsite public exhibit, and public exhibit materials
5	n/a	Solar Application[2]	100	n/a	n/a	Juried	Solar Application Jury reviews and evaluates the drawings, construction specs, energy analysis results and discussion, audiovisual solar application presentation, and final constructed project
6	6-1	Comfort Zone	100	Temperature	75	Measured | Monitored	Keep zone temperature in 22°C – 25°C range
	6-2			Humidity	25	Measured | Monitored	Keep zone relative humidity below 60%
7	n/a	Hot Water	100	n/a	n/a	Measured | Task	Deliver 60 liters of water at average 45°C temperature within 10 minutes; 16 water draws during contest week
8	8-1	Appliances	100	Refrigerator	10	Measured | Monitored	Keep refrigerator temperature in 1°C - 4°C range
	8-2			Freezer	10	Measured | Monitored	Keep freezer temperature in -30°C to -15°C range
	8-3			Clothes Washer	20	Measured | Task	Successfully wash 8 loads of laundry (one load = six bath towels) during contest week
	8-4			Clothes Dryer	40	Measured | Task	Return 8 loads of laundry to their original weight (one load = six bath towels) during contest week
	8-5			Dishwasher	20	Measured | Task	Successfully wash five loads of dishes (one load = six place settings) during contest week
9	9-1	Home Entertainment	100	Lighting	40	Measured | Task	All interior and exterior lights on at full levels at night
	9-2			Cooking	20	Measured | Task	Successfully perform four cooking tasks (one task = vaporize 2kg of water in less than 2 hours) during contest week
	9-3			Dinner Party	10	Juried	Host two dinner parties for up 8 guests; teams score each other
	9-4			Home Electronics	25	Measured | Task	Operate a TV and computer during specified hours
	9-5			Movie Night	5	Juried	Invite neighbors to watch a movie on the home theater system; teams score each other
10	n/a	Energy Balance	100	n/a	100	Measured | Monitored	Produce at least as much electrical energy (kWh) as is consumed during contest week
TOTALS			**1,000**	**515 total juried points and 485 total measured points from 19 individually scored contest elements**			

The Architecture contest is the first contest and all the points are awarded through jury evaluation (SD China 2012b). The jury will be entirely composed of Architects and will be looking to award points for design and implementation, innovation, and documentation. These criteria include such things as the use of lighting, holistic design, new architectural concepts, and environmentally friendly design. One of the more interesting criteria is “Will the overall architectural design offer a sense of inspiration and delight to the Solar Decathlon China visitors,” (SD China 2012b) The inclusion of this criteria shows that at the heart of the Solar Decathlons is the hope not to only create an architecture or engineering success but also to make more people interested in the solar design.

In order to achieve Team BEMANY’s architecture goals, all the architectural elements must be structurally secure and properly documented for contest submission. This report directly relates to making the entire structure up to code.

For a house design to be successful it must appeal to a wide market, this is the idea behind the Market Appeal contest (SD China 2012). A jury of “professionals from the homebuilding industry” will award points based on livability, marketability and buildability. In practical terms, the jury will judge how easy it is to live in the house, how desirable the market will find the house, and how easy it will be for an outside contractor to build the house after the decathlon.

This report directly covers Team BEMANY’s methods for the Market Appeal subsection, buildability. The construction of Team BEMANY’s entry will have to be completed in 10 workdays. This report documents the construction methods and schedule used in order to achieve complete construction in 10 workdays.

2.3 TEAM BEMANY

The possible global benefits of solar power that allowed the international SD China to be created also allowed the creation of multi-national teams. Many participants formed teams through international partnerships between England, American, and Swiss schools and Chinese counterparts.

Two American universities are partnering with a Belgian university to create the Team BEMANY (**BE**lgium-**MA**ssachusetts-**N**ew **Y**ork): Ghent University from Ghent Belgium, Worcester Polytechnic Institute (WPI) from Worcester, MA, and Polytechnic Institute of New York University (NYU-Poly) from New York, NY. Ghent University was entered into the 2011 Solar Decathlon where they placed 16th overall but tied for first in the affordability contest with the E-Cube design, but for both WPI and NYU-Poly this is their first Solar Decathlon entry.

By the competition in the summer of 2013, students and professors from all three universities will have worked for over a year to complete the design and building of the Solatrium, the team’s entry in SD China. For many of the students and professors involved this is their first solar design competition and some students have had to leave their countries to work with the team.

The multi-national and multi-institutional nature of this project has created many chances to create solutions to communication issues. This section will discuss the communication solutions and provide an overview of the design of the Solatrium house.

2.3.1 Team Communication

Team BEMANY is separated by an ocean and 3500 miles in addition to being in a different country than the competition itself. The physical separation of the team has created obstacles that many other teams did not have to overcome, such as organizing student work, sharing documents, and using compatible software. WPI was the focal institution on the BEMANY team and many of the student workers came from WPI's fledgling Architecture Engineering department and the Civil Engineering department.

The faculty leads for team BEMANY are Prof. Steven Van Dessel from Ghent University, Tahar El-Korchi, from WPI and Professor Masoud Ghandehari from NYU Poly. Professor Van Dessel was the primary advisor of Ghent University's 2011 E-Cube design. Prof. Van Dessel is a visiting professor at WPI for the duration of this project. Prof. Van Dessel's relocation to WPI created a more centralized location to organize the project, as the majority of students on the project are from WPI. The four students from Ghent University working on the project have split their time between their classes in Belgium and spending weeks at a time at WPI directly working on the Solatrium. Similarly students from NYU-Poly have been working on a special concrete (described in the next section) for the Solatrium, but have also spent time working at WPI.

The SD China competition requires large documents as deliverables before arriving at Datong, China. These documents are worked on by multiple team members so sharing of documents was essential for the completion of the project. The internet has greatly helped in overcoming the obstacles of physical separation. The organizers of SD China provided each team with a FTP (File Transfer Protocol) server for document submittal. This eliminates the need to ship documents overseas to the organizers, but is not suitable for day to day document sharing because the server must be keep clear and organized for the organizers to be able to access the necessary deliverables.

For day to day file sharing, the online service DropBox was used. DropBox is a service where you can save up to 2 GB of files to their servers for free, and they can be accessed by from any computer in the world with internet access (DropBox). Team BEMANY created a folder used to hold all the documents and drawings that would be created for the project and granted access to all the project members, so everyone has access to the files whether they were in Belgium, Massachusetts, or New York and could still be accessed, if need be, while in China during the competition. In addition, in an effort to unclutter the main DropBox file, some groups, like the structural design group, created DropBox folders just for files that they created and used. The use of internet services like DropBox greatly helped communication between the large numbers of people working on the project, by centralizing many of the files in a way that all members of the team could access.

One issue with a multi-national team is the use of compatible software. Microsoft office programs are internationally available and widely used so documents and spreadsheets were almost always created in Microsoft Word and Office creating few, if any, compatibility issues. But for the structural design group, which consisted of the four Belgium students (Tine Lanssens, Thomas Tassignon, Charlot Tanghe, and

Tim Van Parys) and one American (Gregory Freeman), a decision to use compatible modeling software had to be made early on. The first program used was PowerFrame by BuildSoft (BuildSoft), a Belgian company, to design the truss surrounding the atrium. This program eventually gave way to a more comprehensive program by BuildSoft called Diamonds 2012. Diamonds 2012 was selected for 3 reasons; 1) four out of five of the structural group members were already familiar with the program, 2) even though it was a Belgian product, it came with an English language package so non-Dutch speakers could easily use it 3) and finally the product can be obtained free for students from the BuildSoft website, so it did not add to the overall budget of the project.

In conclusion, many of the communication issues were solved through the centralizing the primary advisor with most of the student workers and through the use of the internet services. The use of DropBox greatly eased the transfer of files among the team members, and the free downloading of the Diamonds 2013 solved the issue of compatible structural models.

2.3.2 Solatrium

The Solatrium (pictured in Figure 2) is the name of Team BEMANY's entry into the SD China. The Solarium is a zero-energy solar powered house whose design emphasizes direct solar heat gain through its expansive windows and passive cooling techniques through the use of phase changing concrete tiles. The wall-to-floor windows and open central atrium creates a strong visual connection to the outdoors. The floor plan of the Solatrium contains few interior walls in the living space of the home, this and the prevalence natural light creates an open environment for the inhabitants.

The floor plan of the Solatrium, shown in Figure 1 is an 11.25m x 11.25m square centered around a raised atrium with a protruding carport extending from the structure. The structure also is characterized by a central raised atrium lined with windows, a number of floor-to-ceiling windows, modular design for ease of transport, phase-changing concrete floors, and being primarily made of FRP materials, Fiber Reinforced Polymer.

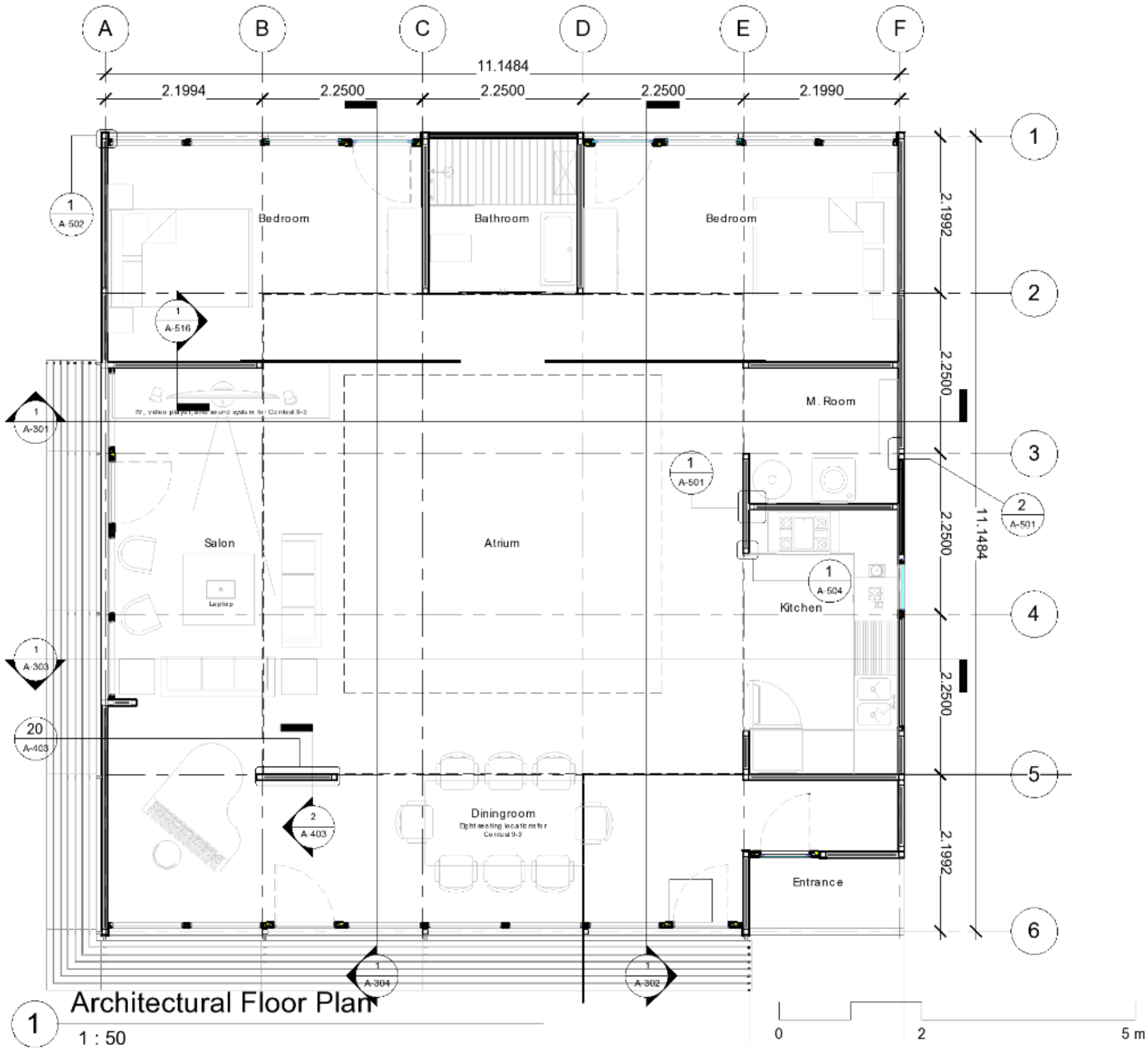


Figure 1 Interior Design Plan of the Solatrium (all units in meters) (BIM Report submitted to SD China 2013 by Team BEMANY on 3/6/2013)

Figure 2 Architectural Rendering of the Team BEMANY's Solatrium (BIM Report submitted to SD China 2013 by Team BEMANY on 3/6/2013)

The Solatrium is so named by the use of a central atrium held in place by a steel truss with windows enclosing the atrium. The atrium is used to create an open central area and provide natural lighting. The atrium is a 6.75m by 6.75m square lined with steel truss angled at 45 degrees that supports a 5.13m by 5.13m roof section. This roof section is additionally supported by a cable stayed truss (not pictured). The atrium is designed to contribute to the Architecure, Market Appeal, and Solar Application contests directly and indirectly to the Energy Balance and Comfort Zone contests. Also area of the house is 126.6 m^2 but contest rules require that the maximum finshed area(mechincal room and parts of the kitchen covered by cabinets are excluded) be 100m^2 (SD China 2012b) calculated by adding 100% of the finished floorplan area with 50% of the “hole” area. “Hole” areas are areas such as patios and decks and for the purposes of the SD China competition, the area under the atrium is being treated like a open patio area. This brings the calculated finshed area to 99 m^2, as pictured in Figure 3.

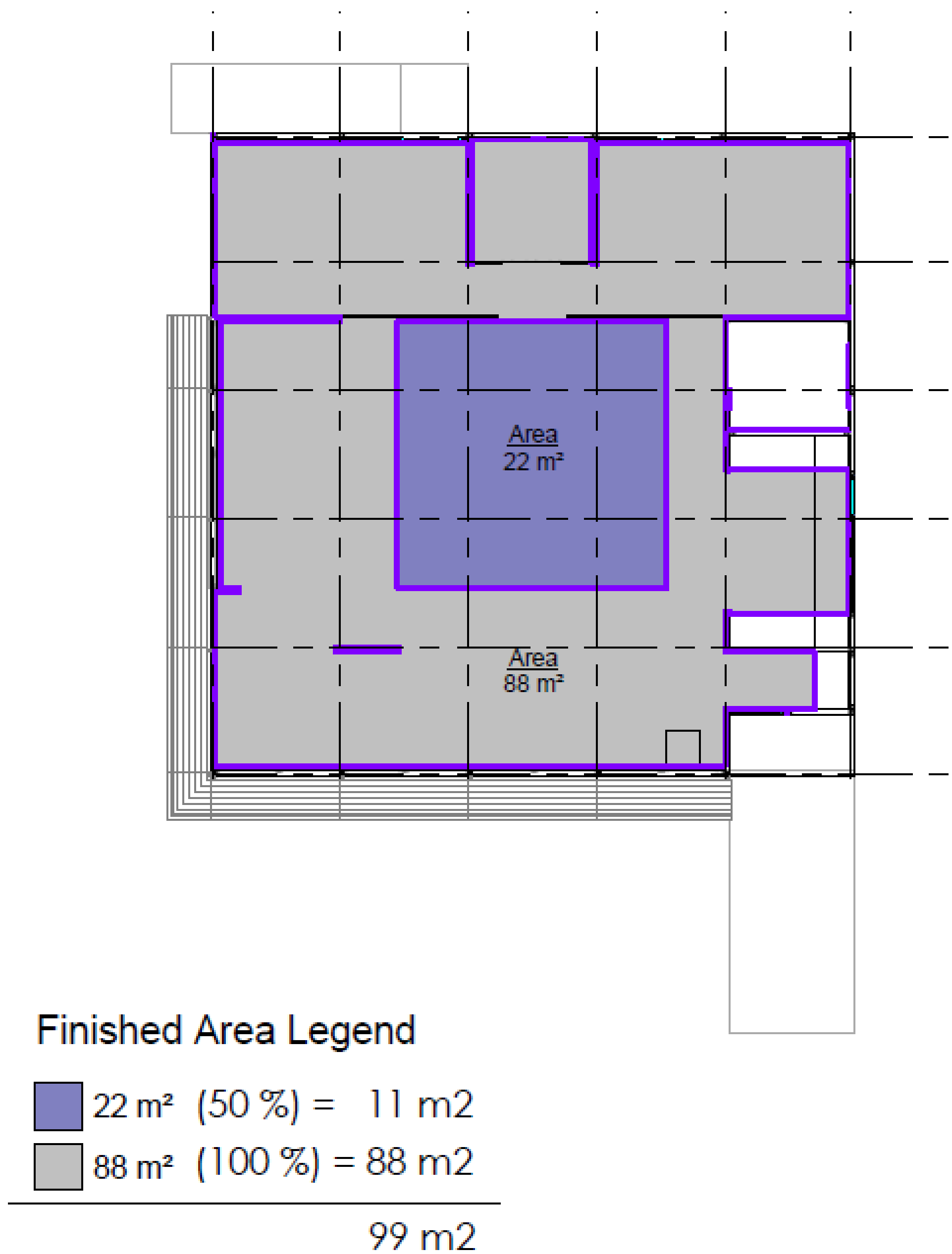


Figure 3 Finished area calculations (BIM Report submitted to SD China 2013 by Team BEMANY on 3/6/2013)

Figure 4 Photo of the interior of the Solatrium after the practice build without atrium attached (taken by a member of Team BEMANY)

About 40% of the Solatrium's exterior wall surface area is double glazed windows. The large number of windows has the dual benefits of naturally lighting the structure during the day, as seen in Figure 4 and to allow for the passive solar heating of the interior. Both natural lighting and passive solar heating decrease the energy loading on the structure during the daytime. The only window in the walls that is not floor-to-ceiling, is the kitchen window shown in Figure 5. The windowed exterior walls also hold floor-to-ceiling windowed doors in 5 locations as pictured in Figure 1. The windows are is designed to contribute to the Architecure, Market Appeal, and Solar Application contests directly and indirectly to the Energy Balance and Comfort Zone contests

Figure 5 Photo of kitchen interior of the Solatrium House after practice build (taken by a member of Team BEMANY)

Because of the necessity of transporting it from the United States to China and then back to the United states and budget considerations, the Solatrium is designed to be taken apart and put together quickly once and able to be transported in 3 shipping containers. To achieve this, the Solatrium is designed around the dimensions of standard shipping containers, 2.3m x 12m x 2.35m.The largest elements of the structure are the roof panels and the largest roof panel is 2.25m x 9m x .1m. The roof panels will be stacked on top of each other during the transportation phase, along with the most of the other elements like the columns, windows, truss, etc., will be placed in 2 shipping containers. The other shipping container will contain the entire kitchen module, complete with cabinets and appliances. This will decrease the necessary construction on site and decreases the effect transportation has on the budget of the Solatrium. The modular nature of the Solatrium is designed to contribute to the Market Appeal contest directly under the subsection, buildability.

The floor of the Solatrium is covered with specially designed concrete tiles created by NYU-Poly. The concrete tiles are designed to be phase changing. In practice, phase changing means that the concrete will be able to absorb heat in warm temperatures, thereby cooling the building, and will release heat in cool temperatures, thereby heating the buildings. The concrete tiles are supposed to store the heat provided by the natural lighting during the day, and release that heat during the cool nights. The concrete tiles are designed to directly contribute the Comfort Zone, Engineering, Solar Application, and Energy Balance contests.

Finally the structure is almost completely designed with FRP materials. The roof, walls, and the floor under the concrete tiles are all FRP panels. Also the columns, beams, and foundation grid are all made from FRP materials, and much of the detailing is FRP channels and angles. The use of the FRP materials is designed to directly contribute to the Architecture and Market Appeal contests.

3 Transonite™ Panels

The material being used for the floor, wall, and roof panels is an FRP panel system. Creative Pultrusions 60% glass fiber by weight in a system that Creative Pultrusions calls Transonite™ (Creative Pultrusions, personal communication). Creative Pultrusions' Transonite™ is custom made to customer specifications for every order. The Transonite™ system is a panel with two skins separated by a foam core with the skin connected by glass fibers. Our custom Transonite™ panels are 90mm thick with 4.5mm thickness FRP skin, thus a foam core of Polyurethane is 81mm thick, as shown in Figure 6.

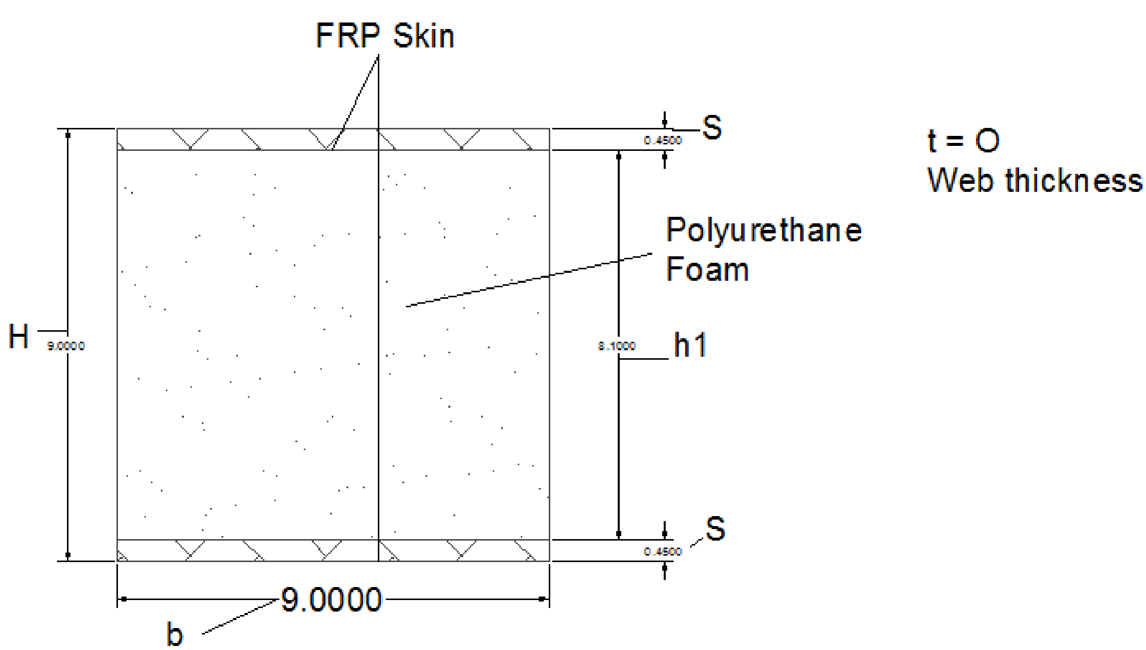


Figure 6 Cross section of Transonite™ Panel in centimeters

The panel's foam core will help insulate the Solatrium. The major benefit of using FRP elements is that they are lightweight compared to equivalent elements of traditional materials such as concrete. The density of the Transonite™ panels for example is about 25 kg/m^2 where as a concrete panel of similar dimensions would be over 200 kg/m^2. Though the panels are lightweight compared to concrete, they are also quite large, this makes many of the panels too heavy or unwieldy to put in place by hand alone. Our construction will use a forklift and a vacuum life to maneuver and place most of the Transonite™ panels. The exception is the atrium roof panel which will be lowered by crane.

The Transonite™ system is not commonly used as a building material, but the BEMANY team is using the Transonite™ panels as structural roof elements, structural floor elements and structural walls. The lightweight nature of the material greatly decreases the dead loading on the vertical elements of the structure. The downside is that the material deflects much more than other standard building materials.

Table 2 was given to team BEMANY by Creative Pultrusions as the excepted maximum uniform loading that result in the given deflections.

Table 2 Deflection of Transonite^{tm} panels under uniform loads for a simple span (Load and Deflection Tables, Creative Pultrusions, 2013, personal communication)

	Allowable Uniform Load Tables (kN/m^2)					
	L/D Ratios			Deflection (mm)		
Span (m)	180	240	360	6	10	Max. Service Load
0.25	****	****	****	****	***	169.3
0.50	****	****	****	****	****	84.6
0.75	****	****	****	****	****	56.4
1.00	****	****	37.0	****	****	42.3
1.25	****	32.9	21.9	****	****	33.9
1.50	27.7	20.8	13.9	20.0	****	28.2
1.75	18.5	13.9	9.2	11.4	19.0	24.2
2.00	12.9	9.7	6.4	7.0	11.6	19.5
2.25	9.3	7.0	4.7	4.5	7.4	15.4
2.50	6.9	5.2	3.5	3.0	5.0	12.5
2.75	5.3	4.0	2.6	2.1	3.5	10.3
3.00	4.1	3.1	2.1	1.5	2.5	8.6

After these tables were provided, the Transonite™ panels were constructed. Then Creative Pultrusions Inc. performed some quality testing on the produced panels, the results of which are found in the lab report in Appendix A. The results of that testing were used to then modify Table 2 to create Table 3and show the deflections informed by the quality testing of Creative Pultrusions Inc.

Table 3 Deflection of Transonite[tm] panels under uniform loads for a simple span adjusted after the quality testing (Load and Deflection Tables, Creative Pultrusions, 2013, personal communication)

	Allowable Uniform Load Tables (kN/m^2)					
	L/D Ratios			Deflection (mm)		
Span (in)	180	240	360	6	10	Max. Service Load
0.25	****	****	****	****	***	122.6
0.50	****	****	****	****	****	61.3
0.75	****	****	****	****	****	40.9
1.00	****	****	11.5	****	****	30.6
1.25	****	9.4	6.2	10.8	****	24.5
1.50	7.5	5.6	3.7	5.4	9.0	20.4
1.75	4.8	3.6	2.4	3.0	4.9	17.5
2.00	3.3	2.4	1.6	1.8	2.9	15.3
2.25	2.3	1.7	1.2	1.1	1.9	13.2
2.50	1.7	1.3	0.8	0.7	1.2	10.7
2.75	1.3	1.0	0.6	0.5	0.8	8.8
3.00	1.0	0.7	0.5	0.4	0.6	7.4

Table 3 shows that for all of the span lengths listed the panels exceed maximum deflection limits well before they exceed strength limits, well before they fail through bending stress. This shows that the deflection of the material, and not the bending stress, is the primary design constraint.

4 Criteria for Structural Design

The Solatrium is a competition house entered in SD China and as such will need to conform to the competition rules and buildings codes of Datong, China. The structure's final location is envisioned to be in Massachusetts where it could be used as a permanent family dwelling and as such must conform to 780 CMR 16.00 Structural Design (State Board of Building Regulations and Standards, 2008a) and 780 CMR 53.00 Building Planning for Single- and Two-Family Dwellings (State Board of Building Regulations and Standards 2008b).

4.1 Structural Criteria

From those documents these following Load Resistance Factor Design (LRFD) loading combinations (LC) were used (State Board of Building Regulations and Standards 2008a).

Load Combination 1 $(1.2)\ Dead\ Loading + (1.6)\ Snow\ Loading$

Load Combination 2 $(1.2)\ Dead\ Loading + (1.6)\ Wind\ Loading + (0.5)\ Snow\ Loading$

Load Combination 3 $(1.2)\ Dead\ Loading\ +\ (1.6)\ Live\ Loading$ + (1.6) *Snow Loading*

Load Combination 4 $(1.2)\ Dead\ Loading\ +\ (1.0)\ Earthquake$

LC 1 and LC2 governed the design of roof members. LC3 governed the floors, and LC4 governed for the whole structure under seismic loading.

The standard resistance factors in LRFD for steel (Breyer, Fridley, Pollock & Cobeen, 2006).

Φ = 0.90 Tension members (yielding state)

Φ = 0.75 Tension members (fracture state)

Φ = 0.85 Compression members

Φ = 0.90 Beams (flexure and shear)

Φ = 0.75 Fasteners

Since the structure will primarily be made of composite materials, there are additional resistance factors that will be used. Composites for Construction (Bank 2006) lists the Allowable Stress Design for composites as

For in-plane Shear Ω= 3

For Max bending stress Ω= 2.5

Using the formula Φ=1.5/Ω, the LRFD resistance factors for composites were computed

Φ=0.5 for In-plane Shear for FRP elements

Φ=0.6 for max Bending stress for FRP elements

To satisfy the serviceability and limit state criteria, a structure must remain functional for its intended use subject to routine (everyday) loading, and as such the structure must not cause occupant discomfort under routine conditions. This implies that the deformations must be limited to certain values.

The deflections should not exceed (International Code Council 2012):

L/360 for Roof
L/240 for Beams
L/175 for Glass bearing members

The rest of this section will describe the different types of loadings on the structure.

For 780 CMR 16.00, The Solatrium is considered a single- and two-family dwellings and thus is subject to 780 CMR 53.00 Building Planning for Single- and Two-Family Dwellings which contains separate snow and wind loading than 780 CMR 16.00.

4.1.1 Snow Loading

The Worcester ground snow load for a single- and two- family dwellings is 1.92 KN/m^2 (State Board of Building Regulations and Standards, 2008b) and is 0.25KN/m^2 for Datong (SD China 2012b), so Worcester conditions govern.

$$0.7 \times p_g \times C_t \times C_e \times I_f = p_f$$

$$I_f = 1$$

$$C_t = 1$$

$$C_e = 1$$

$$p_f = 1.344 \text{ KN/m}^2$$

$$p_f \times C_s = p_s$$

$$C_s = 1 \text{ (mostly flat roof)}$$

$$p_f = p_s$$

$$S = p_f$$

$$S = 1.344 \text{ KN/m}^2$$

4.1.2 Wind Loading

The wind speed for Worcester is 40.3 m/s (90mph) (State Board of Building Regulations and Standards, 2008b); whereas the wind speed for Datong is 29.67 m/s. Worcester conditions govern the design.

From the 780 CMR 53.00, the wind effect zones for the roof are shown in Figure 7.

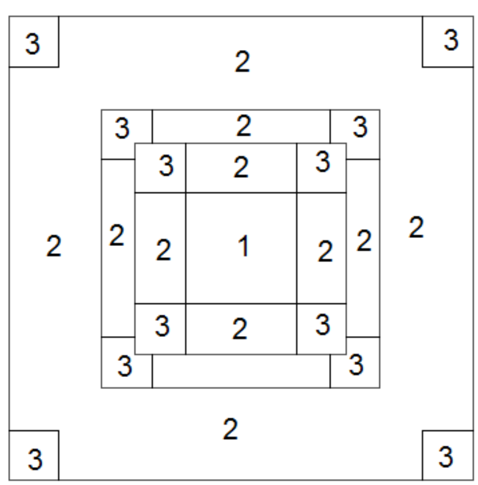


Figure 7: Wind Load Areas of the Solatrium roof

The vertical wind loading loadings on these areas are presented Figure 7 below.

Table 4 Vertical wind loads by wind zone and roof angle

zone	roof angle [°]	area [m²]	load [Pa]	
1	0	7.2447	478	-654.86
2	0	81.5542	478	-755.24
	0	3.2816	478	-1042.04
	45	3.8116	621.4	-779.14
3	0	1.4864	478	-1759.04
	45	1.4864	635.74	-812.6

4.1.3 Seismic Loading

780 CMR 16.00 does not require seismic calculations "detached one- and two-family dwellings," such as the Solatrium.

The Solar Decathlon Building code gives a basic seismic response factor of 0.15g in fortification 7 region. Under the GB50011-2001 Code for Seismic Design of Buildings, this structure can be analyzed using Base Shear method in the following equation.

$$V = \alpha G_{eq}$$

α is given as 0.12 for 0.15g in fortification zone 7, and G_{eq} is determined by the following equation.

$$G_{eq} = Dead\ weight + 0.5\ Snow\ load + 0.5\ Live\ loading$$

Which results in G_{eq}= 310.4KN. Therefore the base shear is 37.248 KN

4.2 Construction Criteria

The SD China rules (2012b) state that the construction lot will be 25m x 25m, have up to 10cm of vertical elevation variability, and that the competition will provide a truck mounted crane. Also generators are allowed during construction and deconstruction. The most important constraint though is that each team will only have 10 work days to complete their building construction. Both the lot conditions and the time constraints act as design criteria for construction

5 Finite Element Modeling

Finite Element Modeling was used for the structural review of the Transonite™ panel elements of the Solatrium, but the composite panel is difficult to model using FEA tools. The foam core is relatively soft compared to the FRP skin and could be modeled as a void space, but the insertions contribute to the moment of inertia. A simplification is made by changing the sandwich panel into a solid section panel with an equivalent thickness so it has the same moment of inertia as that the producers' properties provided. This equivalent solid panel can only be used to calculate the deflections, not for the stresses in them. It is more important the model the deflections of the panels since the deflections, not the stresses, are the primary design constraint

Table 5 gives the properties of the equivalent solid panel.

Table 5 Quality tested Transonite^{tm} panel properties and FEM equivalent solid panel properties

Real panel		
thickness	0.0889	m
density	259.7414	kg/m^3
moment of inertia per m	1.69E-05	m^4/m
Equivalent panel		
thickness	0.0588	m
density	392.9062	kg/m^3
moment of inertia per m	1.69E-05	m^4/m

6 Atrium

The atrium roof structure can be divided up in two sub-structural elements. One of them will be the roof cable stayed truss; the other will be the steel atrium truss itself. After the truss substructure is checked and dimensioned in this section, the forces of the truss cable transfer to the atrium truss, which is the supporting structure for the roof. Two loading combinations are looked at. The first and most critical loading combination is that of the self-weight and maximum snow-load. The second combination that will be looked at is the dead weight, wind uplift and half of the snow-load so wind uplift can be modeled.

A system of cables and compression struts will be used to counteract the deflection of the roof in the midsection. The deflection is caused by a combination of loads. First, a simple one truss system with cable was looked upon, this truss did not satisfy the needs, so it was modified to be a system with 4 struts, all struts positioned on the diagonals of the roof, each placed at one third along the diagonal. Every strut is connected with 1 cable to the nearest corner, and with 1 cable connected to each adjacent corner. That brings it to a total of 3 cables per corner strut, leaving the middle of the ceiling free of cables as seen in Figure 8 and Figure 9.

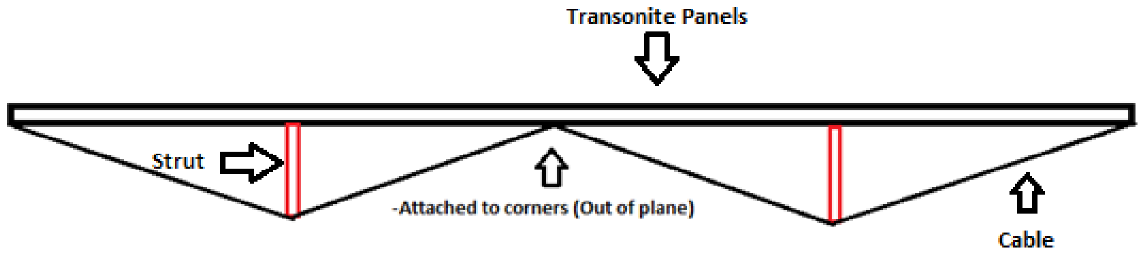


Figure 8: Diagonal section view of the roof and four strut cable stayed trusses

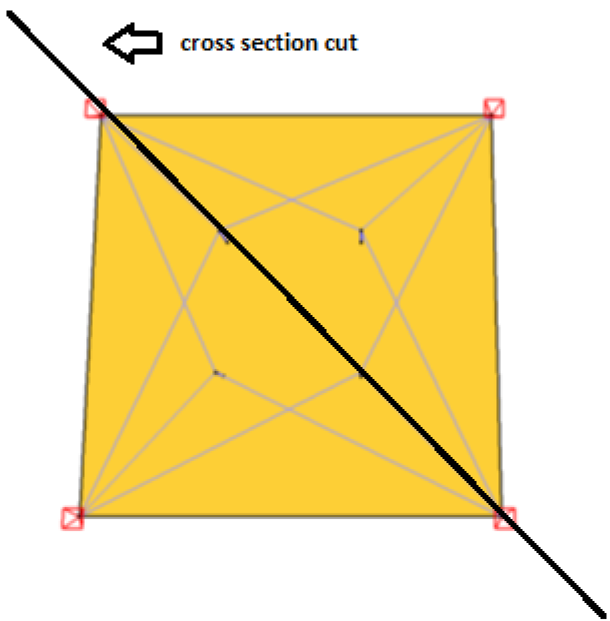


Figure 9: View from below of the four strut cable truss with the cross section cut for Figure 8

6.1 Structural Review of the Atrium

This structural review was carried out using an excel spreadsheet developed by Tim Van Parys of Ghent University specifically for this project.

Relevant Dimensions

- Roof:
  - Dimensions: 5.13 m by 5.13 m
  - Diagonal: 7.25 m
- 4 struts located one third of the diagonal away from each corner
  - Height: 0.60 m
  - Section: To be designed, perhaps cone as an aesthetic element

- Cables:
    - Diameter: 0.01 m
    - Area: 0.00785 m²

6.1.1 Loading Combination 1

First the loading case, LRFD with all combination factors equal to 1 since it's the deflection that is calculated.

Divided surface load = dead weight panels = 0.24 kPa + 1.35 kPa = 1.59 kPa = 1.59 kN/m².

Then we use the combination factors to check for strength

$(1.2)\ Dead\ Loading\ +\ (1.6)\ Snow\ Loading$= (1.2) 0.24kPa + (1.6) 1.35 kPa= 2.45kPa=2.45 kN/m^2

6.1.1.1 *Deflections*

Figure 10 shows the deflections in the direction of gravity when four struts are used, given in mm.

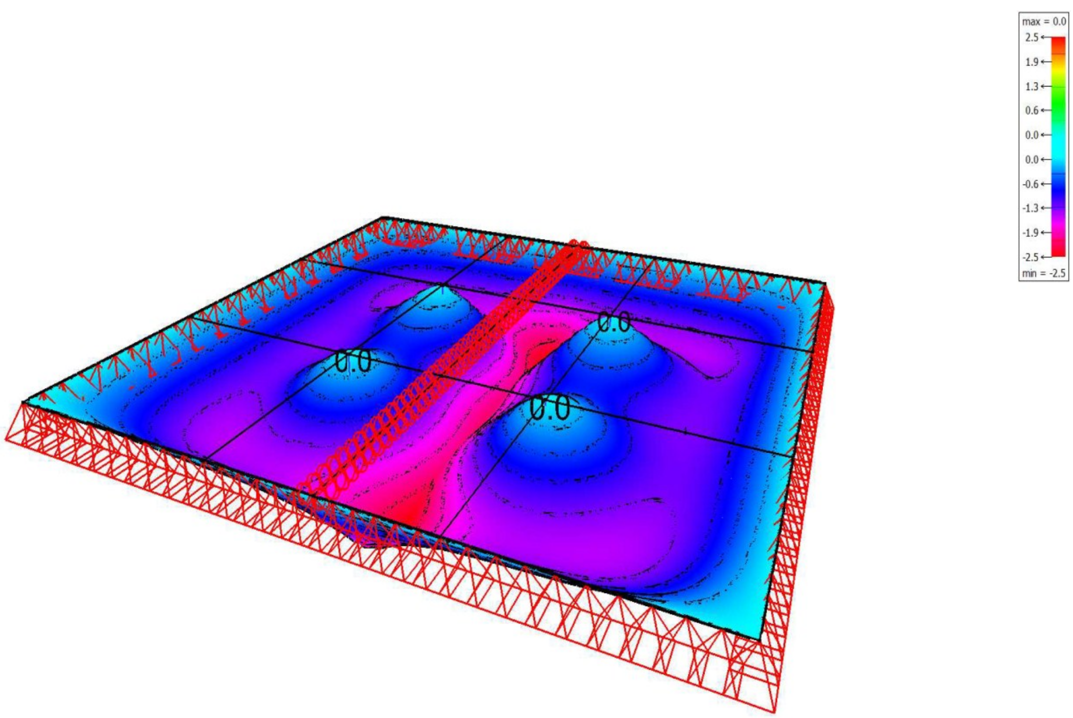


Figure 10: Deflection of the FEA Diamonds 2012 model with in four strut system (LC 1) (dimensions in mm) (BuildSoft)

The maximum deflection is 2.6 mm, which is below the L/360 service limit of 4.75mm given the span of 1.71m between the struts and the truss supports.

In this case, the maximum deflection happens to be at the quarter-points of the seam between the panels. That seam will be a wide flange and 2 L-profiles (as seen in Figure 11) at the seam of the roof to uphold the impermeable function of the roof. Those elements will add to the stiffness of the panel system.

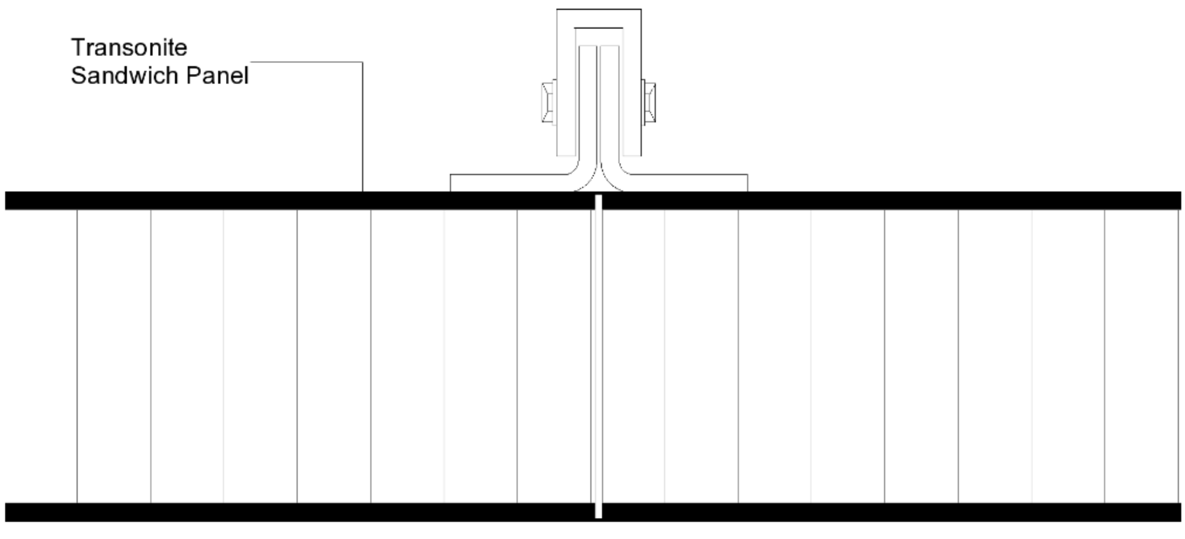


Figure 11: Detailed design of the seam between the Transonite[tm] atrium roof panels (BIM Report submitted to SD China 2013 by Team BEMANY on 3/6/2013)

6.1.1.2 *Strength*

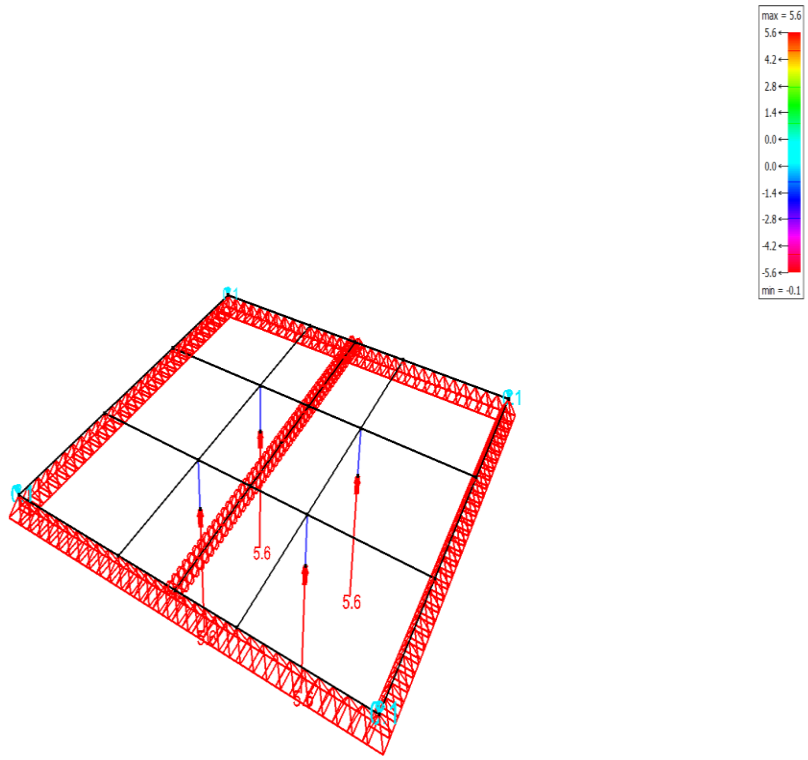


Figure 12: Reaction forces given by the FEA model on the four struts (LC 1) (forces in kN) (BuildSoft)

Figure 12 gives the reaction forces (5.6 KN in all struts) of the struts on the roof, as given by *Diamonds*.

To confirm that the model is accurately modeling the behavior of the truss system, the reaction forces were taken and used in manual calculations. These calculations are for checking the strength of the cable truss system. The results are in Table 6 below.

Table 6 : Calculations of the deflections of the 4 struts after induced strain in the cables

	Force by FEA	
Length strut	0.600	m
side square	5.130	m
horizontal length to nearest corner	2.420	m
horizontal length to adjacent corners	4.830	m
reaction in strut	5.6	kN
Cable angle between nearest corner and strut	76.075	degree
Cable angle between adjacent corners and struts	82.919	degree
load in cables leading to nearest corners	11.357	kN
load in cables leading to adjacent corners	11.635	kN
Force at Corners	34.349	kN
Cable diameter	0.01	m
Cable area	0.00007854	m^2
Pre-stress	0	kN/m^2
stress in cable to nearest corner	148145	kN/m^2
stress in cables to the adjacent corners	218669	kN/m^2
Young's Modulus of the cable	200000000	kN/m^2
strain in cable to nearest corner	0.00074072	%
strain in cables to the adjacent corners	0.00109335	%
length unstressed of cable to nearest corner	2.493	m
length unstressed of cables to the adjacent corners	4.867	m
length strained of cable to nearest corner	2.495	m
length strained of cables to the adjacent corners	4.872	m

The deflections are less than 1 mm and are acceptable by itself or could be cancelled out by adding some pre-tensioning to the cables.

6.1.2 Loading combination 2: dead weight + wind + half of snow-load

By looking at the wind loading, introduced in chapter four of this report, one can observe that the downward pressure exerted by the wind is far below the pressure exerted by the snow loading. Since the building is designed to handle the snow loading, it is able to withstand the downward wind loading as well. The downward wind load gives a uniform loading of 0.478 kN/m². The upward wind loading will be distributed by applying the loads stated as in Figure 7. We have checked section LC1 but it does not govern design.

6.1.2.1 *Load combination 2a: Downward wind loading*

The downward wind does not have to be distributed dependent on the location of the loading. Figure 13 gives the deflections caused by load combination 2a, while Figure 14shows the reaction forces.

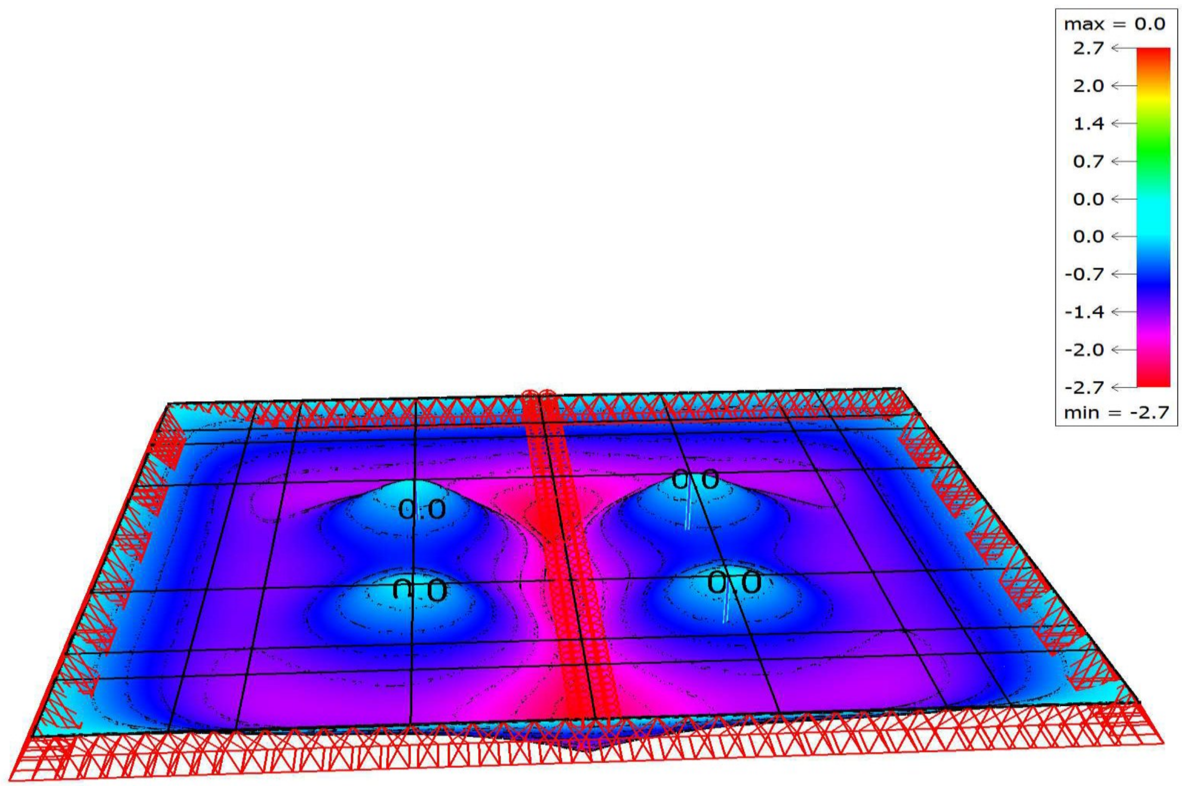


Figure 13: Deflections of the FEA model with 5 struts (LC 2a) (dimensions in mm) (BuildSoft)

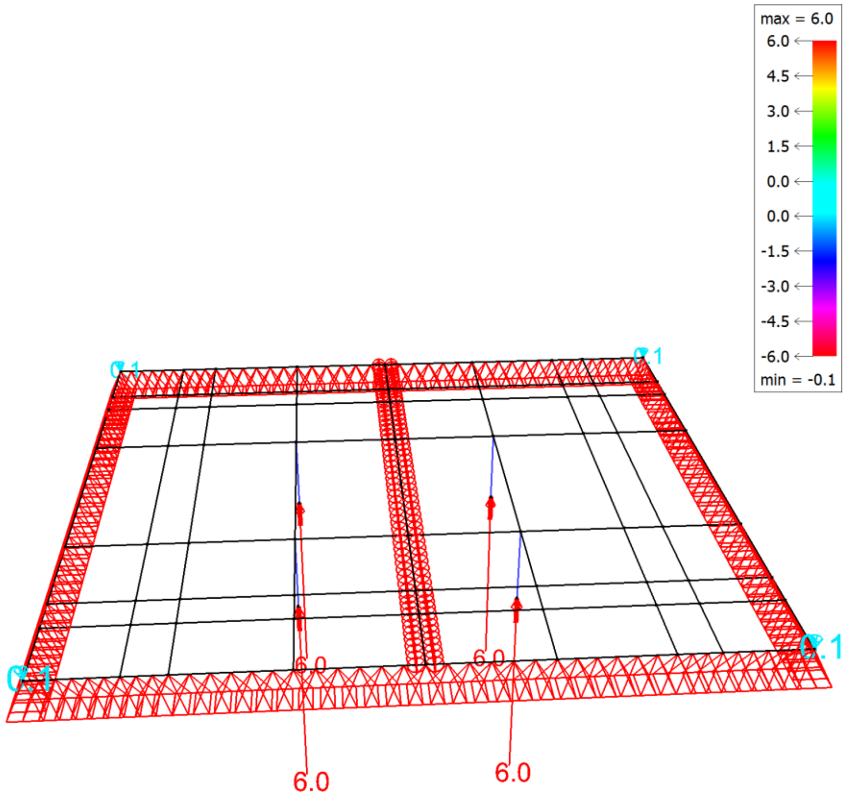


Figure 14: Reaction forces given by the FEA model on the struts (LC 2a) (forces in kN) (BuildSoft)

These forces are larger than the forces of load combination 1, which implies the deflections and stresses will be higher. In Table 7, the calculations for the deflections and stresses in the cable are given.

Table 7 Calculations of the deflection of the struts after strain of the cables

	Force by FEA	
Strut Length	0.600	m
side square	5.130	m
Horizontal distance to nearest corner	2.420	m
Horizontal distance to adjacent corner	4.830	m
reaction in strut	6	kN
Cable angle between nearest corner and strut	76.075	degree
Cable angle between adjacent corners and struts	82.919	degree
load in cables leading to nearest corners	12.168	kN
load in cables leading to adjacent corners	12.466	kN
Force at Corners	36.802	kN
Cable diameter	0.01	m
Cable area	0.00007854	m^2
Prestress	0	kN/m^2
stress in cable to nearest corner	158727	kN/m^2
stress in cables to the adjacent corners	234289	kN/m^2
Young's Modulus of the cable	200000000	kN/m^2
strain in cable to nearest corner	0.00079363	%
strain in cables to the adjacent corners	0.00117144	%
length unstressed of cable to nearest corner	2.493	m
length unstressed of cables to the adjacent corners	4.867	m
length strained of cable to nearest corner	2.495	m
length strained of cables to the adjacent corners	4.873	m

6.1.2.2 *Load combination 2b: Upward wind loading*

In this case, the wind loading is reversed in direction and will try to uplift the roof from the atrium. The loads applied on the roof are negative and dependent on the location where they take place. The loads are again in agreement with the wind load distribution as shown in Figure 16.

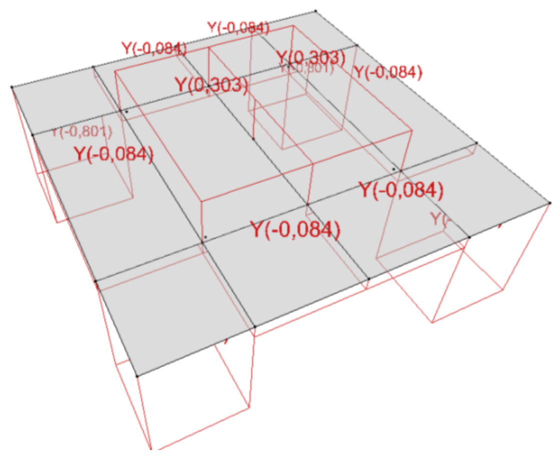


Figure 15: Wind loading distribution for upward lift loading (LC 2b) (loads in kN/m²) (BuildSoft)

Figure 16 shows the deflections caused by load combination 2b and Figure 17 is the reaction forces.

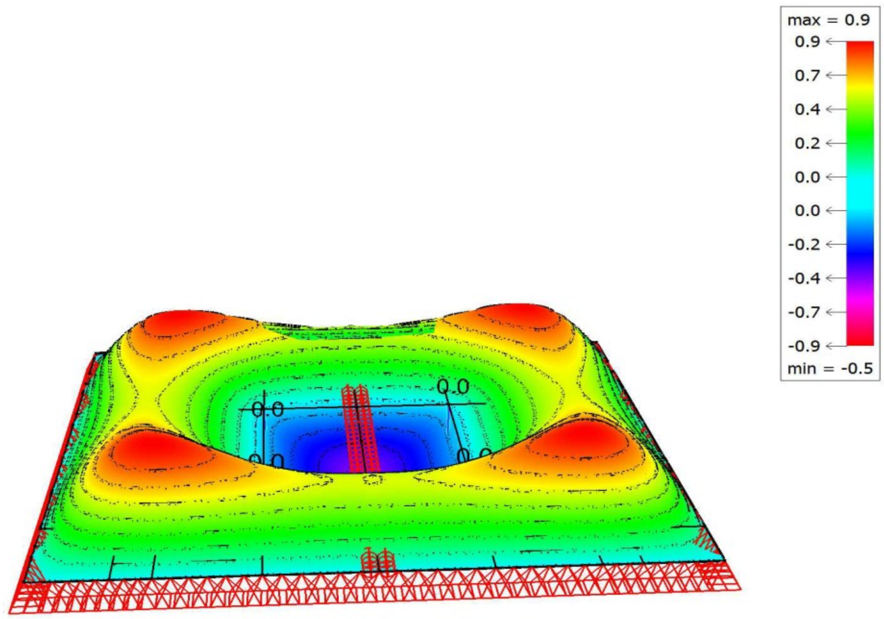


Figure 16: Deflections of the FEA model with 4 struts (LC 2b) (dimensions in mm) (BuildSoft)

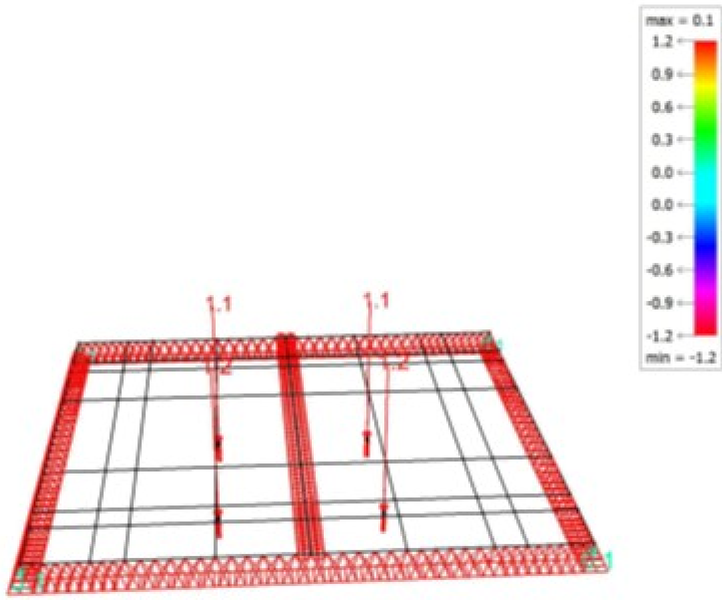


Figure 17: Reaction forces given by the model on the four struts (LC 2b) (forces in kN) (BuildSoft)

The reaction forces are very low, and still positive reactions, so the struts will not be under compression. Since the sturts are not under compression, some cables are needed to counteract the uplift. Since the reactions are 1.2 KN which are much less than the 6.0 KN of the LC2a, the loading is less than the already acceptable loading.

The uplift resiting cables will be positioned the same way as the downward force resiting cables, except that they will be connected to the top of the struts and the bottom of corners instead of the bottom of the strut and the top of the corners.

6.2 Construction

The atrium roof will have struts attached to the panel .then it will be lifted into place by a crane after the Atrium trusses have been attached. After the panel is attached to the roof, the cables will be attached to truss and struts (pictured in Figure 18). During the construction process, the crane will remain attached to the roof panel in order to support the roof until it is securely attached.

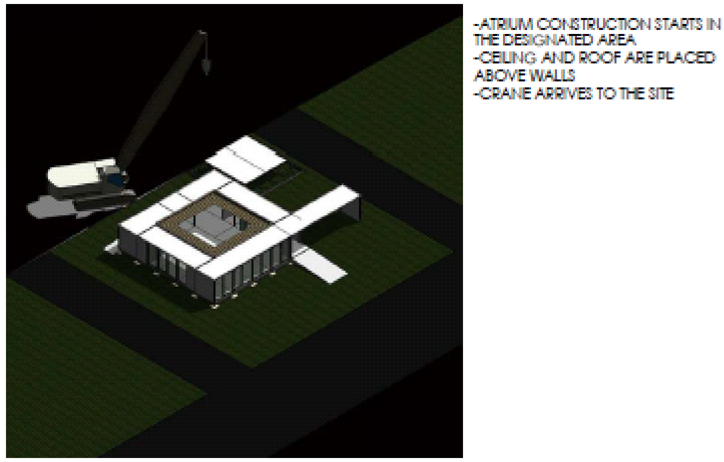


Figure 18 Rendering of construction of the Atrium roof panel with crane (BIM Report submitted to SD China 2013 by Team BEMANY on 3/6/2013)

7 Atrium Truss

The atrium truss is a steel truss angled at 45 degrees and is designed to support the atrium roof.

7.1 Structural review

The loads applied on the atrium roof for these calculations are dead weight of the panels and snow loads. The weight of the glass is small compared to the two other loads. The Transonite FRP roof panels have a dead weight of 3.9 kN/m. For the snow loads, 780 CMR 53.00 requires 1.35 kPa, but the original modeling was done with 1.92 KPa, so all the calculations are based on this higher loading. These loads will be divided to the upper edges of the atrium truss. Under the roof slab, there will sit a cable truss system which will be supporting the slab on 4 points. This cable truss has been discussed in a separate chapter. A part of the loads coming from dead weight and snow load will be transferred to these points. For the calculations we used the FEM software Diamonds. Using this software and after a verification through manual calculations we will derive forces in all the constituent parts.

7.1.1 Axial forces

Load combination 1 governs the design of the truss. Figure 19 shows the 5 most loaded bars if we look at the biggest axial forces, which are also listed in Table 8.

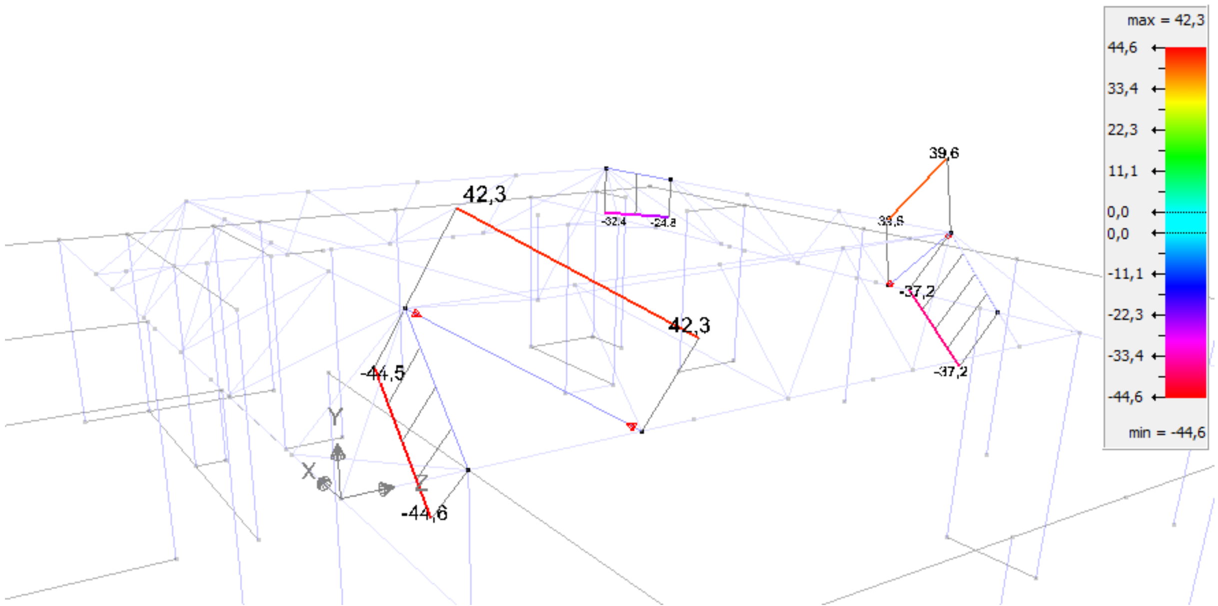


Figure 19: The 5 most axial loaded bars (loads in kN) (Thomas Tassignon) (BuildSoft)

Table 8 Maximum axial forces of the steel trusses

maximum axial forces	
[kN]	
-44.6	(+): Tension
-37.2	(-): Compression
-32.4	
39.6	
42.3	

The biggest axial force will be taken by a square tube. This maximum is - 44.6 kN. The second biggest axial force will be taken by a diagonal cable and is 42.3 kN.

7.1.2 Moments

The bottom chord of the truss develops moments unlike most trusses because of distributed loads across the bottom of the truss caused by the dead load and snow loading of the roof panels connected to the bottom chord. Figure 20 and Table 9 give the maximum moments in the bottom chords of the truss.

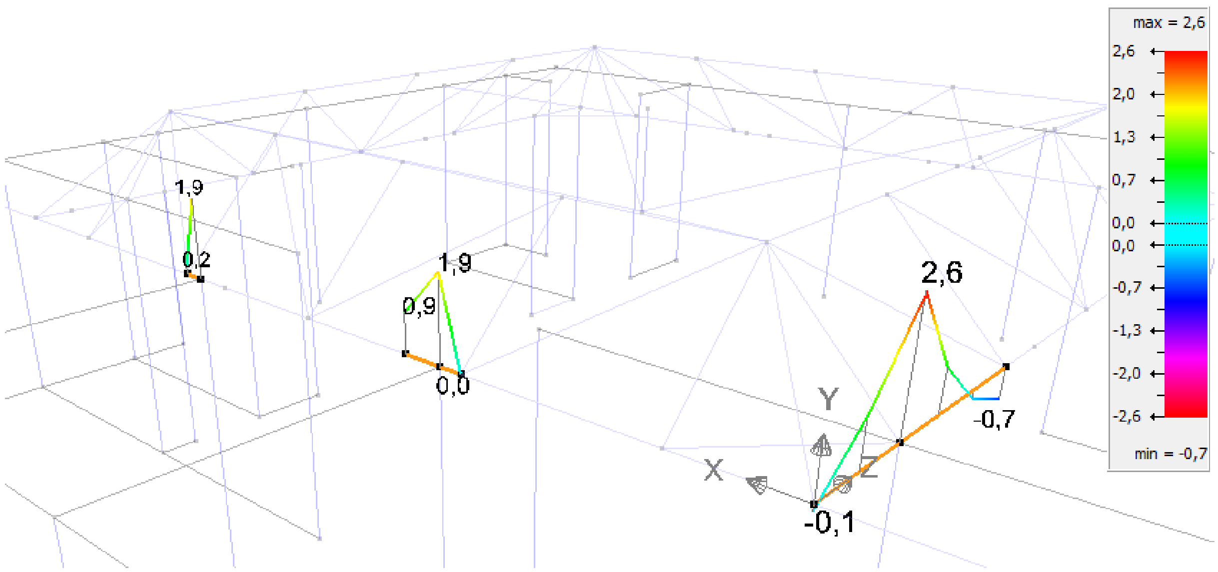


Figure 20: Moments of 5 most loaded bars (moments in kNm) (Thomas Tassignon) (BuildSoft)

Table 9 Moments in bottom chord [kNm] of the steel trusses

maximum moments		
	[kNm]	(+): Tension
	-0.1 -> 2.6	
	0.2 -> 1.9	
	-0.7 -> 2.6	(-): Compression
	0.9 -> 1.9	
	0.0 -> 1.9	

When we review at the maximum moments in the steel elements of the truss, we get the results as shown in Figure 21.

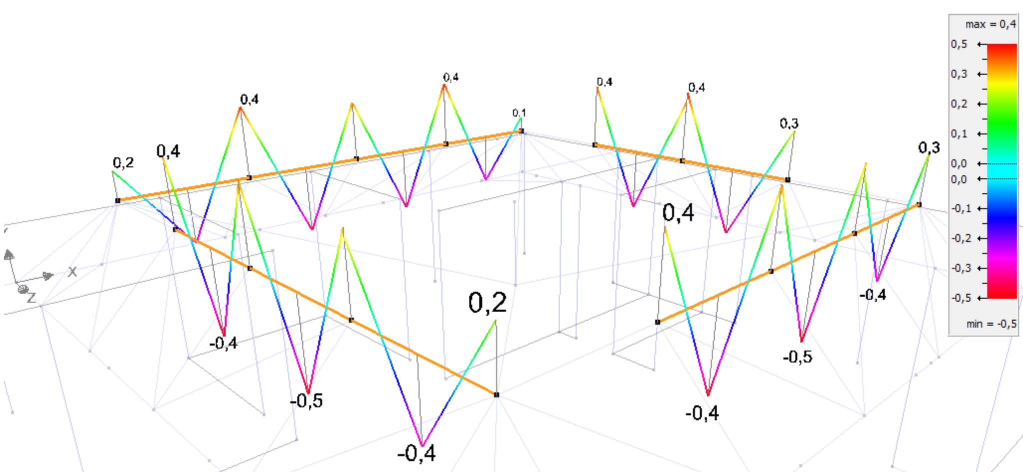


Figure 21: Moments in steel elements truss (moments in kNm) (Thomas Tassignon) (BuildSoft)

The maximum appearing moment is -0.5 kNm.

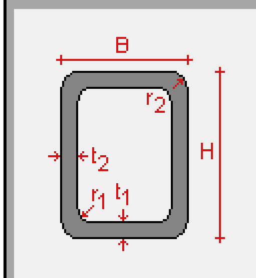
7.1.3 Overview of the stresses in all elements of the atrium truss

Now that we have spoken about all the appearing maximum forces in every structural element, we can analyze their dimensions and maximum stresses.

7.1.3.1 *Inclined members of the truss*

Tubes will be used for all inclined elements, except for the diagonals, and for the top chord of the truss. For these we want to use square tubes of 50.8x50.8x6.35mm with the properties given in Table 10.

Table 10 Properties square profile 2x2x0.25"



square profile 2"x2"x1/4"	
material	Steel S235
atrium truss	
strength properties	[N/mm^2]
tensile strength (LW)	235
compression strength	Limited by buckling
dimensions	[mm]
width	50.8
height	50.8
thickness	6.35
area	[mm^2]
	1129.03
weight	[kg/m]
	6.60
moment of inertia	[mm^4]
	379377.4627

The 15 maximum appearing stresses in these elements are shown in Figure 22. These stresses are calculated in the most extreme fiber of the tubes and take axial force as well as moments and shear stresses into account.

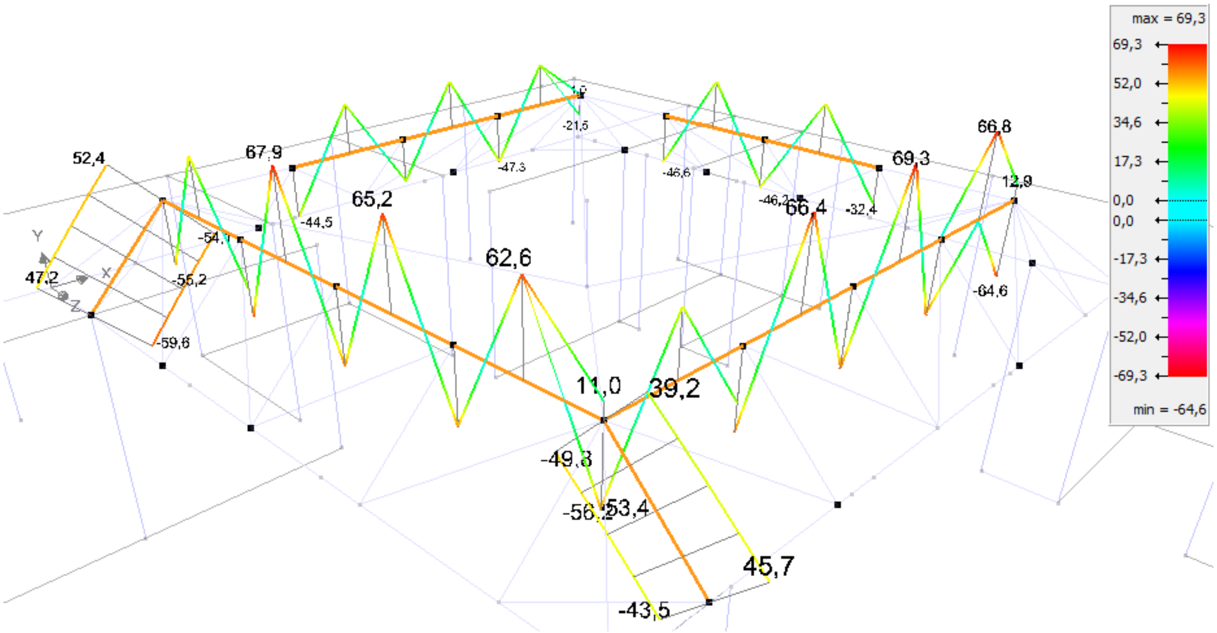


Figure 22: 15 maximal stresses in square tubes (stresses in kN/mm²) (Thomas Tassignon) (BuildSoft)

From this figure we can derive that the maximal appearing stress is 69.4 N/mm². The tubes will be made of steel S235 which have a characteristic yield strength of 235 N/mm². When we multiply this by the resistance factor for steel elements in compression of 0.85, the maximal stress is 199.75 N/mm². We can conclude that the dimensions of the chosen square tubes are sufficient.

7.1.3.2 *Diagonal cables*

The maximal axial force in the tension cables which span the diagonal of every rectangular piece in the truss is 42.3 kN. In Table 11 capacities of several thicknesses of cables are shown.

Table 11 Cable sizes and breaking force for 6x19 IWRC (dimensions in inches) (Union)

Diameter (in)	Weight (lb/ft)	Minimum Breaking Force (tons of 2000 lbs.)		
		IPS	XIP	XXIP
1/4	0.116	2.94	3.40	--
5/16	0.18	4.58	5.27	--
3/8	0.26	6.56	7.55	8.30
7/16	0.35	8.89	10.2	11.2
1/2	0.46	11.5	13.3	14.6
9/16	0.59	14.5	16.8	18.5
5/8	0.72	17.9	20.6	22.7
3/4	1.04	25.6	29.4	23.4
7/8	1.42	34.6	39.8	43.8
1	1.85	44.9	51.7	56.9

The table uses a design factor of 5. When we convert 42.3 kN to ton-force, we get 4.31 tf. So we can conclude that wires of 5/16" or 0.79375 cm will be sufficient for this application. Slightly larger cables of 1cm are used, so the cable will be sufficient for this application

7.1.3.3 *Bottom chord of the truss*

Table 12 shows the properties of the assembled FRP profile for the bottom chord of the truss.

Table 12 Properties of FRP assembled profile

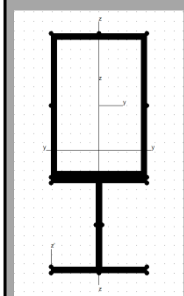
	H-profile 4"x4"x1/4"		rectangular profile 4"6"x1/4"	
	material	FRP	**material**	FRP
	bottom beam truss		bottom beam truss	
	strength properties	N/mm²	**strength properties**	N/mm²
	tensile strength (LW)	275.790	**tensile strength (LW)**	227.527
	compression strength	315.573	**compression strength**	227.527
	dimensions	[mm]	**dimensions**	[mm]
	Width	101.6	width	101.6
	Height	101.6	height	152.4
	thickness	6.35	thickness	6.35
	Area	[mm²]	**area**	[mm²]
		1883.8672		2980.639
	Weight	[kg/m]	**weight**	[kg/m]
		3.63		5.73
	moment of inertia	[mm⁴]	**moment of inertia**	[mm⁴]
	X-X axis	3350662.976	X-X axis	9286123
	Y-Y axis	1094688.649	Y-Y axis	4928180

Figure 23 and Figure 24 give the compression and tension stresses in the bottom chord of the truss.

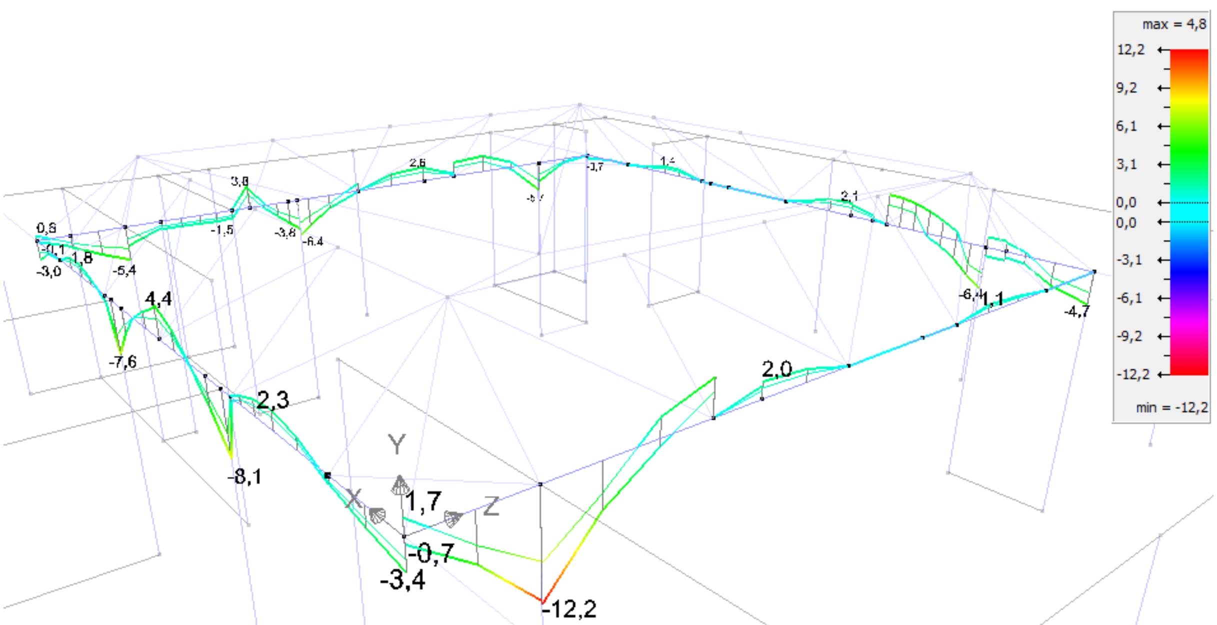


Figure 23: Compression stresses in FRP bottom chord (stresses in N/mm²) (Thomas Tassignon) (BuildSoft)

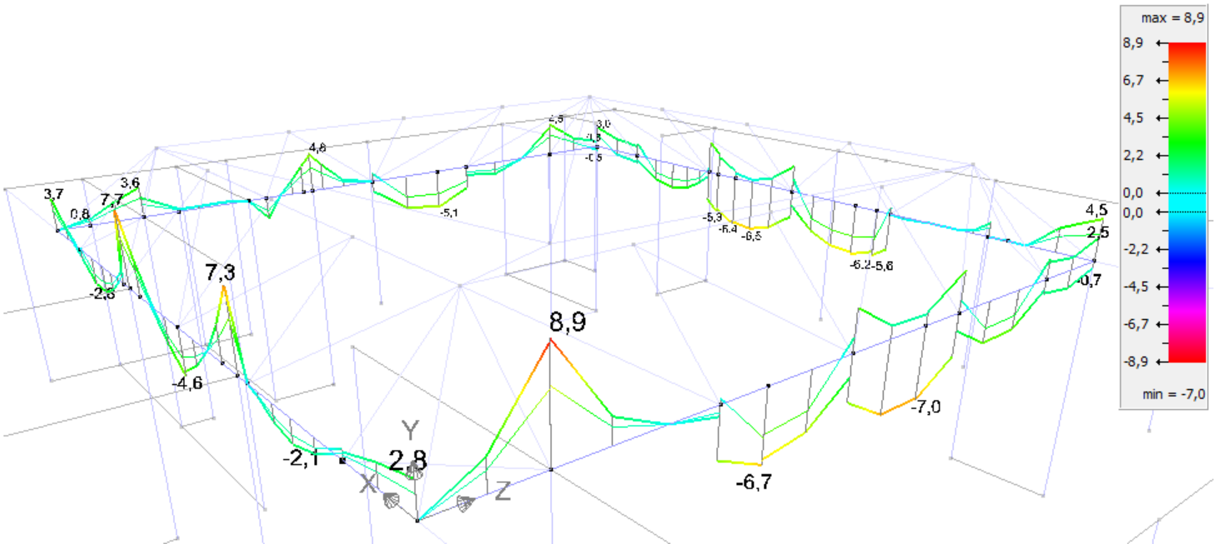


Figure 24: Tensile stresses in FRP bottom chord (stresses in N/mm²) (Thomas Tassignon) (BuildSoft)

The maximal compression stress appears in the bottom flange of the wide flange profile and is 12.3 N/mm². The maximal stress in this profile is 315.573 N/mm² so this is more than sufficient.

The maximal tensile stress appears in the top flange of the box profile and is 8.9 N/mm². The maximal for this profile is 227.527 N/mm².

7.1.4 Deflections

The deflections will be calculated with combination factors 1 and 1, respectively for the dead weight and the snow load. This is according to LRFD (Load resistance factor design).

7.1.4.1 *Top chord*

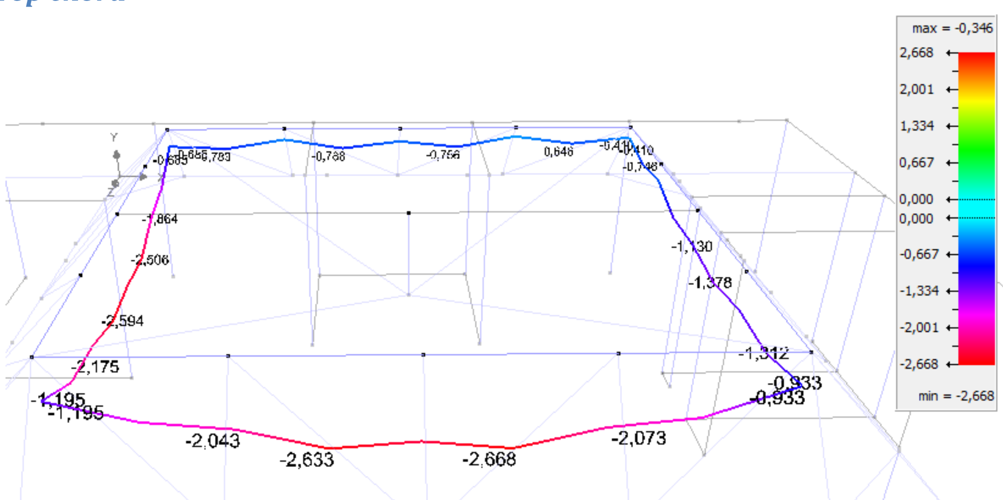


Figure 25: Deflections in upper chord atrium truss (dimensions in mm) (Thomas Tassignon) (BuildSoft)

Figure 25shows the deflections in the top chord of the truss. They are maximum 2.668 mm in the vertical direction. Over a span of 4.91 m, this gives us a deflection of L/1840, well higher than the L/240 necessary.

7.1.4.2 *Bottom chord*

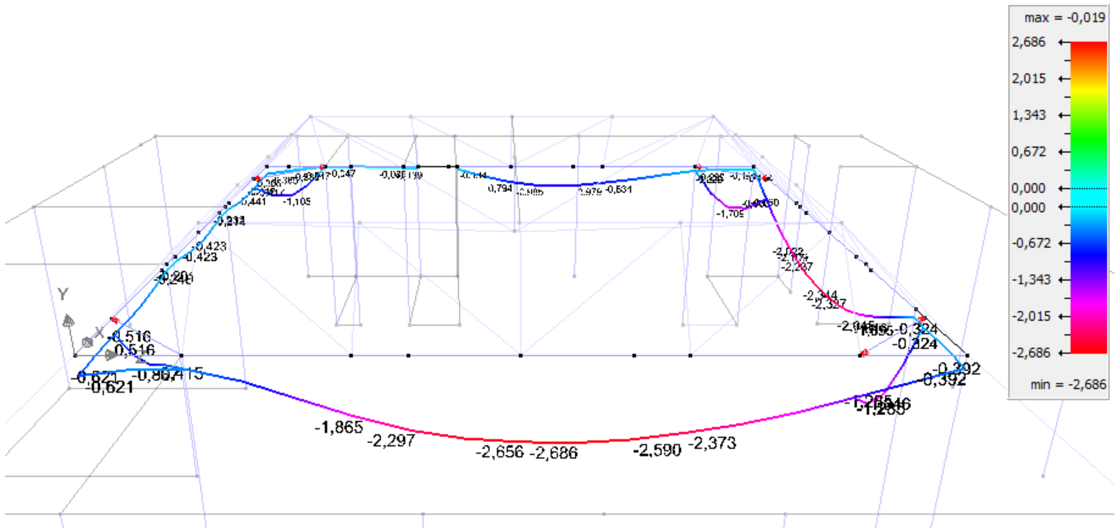


Figure 26: Deflections in bottom chord of atrium truss (dimensions in mm) (Thomas Tassignon) (BuildSoft)

Figure 26 shows the deflections in the bottom chord of the truss. They are maximum -2.686 mm in the vertical direction. This gives us a deflection of L/2257, which is well above the maximum service deflection of L/240 required by the code.

7.2 Construction of the Atrium Truss

Each truss was welded together by the students of the Worcester Technical High School during the practice build. The trusses will be transported pre-welded to the competition site via shipping container. The trusses will be put in place by crane after the outer shell of the house, except for the atrium, has been constructed.

8 Columns and Walls

The walls of the Solatrium are made out of the transonite panels, and also include a column placed between the skins at each end of a wall panel. These columns, along with the columns outside of the walls, are primarily FRP square tubes made by the same company as the transonite panels, but a few FRP columns are reinforced with smaller steel square tubes that can fit within the larger FRP tubes.

8.1 Structural Review

The structural review on the Columns was completed by manual calculation using loads determined by Diamonds 2012.

8.1.1 Tributary Areas for Columns and Walls

It is assumed that the FRP Panel walls will not contribute to the load bearing capabilities of the structure for the purposes of this structural review, so only the columns are bearing loads from the roof. The loads are distributed to the nearest column. These loads include the dead weight of the roof panels and any other loads on the roof. The estimated areas that each column supports is represented in Figure 27.

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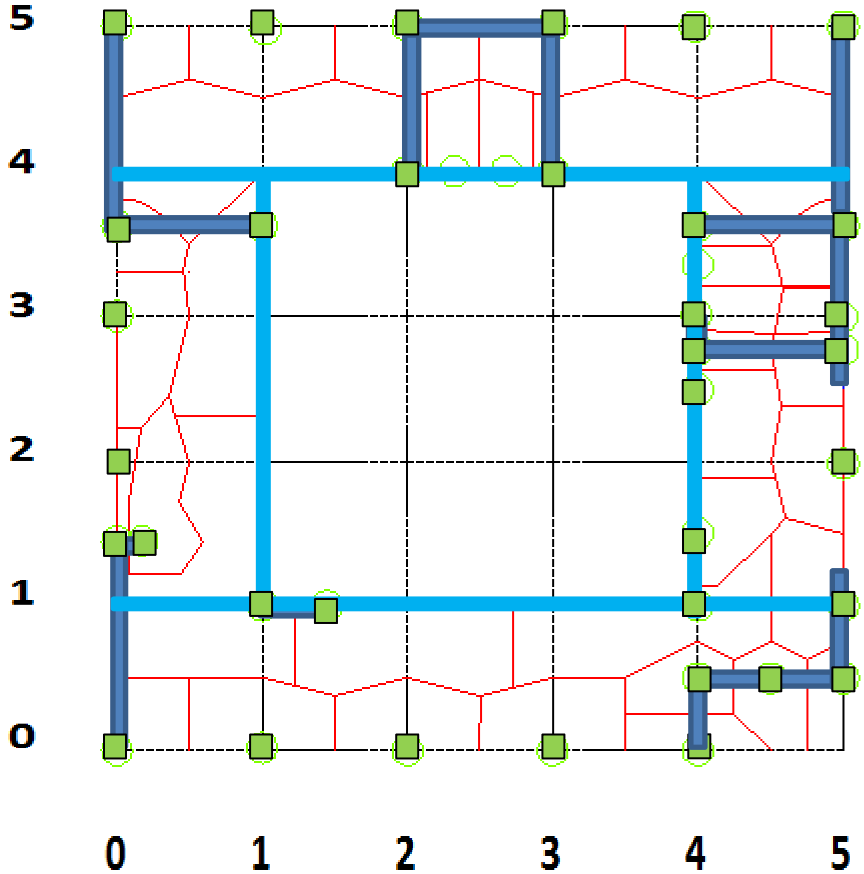


Figure 27: Tributary areas flat roof (blue represents walls, light blue represents beams, green represents columns)

In this figure, the blue lines represent the walls, while the four green lines represent beams. The green circles indicate where the columns are placed. At last, the areas lined with the red lines are the tributary areas of the columns. The black dotted lines make up the grid of the foundation

Each column was given a name based on its coordinates on the grid pattern. The column names range from column (0-0) to column (5-5). The first number indicates the position in the horizontal direction of the figure starting at the left, while the second number is the vertical direction starting from the bottom. So for example, the column in the upper left corner gets the name 'column 0-5', because it's on the first foundation grid border in horizontal direction and on the sixth one in vertical direction. For each column, Table 13 gives the tributary area, the dead weight of the panel and snow load going to the column. For the columns under the atrium roof, also the loading going from the atrium roof to the columns is included. These forces were derived from the model in the finite element modeling software *Diamonds*.

column X-Y	area	snow load	dead weight of panels	load atrium roof	total load on column
	$[m^2]$	[kN]	[kN]	[kN]	[kN]
0-0	1.27	2.42	0.31		4.25
1-0	2.37	4.54	0.58		7.97
2-0	2.21	4.23	0.54		7.42
3-0	2.36	4.53	0.58		7.94
4-0	1.27	2.42	0.31		4.25
4-0.5	1.19	2.27	0.29		3.99
4.5-0.5	1.11	2.12	0.27		3.72
5-0.5	1.50	2.88	0.37		5.05
1-1	7.12	13.63	1.75	29.50	53.40
1.5-1	4.35	8.34	1.07	36.10	50.72
4-1	4.44	8.50	1.09	22.10	37.00
5-1	2.18	4.18	0.54		7.33
4-1.3	1.67	3.19	0.41	44.90	50.50
0-1.5	0.12	0.23	0.03		0.41
0.2-1.5	1.07	2.04	0.26		3.58
5-2	1.91	3.67	0.47		6.43
4-2.5	1.73	3.32	0.43	6.70	12.52
4-2.75	0.71	1.35	0.17	1.60	3.97
5-2.75	1.21	2.31	0.30		4.06
0-3	1.94	3.71	0.48		6.50
4-3	0.85	1.62	0.21	4.60	7.44
5-3	0.76	1.46	0.19		2.55
4-3.3	0.79	1.51	0.19	1.90	4.55
0-3.5	0.98	1.87	0.24		3.29
1-3.5	3.98	7.62	0.98	62.50	75.86
4-3.5	0.66	1.26	0.16	40.60	42.80
5-3.5	1.19	2.28	0.29		4.01
2-4	7.44	14.25	1.83	19.60	44.58
2.2-4	1.08	2.07	0.26	1.20	4.82
2.8-4	1.08	2.07	0.26	1.30	4.92
3-4	7.43	14.23	1.82	19.20	44.16
0-5	1.11	2.12	0.27		3.72
1-5	2.21	4.24	0.54		7.44
2-5	2.21	4.24	0.54		7.44
3-5	2.21	4.24	0.54		7.44
4-5	2.21	4.24	0.54		7.44
5-5	1.11	2.12	0.27		3.72

Table 13: Loads on columns

8.1.2 Combined flexure and compression check

Since the columns are eccentrically loaded, the following condition for combined flexure and compression must be satisfied:

$$\frac{P}{P_n} + \frac{M}{M_n} \frac{C_m}{\left(1 - \frac{P}{P_E}\right)} \leq 1$$

In this formula, P_n is the nominal axial load-carrying capacity and approaches the Euler load-carrying capacity for long columns, M_n is the nominal bending moment capacity and C_m is a moment magnifier, depending on the loading and end conditions. It is safe to assume C_m is 1, since the house is braced against side sway with shear walls, the columns are braced laterally by the wall panels.

The Euler buckling load is calculated as

$$P_E = \frac{\pi^2 EI}{l^2}$$

and the maximum moment on the columns as

$$M_{max} = \frac{p_{F,LRFD} \cdot I}{y}$$

These values are given in Table 14 and Table 15 for both the FRP and steel column.

buckling strength FRP column		
P_E	**59.45349**	**kN**
resistance factor		0.6
$P_{E,LRFD}$	**35.67209**	**kN**

buckling strength steel column		
P_E	**283.5683**	**kN**
resistance factor		0.85
$P_{E,LRFD}$	**241.03305**	**kN**

Table 14: Buckling strength FRP and steel column

flexural strength FRP column		
p_F	227527	kN/m²
resistance factor		0.6
$p_{F,LRFD}$	136516.2	kN/m²
eccentricity	0.0381	m
distance to ultimate fiber		
	0.0381	m
$M_{max,LRFD}$	**5.175157**	**kNm**

flexural strength steel column		
p_F	227527	kN/m²
resistance factor		0.9
$p_{F,LRFD}$	204774.3	kN/m²
eccentricity	0.03175	m
distance to ultimate fiber		
	0.03175	m
$M_{max,LRFD}$	**5.159311**	**kNm**

Table 15: Flexural strength FRP and steel column

Table 16 gives the loads and moments on each column and gives the value of the combined load.

Table 16: Combined flexure and compression check of column

Column X-Y	P [kN]	M_{FRP} [kNm]	Check for FRP	M_{steel} [kNm]	Check for steel
0-0	4.25	0.162011	0.15474651	0.135009	0.04428
1-0	7.97	0.303675	0.29900012	0.253062	0.083795
2-0	7.42	0.282816	0.277098106	0.23568	0.077929
3-0	7.94	0.302395	0.297648988	0.251996	0.083435
4-0	4.25	0.162011	0.15474651	0.135009	0.04428
4-0.5	3.99	0.151901	0.144811058	0.126585	0.041489
4.5-0.5	3.72	0.141664	0.1347921	0.118053	0.038666
5-0.5	5.05	0.19234	0.184812493	0.160284	0.052676
1-1	53.40	2.034463	2.288040179	1.695386	0.643661
1.5-1	50.72	1.932467	2.307010689	1.610389	0.605752
4-1	37.00	1.409817	8.338572524	1.174847	0.422531
5-1	7.33	0.279361	0.273494613	0.2328	0.076958
4-1.3	50.50	1.924018	2.310105104	1.603348	0.602645
0-1.5	0.41	0.015484	0.014419692	0.012904	0.004191
0.2-1.5	3.58	0.136289	0.129548814	0.113574	0.037186
5-2	6.43	0.244936	0.237952601	0.204114	0.067318
4-2.5	12.52	0.476916	0.492877743	0.39743	0.133184
4-2.75	3.97	0.151179	0.14410312	0.125983	0.04129
5-2.75	4.06	0.154589	0.147448037	0.128824	0.04223
0-3	6.50	0.247752	0.240835626	0.20646	0.068105
4-3	7.44	0.283395	0.277703354	0.236163	0.078091
5-3	2.55	0.097258	0.091801884	0.081048	0.026468
4-3.3	4.55	0.173231	0.165822871	0.144359	0.047382
0-3.5	3.29	0.125284	0.118847591	0.104403	0.034158
1-3.5	75.86	2.89019	2.622280765	2.408492	0.995938
4-3.5	42.80	1.630809	2.776216734	1.359007	0.497869
5-3.5	4.01	0.152669	0.14556418	0.127224	0.041701
2-4	44.58	1.698608	2.563757387	1.415506	0.521589
2.2-4	4.82	0.183801	0.176306454	0.153167	0.050308
2.8-4	4.92	0.187611	0.180097447	0.156342	0.051364
3-4	44.16	1.6826	2.604003961	1.402167	0.515962
0-5	3.72	0.141664	0.1347921	0.118053	0.038666
1-5	7.44	0.283328	0.277632536	0.236106	0.078072
2-5	7.44	0.283328	0.277632536	0.236106	0.078072
3-5	7.44	0.283328	0.277632536	0.236106	0.078072
4-5	7.44	0.283328	0.277632536	0.236106	0.078072
5-5	3.72	0.141664	0.1347921	0.118053	0.038666

8.1.3 Conclusion

As indicated in yellow in Table 16 the condition for combined flexure and compression isn't satisfied for the FRP columns in eight cases. In these columns, a steel column will be inserted. For all columns, the steel tube is sufficient. In Figure 28 the columns with a steel tube inserted are shown in a thick green circle, the columns where only a FRP tube is needed have a thin green circle.

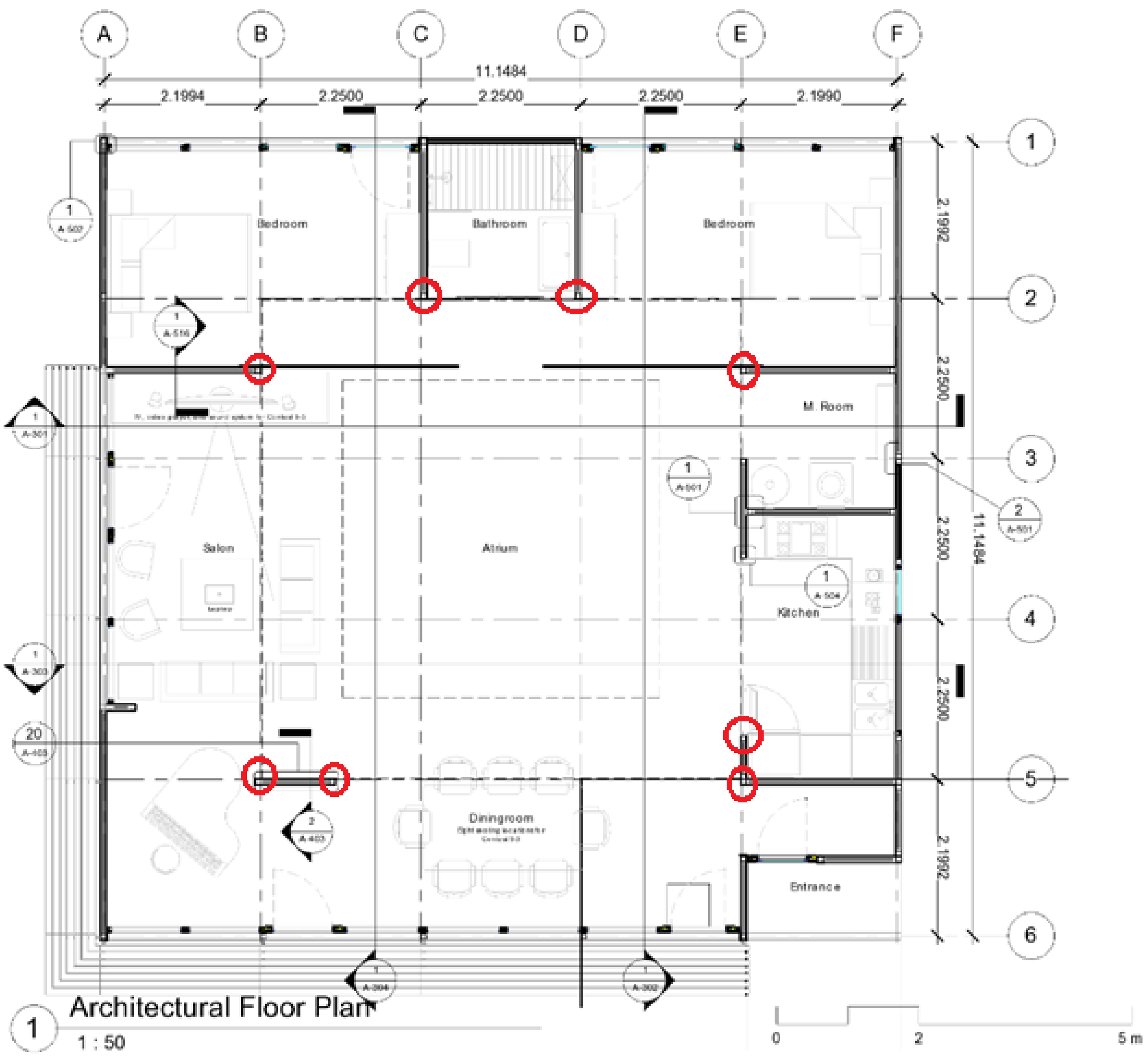


Figure 28 Floor plan with reinforced columns indicated by red circles (BIM Report submitted to SD China 2013 by Team BEMANY on 3/6/2013)

8.2 Construction

After the floor is connected to the foundation, the walls and columns are put into place and connected to the floor. The columns are lightweight and easy to put in place. The walls are heavier and will be put in place by vacuum lift and forklift. The walls and columns will be by placing columns around High Density Plastic Connection Cube (pictured in Figure 29) connected by 1/2 inch threaded bolts.

Figure 29 High Density Plastic Connection Cube (BIM Report submitted to SD China 2013 by Team BEMANY on 3/6/2013)

9 Floor Panels

The floor is concrete tiles on top of Transonite[tm] panels.

9.1 Structural Review

The floor consists of Transonite panels of 2.25 m x 4.5 m. The loads on the panels are given in Table 17.

Table 17 Loads on floor panels

	$[kN/m^2]$
dead load panels	0.2454
live load	1.91521
concrete tiles	0.56064
total load	**2.72125**

One panel is simply supported on the four sides and has one intermediate support, as shown in Figure 30.

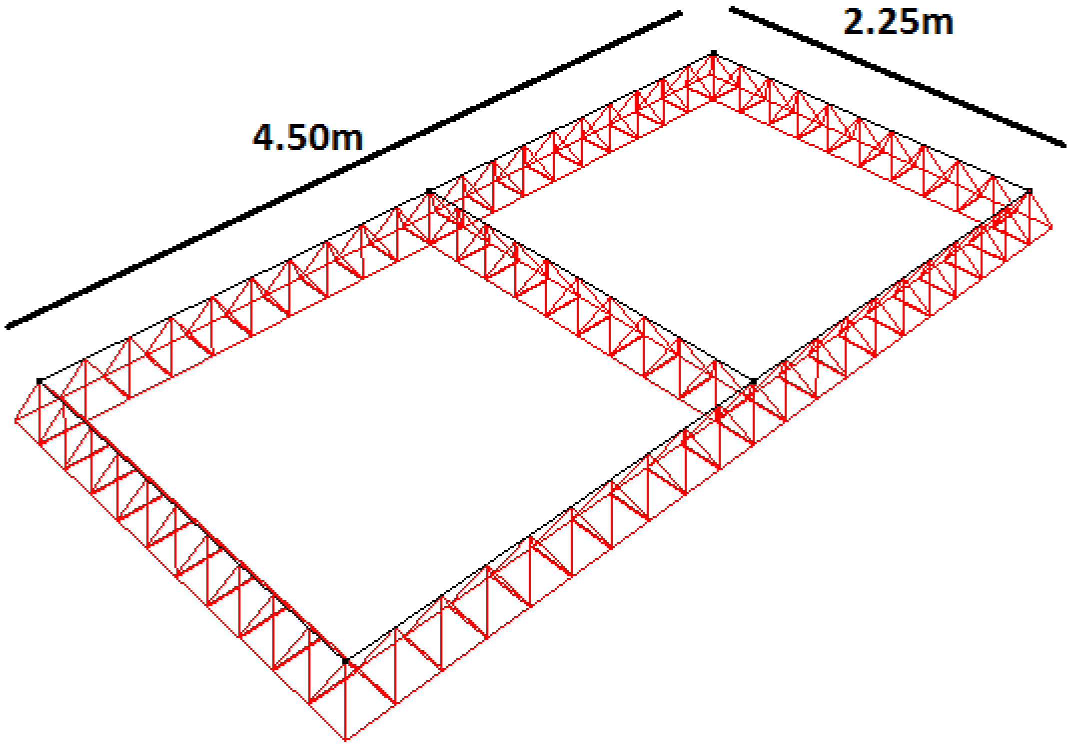


Figure 30: Supports of floor panel (2.25m x 4.50m) (Tine Lanssens and Charlot Tanghe) (BuildSoft)

In a first manual check, the panel is assumed to be a two span beam. In this case, the deflection of the panel, existing of two spans, can be calculated as:

$$v = \frac{pL^4}{192EI} = \frac{2.72125\,\frac{kN}{m^2}\cdot(2.25\ m)^4}{192\cdot 3\,792\,116.35\,\frac{kN}{m^2}\cdot(1.692\cdot 10^{-5})\,\frac{m^4}{m}} = 0.005661\ m = 5.661\ mm$$

The maximum deflection of the panel is $\frac{2.25\ m}{360} = 6.25\ mm.$

The panel does not exceed the maximum service deflection for the floor, which is L/360. In Figure 31, the deflections of the floor panel with the true supports are given as -2.9 mm, as calculated with the FEM software *Diamonds*, which is still below the -6.25mm limit.

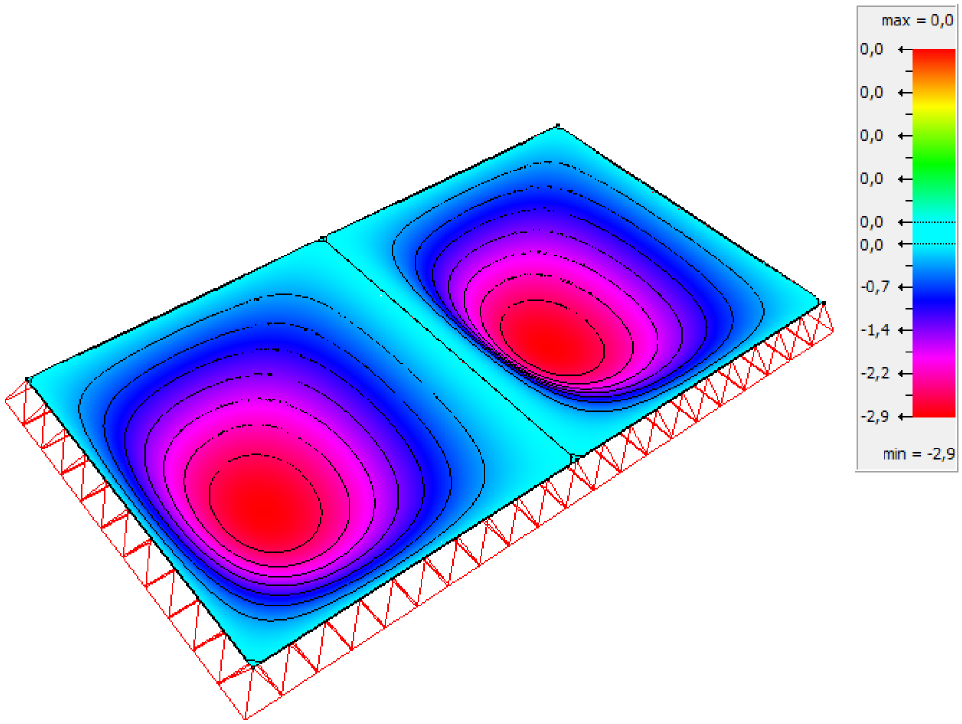


Figure 31: Deflections of floor panel - *Diamonds* (dimensions in mm) (Tine Lanssens and Charlot Tanghe) (BuildSoft)

9.2 Construction

The floor panels will be placed on the foundation grid and attached through a ¾" threaded rod connected to a connection box, as shown in Figure 32. The placement of the flooring schedule can be seen in Figure 33.

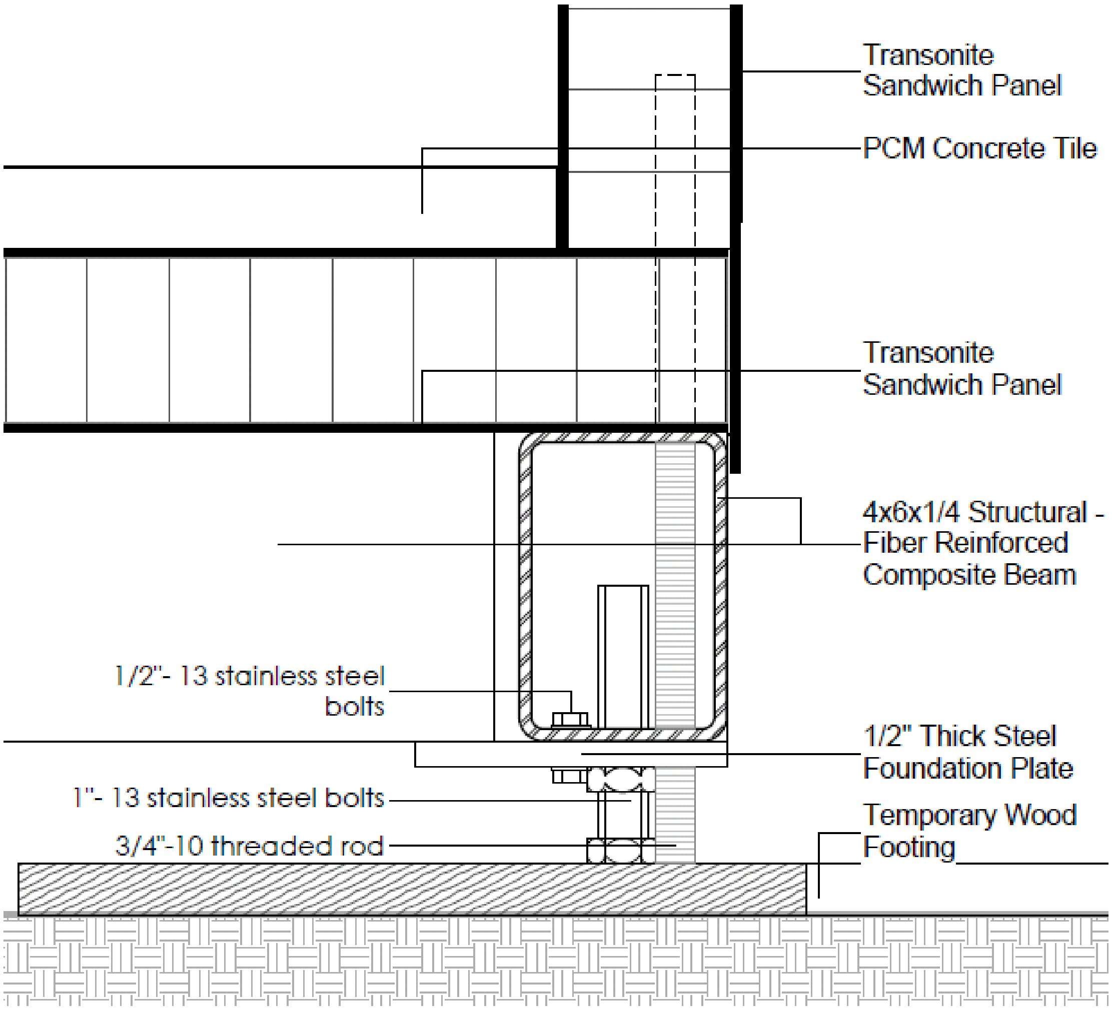


Figure 32 Floor connection diagram (BIM Report submitted to SD China 2013 by Team BEMANY on 3/6/2013)

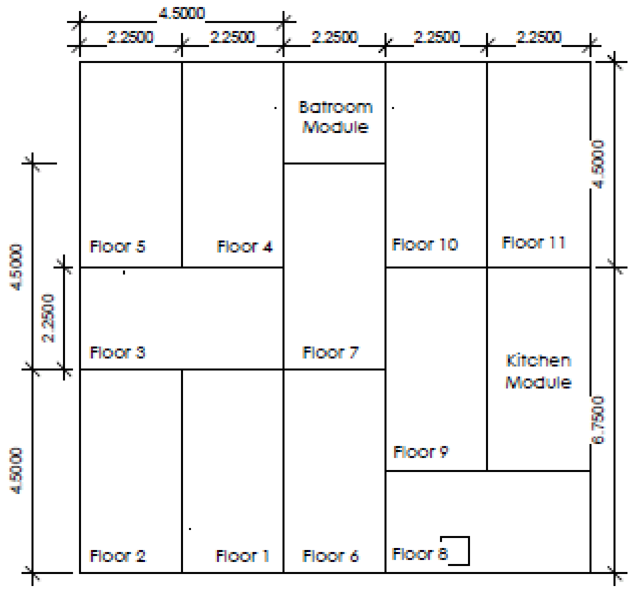


Figure 33 Flooring schedule (BIM Report submitted to SD China 2013 by Team BEMANY on 3/6/2013)

10 Foundation

According to the rules of the SD China competition, the foundation must be made to be adjustable for uneven terrain. To adhere to this rule, a foundation gird of FRP beams was designed with adjustable screw supports. The grid takes up an 11.25 m x 11.25 m square and is made up of 2.25m x 2.25m squares as indicted in Figure 34.

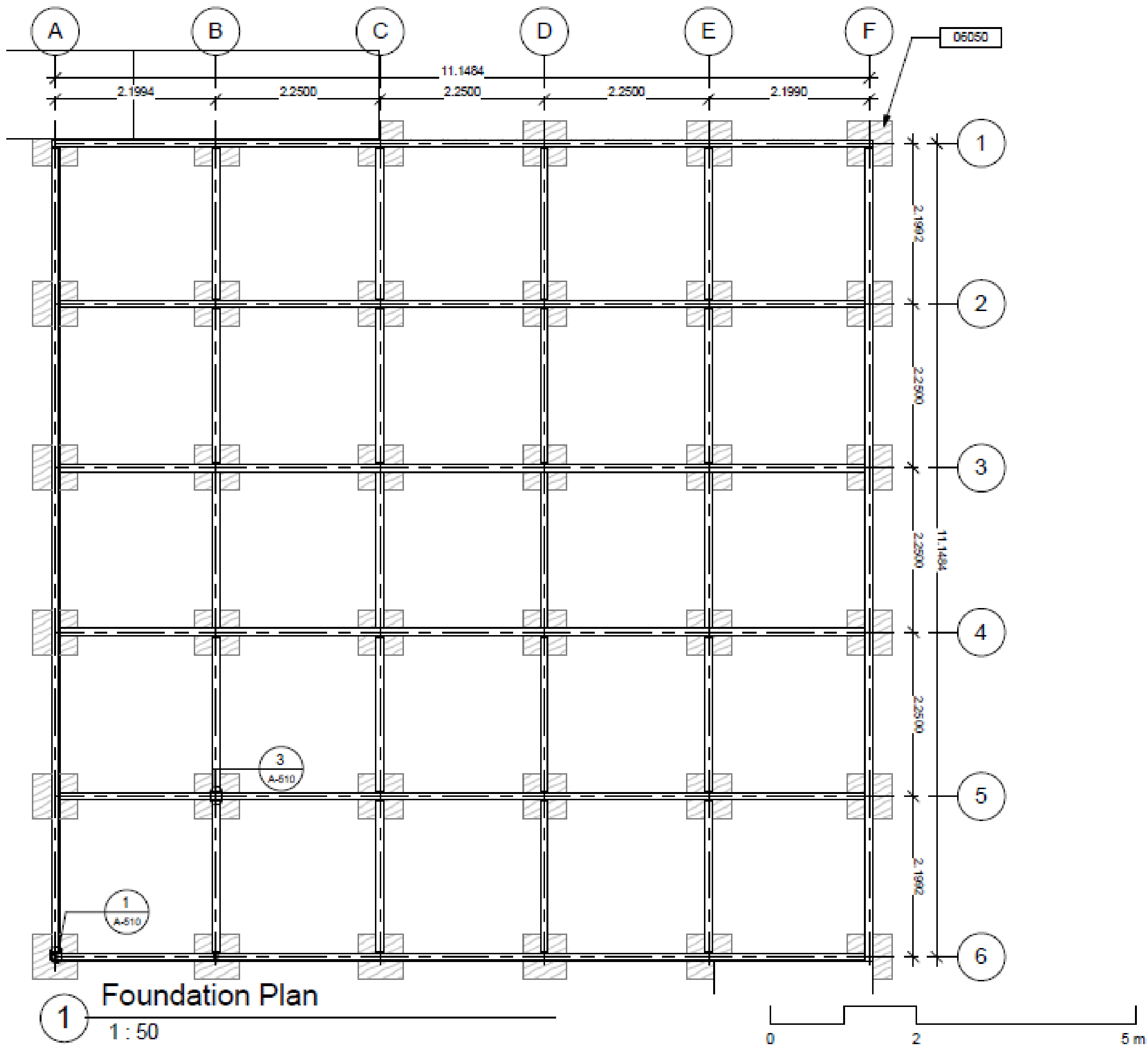


Figure 34 Foundation grid plan (BIM Report submitted to SD China 2013 by Team BEMANY on 3/6/2013)

10.1 Structural Review

The structural review is broken up into two parts, the foundation beams and the foundation supports.

10.1.1 Foundation Beams

The loads acting on the foundation grid are the following:

- point loads coming from the columns;
    - loads on the columns caused by the loads on the flat roof (dead weight and snow);
    - loads on the columns caused by the loads on the atrium roof (dead weight and snow);
- the dead weight of the foundation tubes;
- the dead weight of the floor panels and concrete tiles;
- the live load on the floor.

The point loads coming from the columns are presented in Figure 35, Figure 36 and Figure 37.

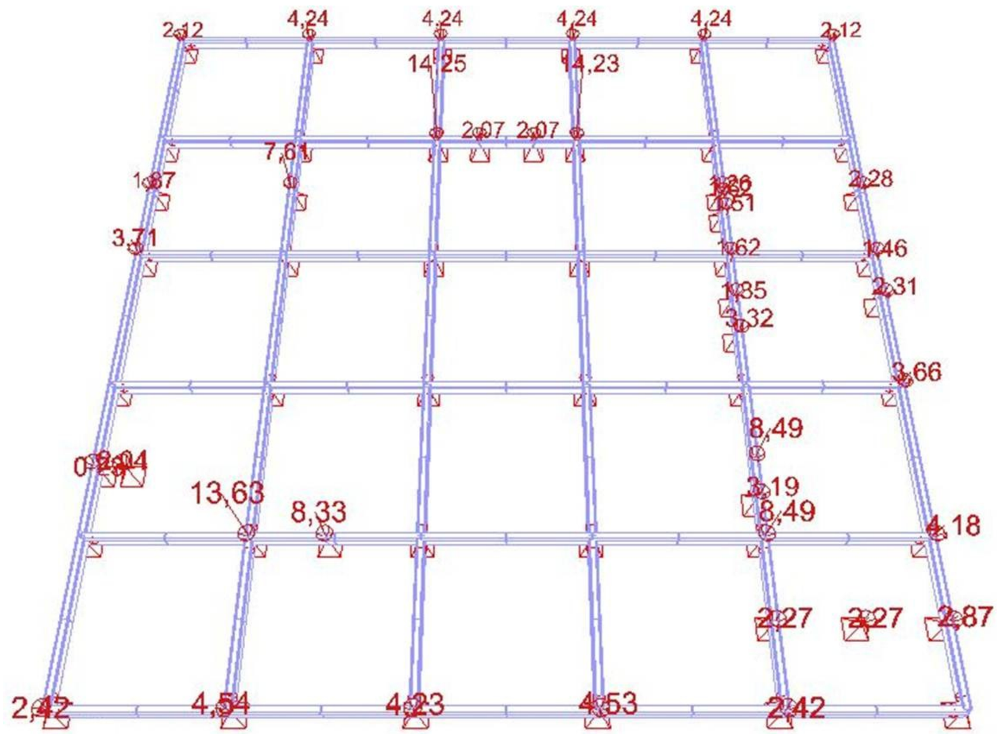


Figure 35: Point loads caused by the snow on the flat roof (without any load modifier) (loads in kN) (Tine Lanssens and Charlot Tanghe) (BuildSoft)

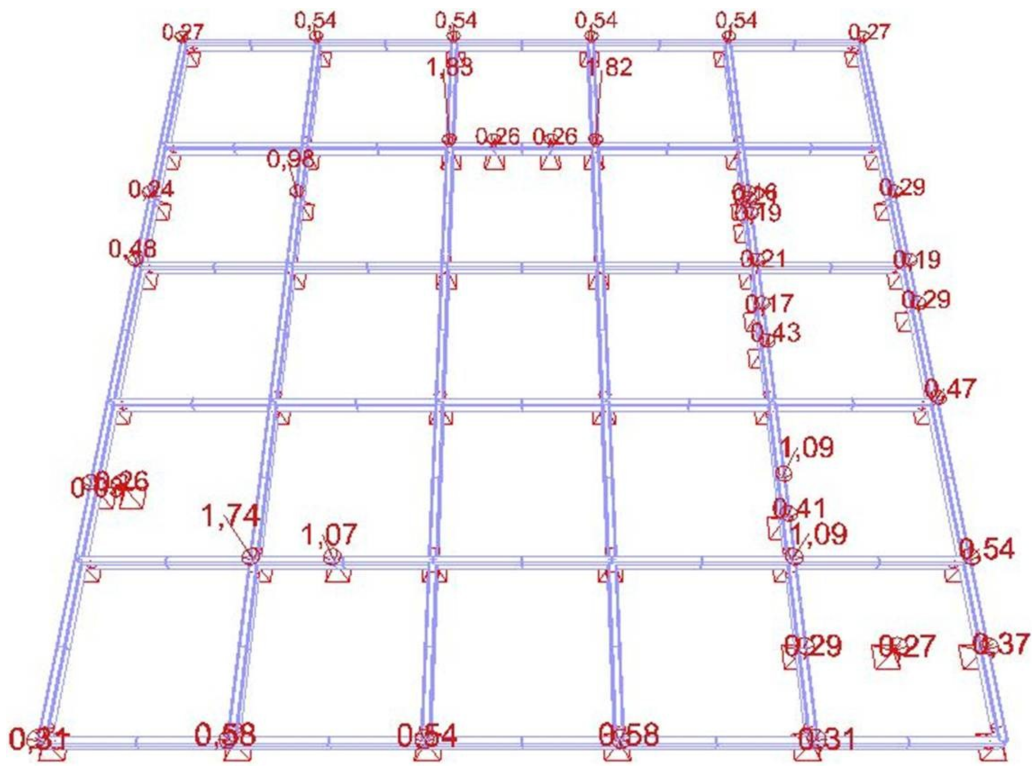


Figure 36: Point loads caused by the weight of the flat roof (without any load modifier) (loads in kN) (Tine Lanssens and Charlot Tanghe) (BuildSoft)

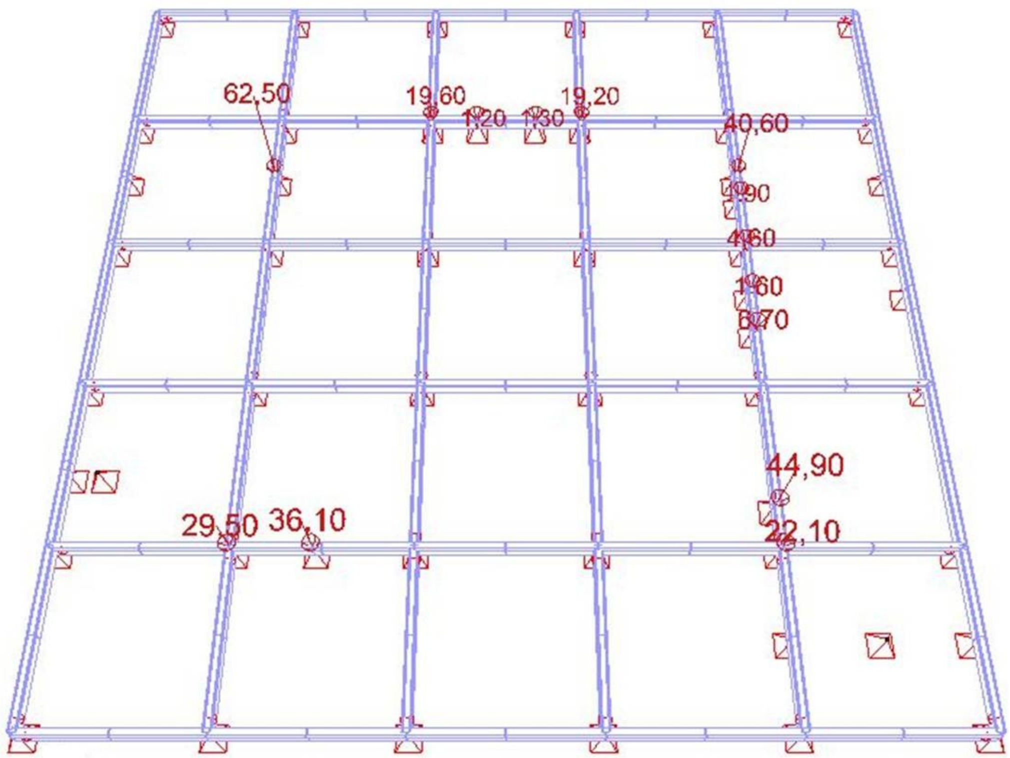


Figure 37: Point loads caused by the loads on the atrium roof (using the load combination 1.2 Dead Weight and 1.6 Snow load) (loads in kN) (Tine Lanssens and Charlot Tanghe) (BuildSoft)

The weight of the floor panels and concrete tiles and the live load on the panels give a triangular line load on the foundation tubes because of the triangular loading areas, as shown in Figure 38. The values of the loads are given in Table 18 and Table 19 for both the beams on the border of the structure and the inner beams.

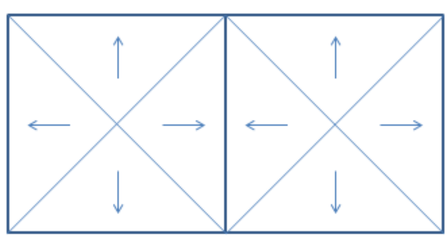


Figure 38: Triangular loading areas (outer beams and inner beams) (Tine Lanssens and Charlot Tanghe) (BuildSoft)

Table 18 Triangular live load on foundation grid

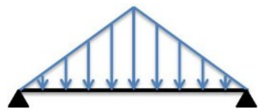
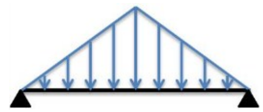
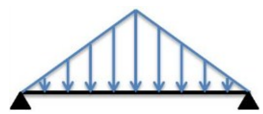
Live load on foundation grid (without load factors)			
distributed load	40 psf = 1.9152104 kPa = 1.9152104 kN/m²		
border beams	loading area	1.265625 m²	
	triangular line load	section	load
		left support	0 kN/m
		mid-span	2.1546117 kN/m
		right support	0 kN/m
inner beams	loading area	2.53125 m²	
	triangular line load	section	load
		left support	0 kN/m
		mid-span	4.30922331 kN/m
		right support	0 kN/m

Table 19 Triangular load on foundation grid caused by the weight of the concrete tiles and floor panels

Weight of concrete tiles & floor panels on foundation (without load factors)			
distributed load	16.83453 psf = 0.80604148 kPa = 0.80604148 kN/m²		
border beams	loading area	1.265625 m²	
	triangular line load	section	load
		left support	0 kN/m
		mid-span	0.90679667 kN/m
		right support	0 kN/m
inner beams	loading area	2.53125 m²	
	triangular line load	section	load
		left support	0 kN/m
		mid-span	1.81359334 kN/m
		right support	0 kN/m

The strength of the FRP-tubes is checked with this load combination:

$$1.2 \cdot DW + 1.6 \cdot S + 1.6 \cdot \ L + 1.2 \cdot W$$

where

- DW = dead weight of FRP-tubes;
- S = loads coming from the snow load;
- L = live load on the floor panels;
- W = weight of the floor & concrete tiles and loads coming from the weight of the roof.

The moments in the tubes are given in Figure 39.

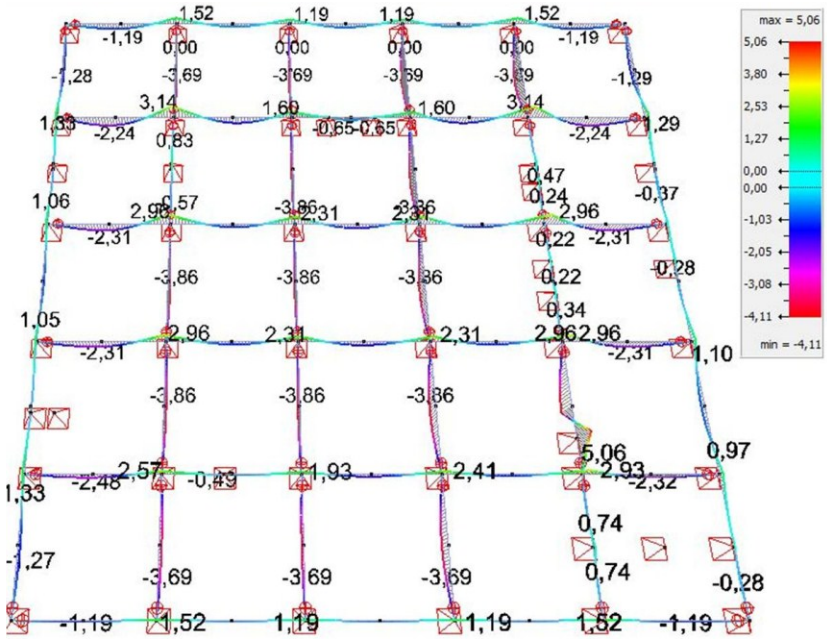


Figure 39: Moments in the FRP-tubes (moments in kNm) (Tine Lanssens and Charlot Tanghe) (BuildSoft)

The maximum moment in a tube is 5.06 kNm.

The normal stresses along the strong axis can be found with the following formula: $\sigma = \frac{M \cdot y}{I}$ where y is half the height of a tube. These stresses are shown in Figure 40, in which positive stresses are compressive stresses.

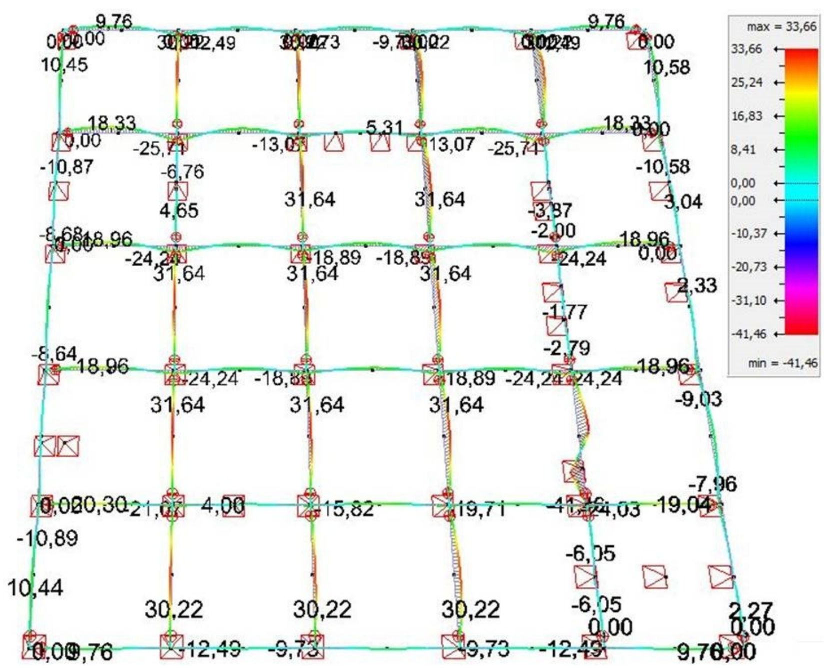


Figure 40: Normal stresses along the strong axis (in N/mm²) (Tine Lanssens and Charlot Tanghe) (BuildSoft)

The maximum compressive stress is 33.66 N/mm²; the maximum tensile stress is 41.46 N/mm². The nominal flexural strength of the 4"x6"x1/4"-FRP tubes is 227.60 N/mm². Multiplying with the LRFD resistance factor of 0.6 for bending stresses in FRP-materials, the design flexural strength becomes 136.56 N/mm². The FRP beam strength far exceeds the strength required by the foundation design of this structure.

10.1.1.1 *Deflections*

LFRD only requires load combination factors of 1 to check service deflections. Thus figure 45 is showing the deflections of the rectangular tubes under the load combination:

$$1 \cdot DW + 1 \cdot S + 1 \cdot L + 1 \cdot W$$

where

- DW = dead weight of FRP-tubes;
- S = loads coming from the snow load;
- L = live load on the floor panels;
- W = weight of the floor & concrete tiles and loads coming from the weight of the roof.

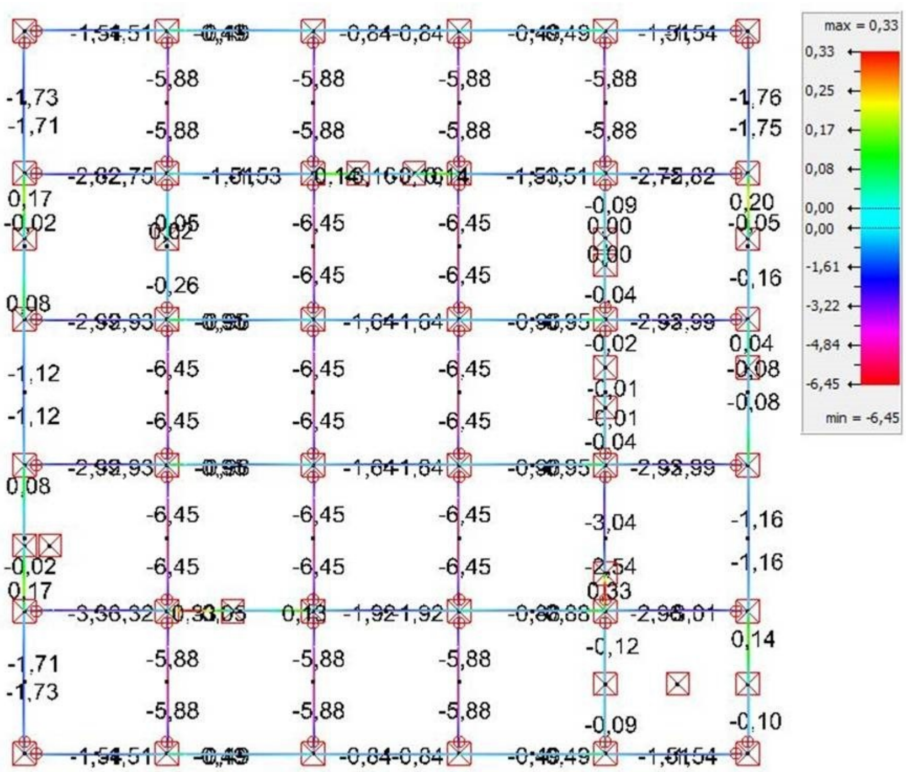


Figure 41: Deflections in the foundation tubes (in mm) (Tine Lanssens and Charlot Tanghe) (BuildSoft)

The maximum deflection is 6.45 mm. This deflection occurs in the short beams. The maximum allowable deflection is $\frac{L}{240} = \frac{2.25\ m}{240} = 9.375\ mm$. The deflections of the beams are below the maximum value.

10.1.2 Foundation supports

10.1.2.1 *Dimensions*

The concept of the supports is shown in Figure 42 (support at the borders of the foundation grid) and Figure 43 (support at the inner nodes of the foundation grid).

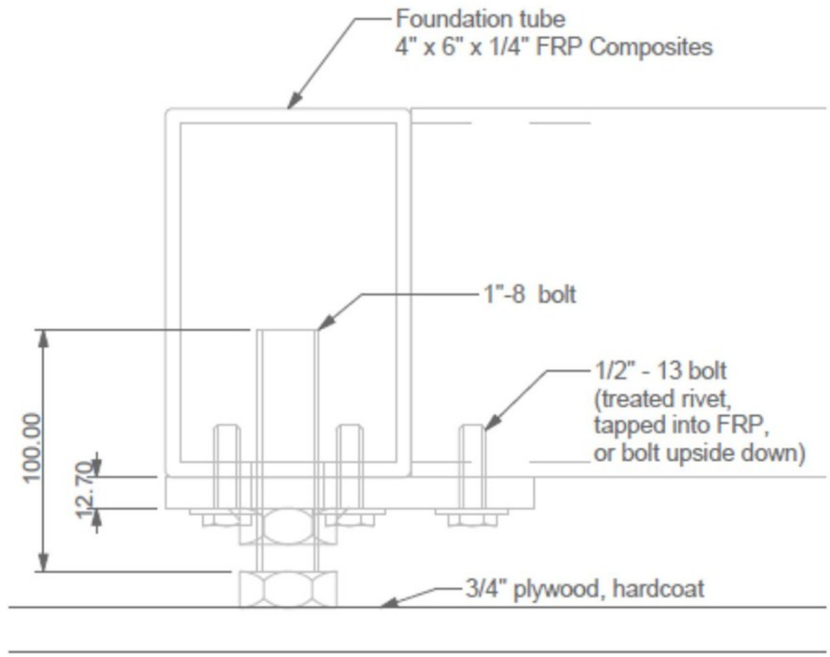


Figure 42: Support at the edge of the foundation grid (dimensions in mm) (BIM Report submitted to SD China 2013 by Team BEMANY on 3/6/2013)

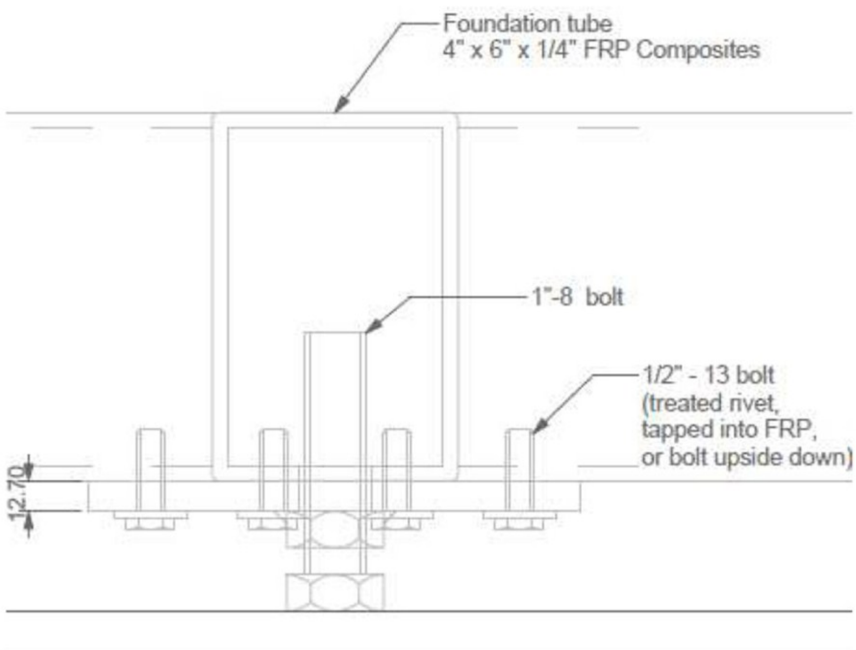


Figure 43: Support at the other nodes of the foundation grid (dimensions in mm) (BIM Report submitted to SD China 2013 by Team BEMANY on 3/6/2013)

10.1.2.2 *Loads*

The vertical loads on the bolt-nut connection are equal to the reaction forces on the foundation tubes. These reaction forces are shown in Figure 44.

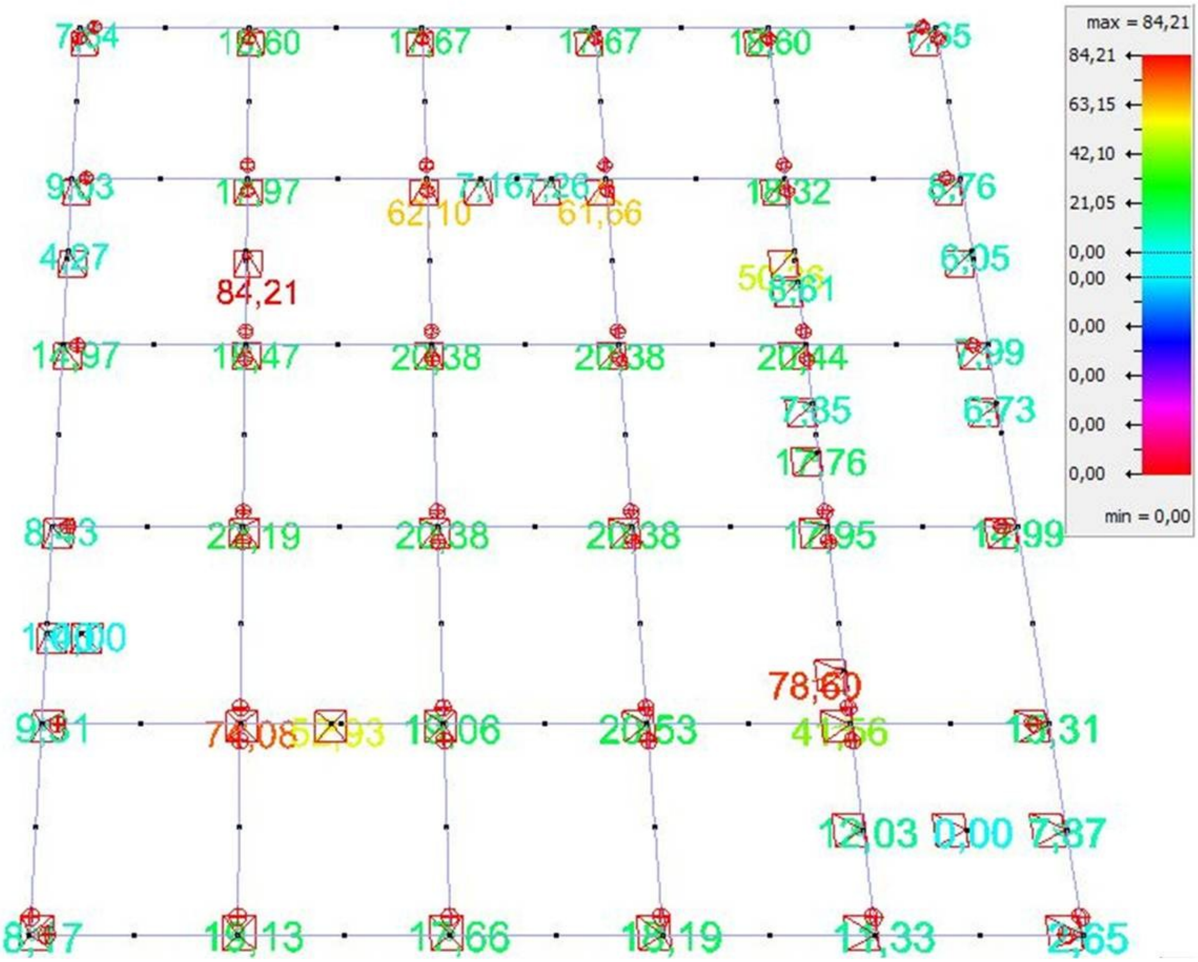


Figure 44: Vertical reaction forces on the foundation grid (reactions in kN) (Tine Lanssens and Charlot Tanghe) (BuildSoft)

The biggest vertical force on the bolt-nut connection will be 84.21 kN.

10.1.2.3 *Strength*

The strength properties of a 1”-8 bolts are given in table 25. Grade 2 screws are low strength fasteners made from carbon steel, achieving their strength primarily from cold forming. Grade 5 screws are medium strength fasteners that achieve their strength from the medium carbon steel and a quench and temper heat treatment. Grade 8 screws are high strength fasteners made from alloy steels that also achieve their strength from the alloy steel and a quench and temper heat treatment (NUCOR FASTENER 2008).

Table 20 Strength properties of a 1”-8 bolt (Halsey Manufacturing)

Nominal diameter and threads per in.	Stress area [mm²]	Grade 2		Grade 5		Grade 8	
		Proof load [kN]	Tensile strength [min, kN]	Proof load [kN]	Tensile strength [min, kN]	Proof load [kN]	Tensile strength [min, kN]
1”-8	390.967	88.96443	161.9153	229.0834	323.3857	323.3857	404.3433

Using a Grade 5 bolt and applying the LRFD resistance factor of 0.75 for fasteners, the maximum allowable load for the connection is 171.81 kN. The support with a 1”-8 bolts is sufficient for an axial load of 84.21 kN.

The base shear is divided up between the supports with this equation

$$V_{bolt} = \frac{V}{\#_{of\ supports}}$$

This results in a shear of .703KN per bolt. The bolts are also in double shear so the resulting shear force on the bolts is 1.4056 KN.

Using Von Mises ratio of .577 to determine the shear strength of the bolts, the shear nominal strength of Grade 2 bolts is 93.425 KN, and the design shear strength is 70.07 KN. The design shear strength far exceeds the shear in the both connections.

10.2 Construction

To construct the foundation grid, the foundation beams are laid out in the grid pattern, and then they are connected to the supports at the appropriate places. This is the first task to be completed in the construction.

11 Horizontal Loadings

The Horizontal loadings of the structure affect the whole structure at once, and they are divided up into Wind and Seismic loads

11.1 Horizontal wind loading

The horizontal wind pressure was applied along the face of the wall and transferred directly to the columns the case of glass walls. The wind loading causes a max moment in the columns of 3.3 KNm as shown in Figure 45. Rearranging the combined flexure and compression check to give the max allowable moment for the given loading gives use that for the loading on the effected columns (Maximum Loading of 4.4KN) the maximum moment allowable is 104700 KNm for the FRP columns. This puts the columns well within the acceptable structural limits for this wind loading case

$$\frac{P}{P_n} + \frac{M}{M_n}\frac{C_m}{\left(1 - \frac{P}{P_E}\right)} \leq 1$$

$$M \leq \left(1 - \frac{P}{P_n}\right) * \frac{M_N \left(1 - \frac{P}{P_e}\right)}{C_m}$$

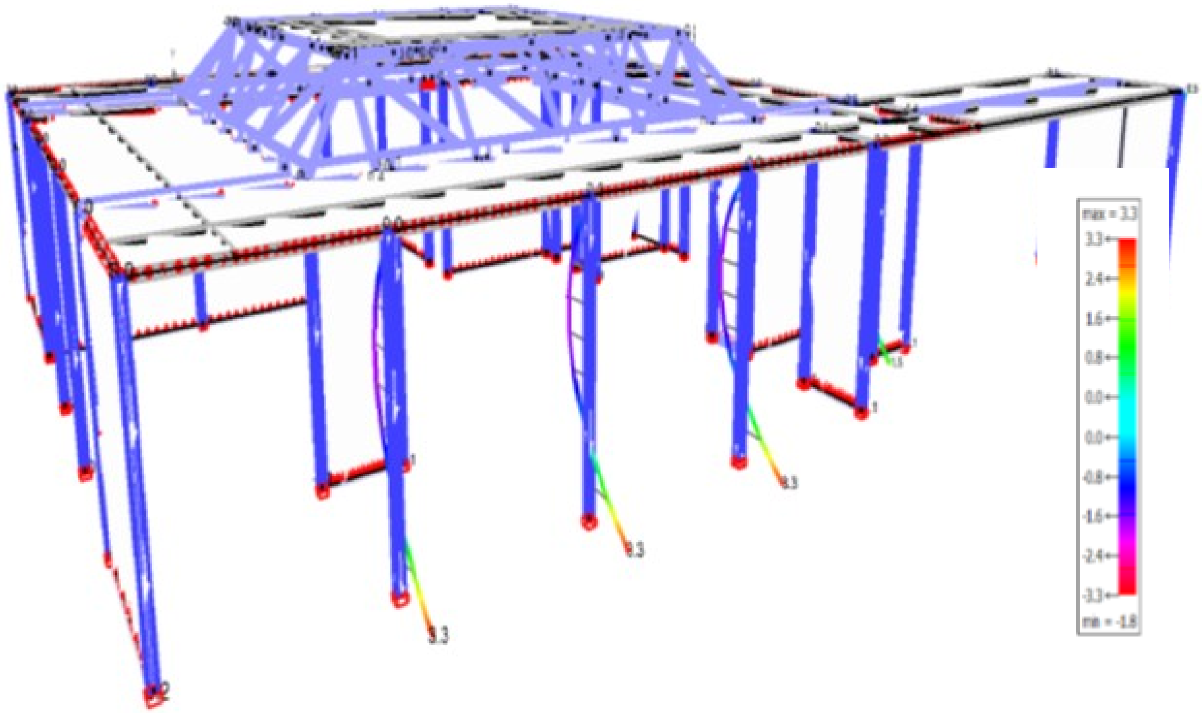


Figure 45 Max moments caused by Horizontal wind loading in KNm (BuildSoft)

11.2 Seismic Loading

The seismic loading was applied to the roof diaphragm as Figure 46 and Figure 47 shows the deflection is only 0.5mm. Transonite walls are carrying the seismic load, together with the columns. Columns are attached to the foundation and the walls are attached to the columns.

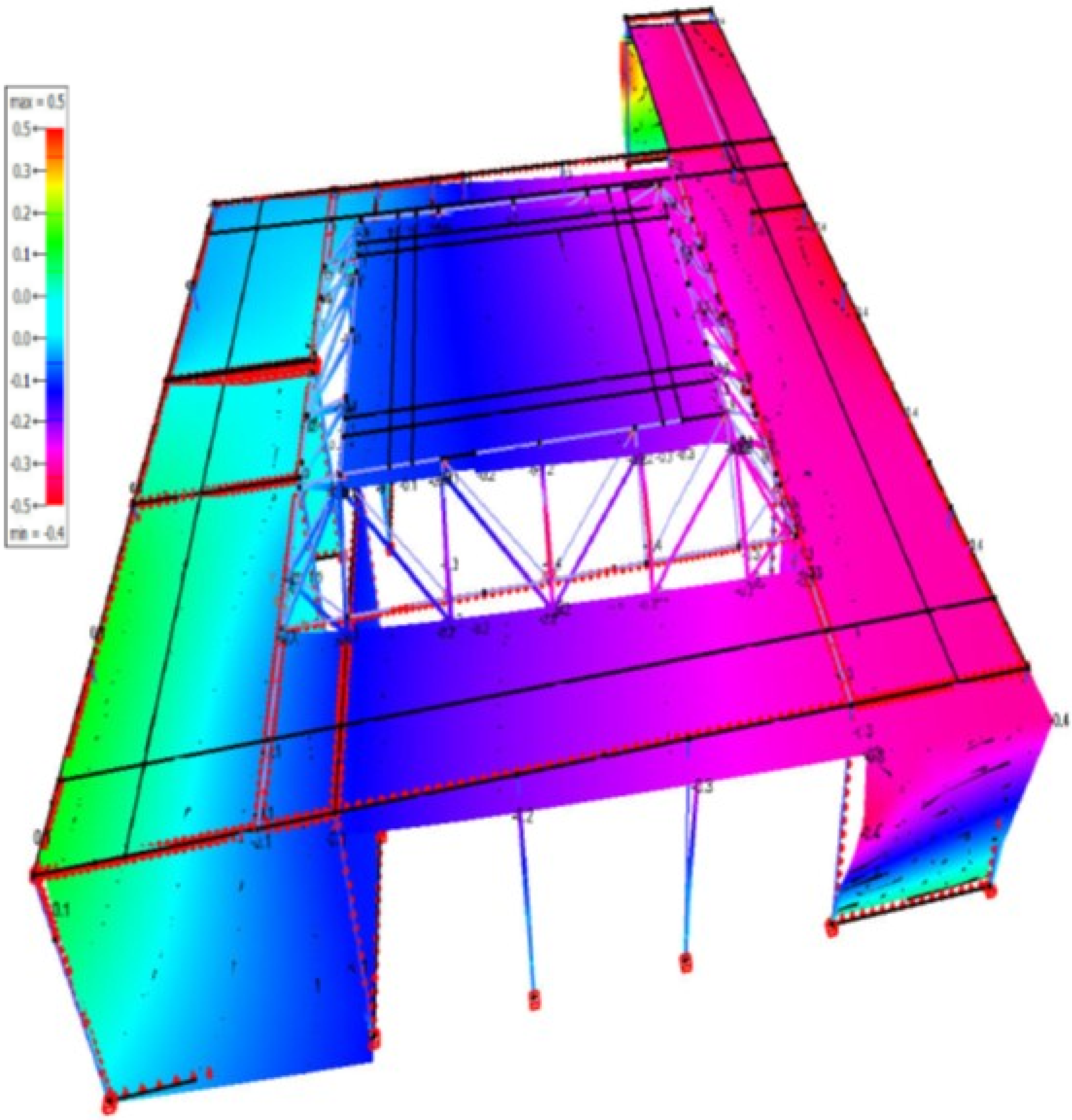


Figure 46 Seismic Deflection in mm (loading applied south to north) (BuildSoft)

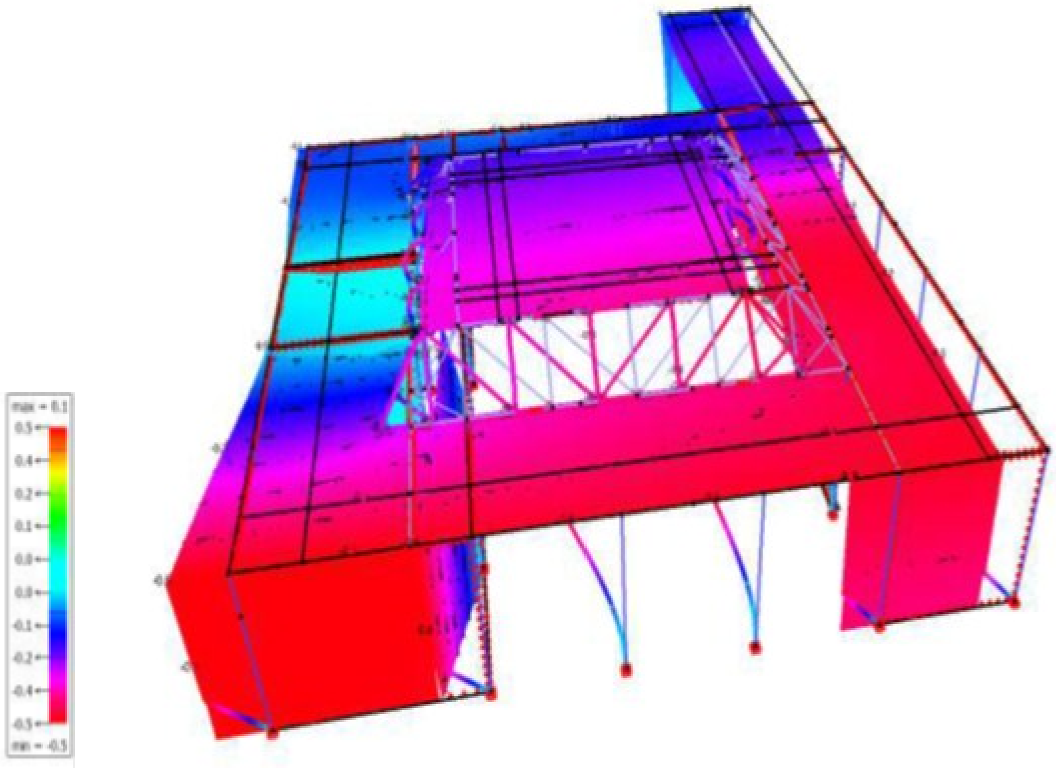


Figure 47 Seismic deflection in mm (loading applied east to west) (BuildSoft)

The highest Moment caused by the Seismic loading is 0.8 KNm (shown in Figure 48) which is much less than the moment loading of the wind pressure and well within the acceptable limits.

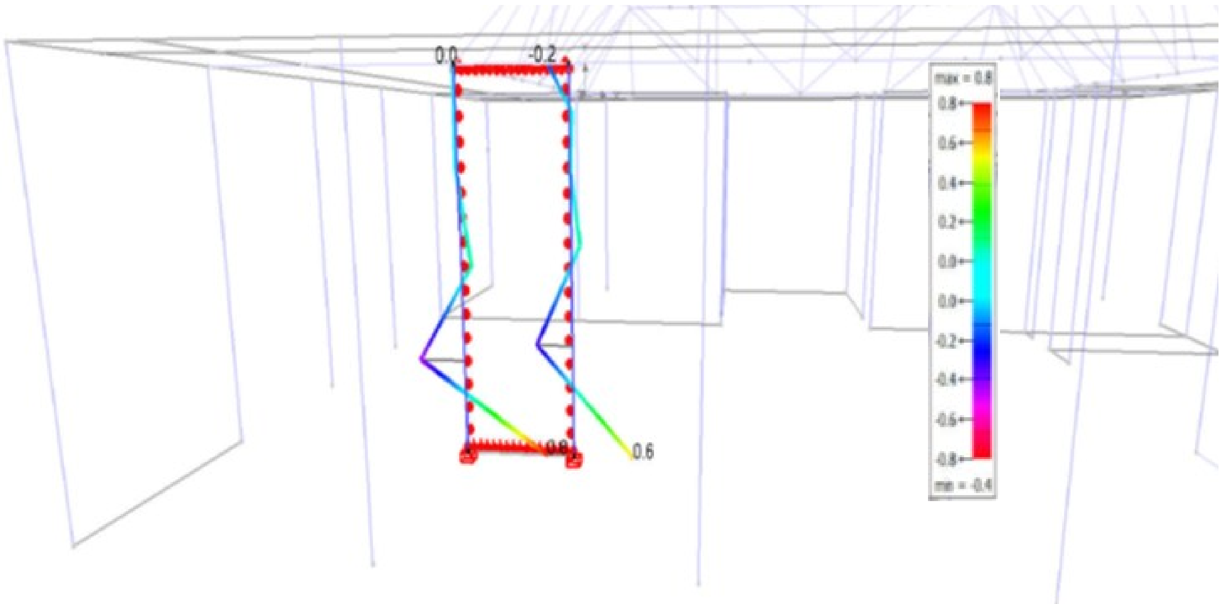


Figure 48 Moment caused by Seismic loading in KNm (BuildSoft)

12 Construction

A total of 40 team members are going to Datong, China to participate in the SD China, but due to some people's schedule not all 40 team members will be on site during the construction phase. For the purposes of the report, it will be estimated that there will be at least 10 workers working at all times. The construction will take place over the course of ten eight hour days. 10 people working ten eight hour days results in a total of 800 man-hours.

This section will over the necessary skills and equipment, the building materials, and the building schedule.

12.1 Equipment and Skills

The Solatrium will be constructed by a collection of student volunteers and professors with very little construction experience. A practice build was performed in Worcester, MA to give the student volunteers construction experience before the competition. In addition to that basic construction skill some additional skills are necessary to build the Solatrium.

12.1.1 Skills

In addition to the use of basic tools, like a socket wrench and hammers, there are five other specialized skills; forklift and vacuum lift operation, plumbing, electrical wiring, carpentry, and crane operation.

Though the structure is lightweight due to the FRP panel systems, the panels are quite large and unwieldy. This means that many of the panels cannot be handled and carried by hand but instead will be maneuvered by a forklift with a vacuum lift attachment, pictured in Figure 49. The vacuum lift creates a vacuum to carry the panels, and the vacuum lift that Team BEMANY has acquired can be manipulated 90 degrees and used to place both walls, as pictured in Figure 49, and roof panels. Prof. Van Dessel is trained in forklift operation because of his last Solar Decathlon competition.

Figure 49 Photo of vacuum lift forklift attachment used to place a wall

The plumbing and wiring skills are needed because the house needs to be fully functioning for the competition. Team BEMANY is inviting 8 members of the Worcester Technical High School students and staff to come to the Datong site, and continue use their training to help with the construction of the Solatrium.

The carpentry skills are needed to create the wall finishing. Some members of the local carpentry union donated their services to create the finishings. All the finishing was completed before shipping the Solatrium to China.

The last skill needed is crane operation. A crane will be used to place the Atrium and atrium truss on the top of the building. This will be the only use of the crane. A professional crane operator will be acquired for the contest to fulfill this needed skill.

12.1.2 Equipment

This section will list the equipment necessary to build the Solatrium and their uses.

Socket wrenches and drills are used to construction the connection in the house. Specifically the wrenches will primarily be used to place the bolts that make up the floor connections, wall connections, and beam connections.

Ladders are necessary because the construction sometimes takes place on an elevated plane especially when connecting and placing the roof beams, roof panels, and atrium.

During the construction, the walls will not always be properly framed as they would be under normal circumstances, therefore there is some method of bracing that must be used. Bracing used in the Solatrium construction is the extra FRP angles, which are connected to the wall columns and then screwed into the floor panels at an angle, picture in Figure 50. This bracing will allow to the walls to remain structurally stable while the home is being constructed and will be removed before the end of construction.

Figure 50 Photo of FRP angle being used for wall bracing

Safety stands will be used to support elevated horizontal members that are not or cannot be completely constructed at the time. The safety stands function in the same respect as bracing, creating a structural sound building element.

Because of the heavy and unwieldy panels, a forklift is necessary to lift and maneuver the panels into place. The forklift will sometimes be used in conjuncture with the vacuum lift, as pictured in Figure 49.The vacuum lift is an attachment for the forklift that creates suction in order to lift up the panel systems. This vacuum lift needs to be plugged into a power source continuously. The battery vacuum lift could not provide the continuous suction for long enough periods of time, so the vacuum lift that can operate while plugged in was brought in to replace the battery pack version. The vacuum lift is able to articulate ninety degrees pictured in Figure 49 allowing it to be used on both the walls and roof panels.

A power source is necessary to operate the vacuum lift and to recharge the powered drills. A generator will be provided for onsite to fulfill this need.

Lastly, a crane is needed to lift and place the entire atrium structure onto the partially completed shell of the Solatrium. The crane will also be used to place the shipping containers ion site.

12.2 Materials

This section contains the list of materials that will be used to construct the Solatrium. These materials include the Transonite^{tm} panels, FRP beams, foundation plates, and connection boxes. Table 21 listed the materials and the amount of them used in the Solatrium.

Table 21 List of Solatrium materials with numbers and description of their uses

Material	Subdivisions	Number of Elements	Uses
Transonite Panels		37	floor, wall, and roof elements
	Wall Panels (with columns)	16	wall
	Roof Panels	6	roof
	Floor Panels	13	floor
	Atrium Panels	2	roof panels in atrium
Columns		41	vertical structural elements
	Columns (in panels)	36	" " " "
	Columns (outside panels)	7	" " " "
FRP beams		36	roof and foundation elements
	4"x 4"x 1/4" Tube	4	roof support
	4"x 6"x 1/4" Tube	28	foundation grid
	Wide flange	4	roof support around base of atrium truss
Atrium truss		4	
Steel tubes		8	resist buckling in critical columns
	2"x 2"x 1/4" Steel tubes	8	" " " "
Connection box		82	connection between walls and floor and roof
Foundation plates		36	Foundation
Cables		15	cable stayed truss

12.3 Construction Site and Schedule

The competition site consists of the 24m by 24m square field pictured in Figure 51. Figure 51 also shows the position of the shipping containers and works spaces that will be used. At this location the house will be constructed in 8 steps.

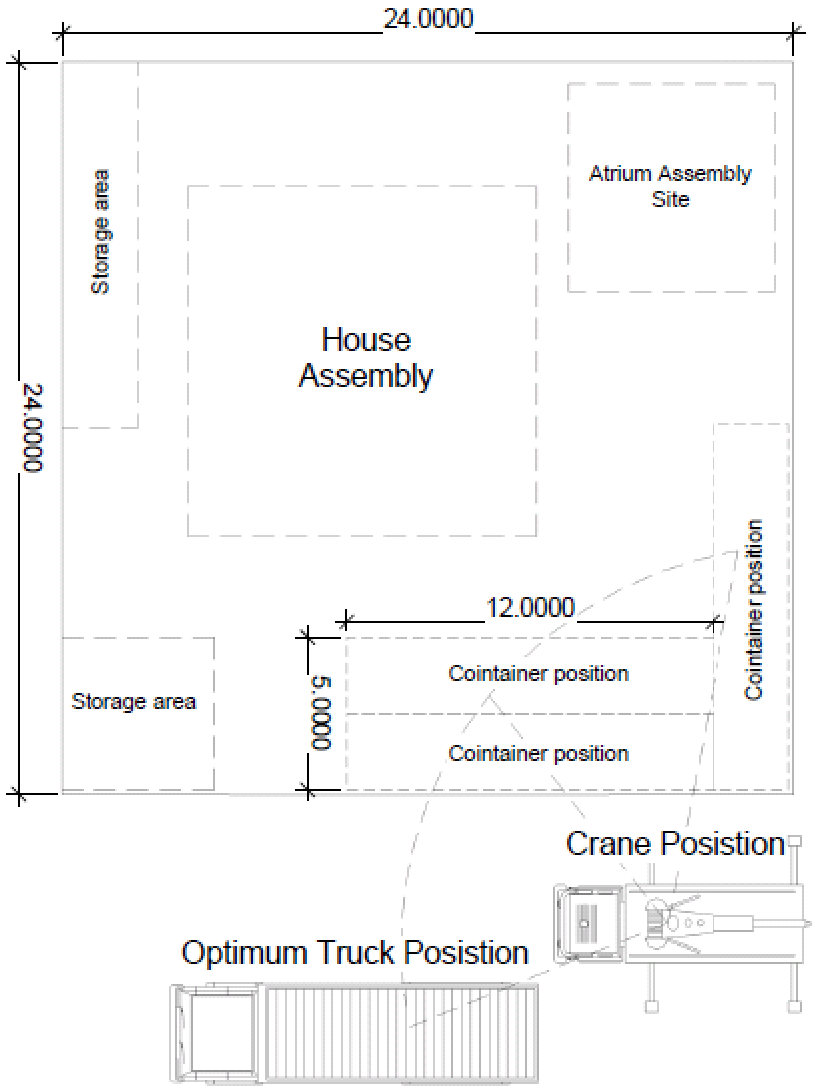


Figure 51 Site plan at arrival (BIM Report submitted to SD China 2013 by Team BEMANY on 3/6/2013)

12.3.1 Step 1 Site Preparation

When the team arrives on site, the trucks carrying the shipping containers containing the Solatrium house will be waiting to be unloaded. The crane will be used to maneuver the shipping containers into their locations on the site. Figure 52 is the rendering of the site preparation.

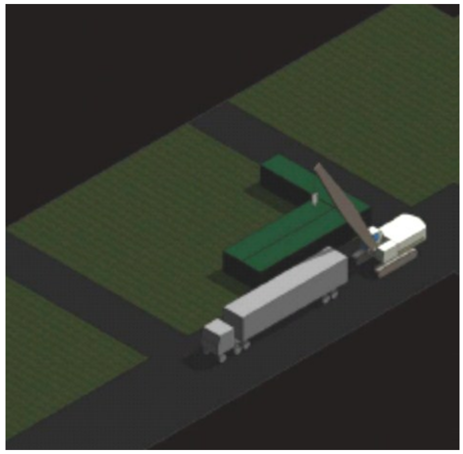


Figure 52 Rendering of the site preparation (BIM Report submitted to SD China 2013 by Team BEMANY on 3/6/2013)

12.3.2 Step 2 Foundation

The second step is the placing of the foundation grid. This task is estimated to take thirty man-hours to complete. This task involves the placement of the 28 foundation beams, the foundation plates, and the bolting of the connections. Figure 53 depicts the site after the foundation is placed.

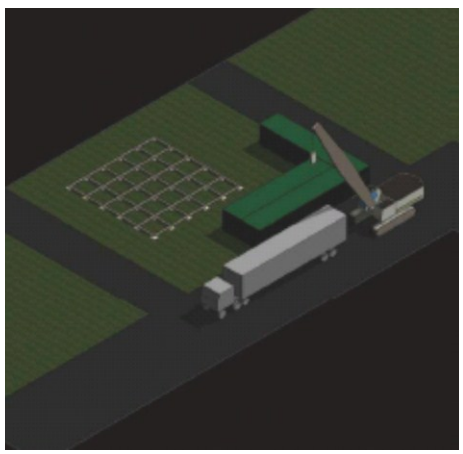


Figure 53 Rendering of the foundation in place at the site (BIM Report submitted to SD China 2013 by Team BEMANY on 3/6/2013)

Figure 54 Photo of the practice build after the foundation grid has been laid out

12.3.3 Step 3 Kitchen Module

The kitchen module was shipped intact, and the step after placing the foundation. The kitchen will be put in place by a forklift. This task is estimated to take 10 man hours. Figure 55 shows the site after the kitchen module has been put in place.

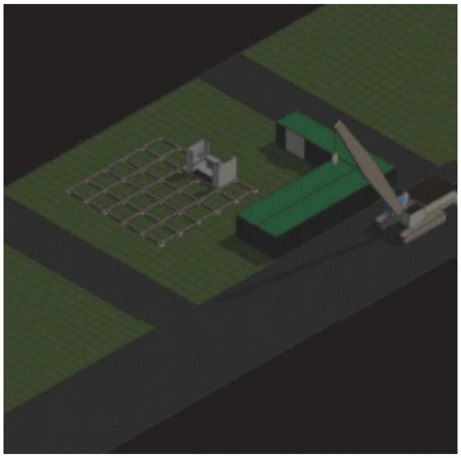


Figure 55 A rendering of the site after the kitchen module is put in place (BIM Report submitted to SD China 2013 by Team BEMANY on 3/6/2013)

Figure 56 Photo of finished kitchen module after the practice build was completed (taken by a member of Team BEMANY)

12.3.4 Step 4 Floor Placement

Step 4 is the placement of the floor panels. The floor panels will be maneuvered into place by a forklift. This task is estimated to take thirty-nine man hours to place the floor, and another 36 man hours to connect the floor to the foundation grid.

12.3.5 Step 5 Wall and Column Placement

After the floor is connected to the foundation, the walls and columns are put into place and connected to the floor. The columns are lightweight and easy to put in place. The columns are estimated to take 10 man hours, and the wall placement is estimated to take 77 man hours.

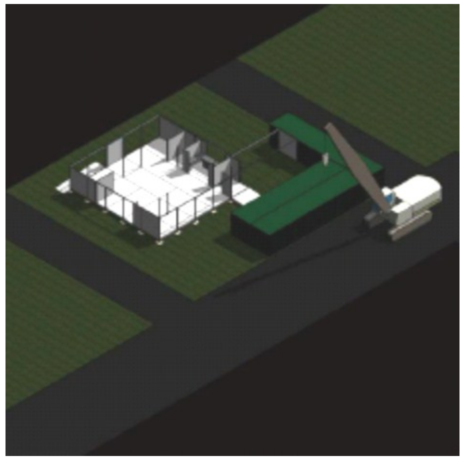


Figure 57 rendering of the site after the walls and columns are put on place (BIM Report submitted to SD China 2013 by Team BEMANY on 3/6/2013)

Figure 58 Photo of the practice build while the walls are being placed

12.3.6 Step 6 Roof Placement

After the walls and columns are constructed, the roof panels can be attached to the structure. Preparing the roof panels will take an estimated 18 man hours, and the placement of each roof panel is estimated to take 30 man hours.

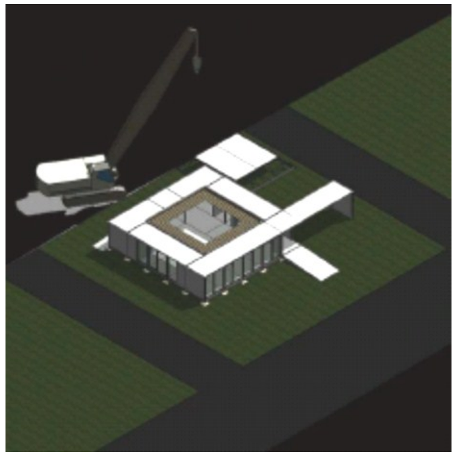


Figure 59 Rendering of the site after the roof places had been placed (BIM Report submitted to SD China 2013 by Team BEMANY on 3/6/2013)

Figure 60 Photo of Solatrium practice build after one of the roof panels have been connected.

12.3.7 Step 7 Atrium

The final step in completing the structure is the placing of the atrium. The atrium will be constructed in the space indicted in Figure 51 and will take 18 man hours in preparation, and then another 30 man hours to place and connect the complete Atrium using a crane.

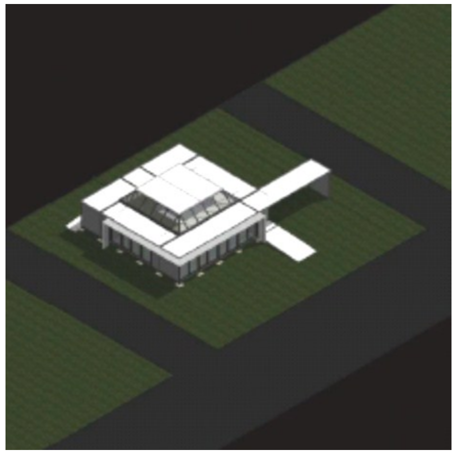


Figure 61 Rendering of the completed Solatrium onsite (BIM Report submitted to SD China 2013 by Team BEMANY on 3/6/2013)

12.3.8 Step 8 Finishing, Electrical, and Plumbing

The final step in preparing the structure for competition is preparing the now completed structure for living condition by preparing the electrical systems, plumbing, finishings, putting the furniture in, and installing the appliances. These tasks are estimated to take a total of 120 man hours of work.

12.3.9 Schedule

Out of the estimated available 800 man-hours if ten team members are working, It is estimated it will take 448 man hours to construction the house up to competition standards. This means if only ten people will onsite for the ten days of construction, the structure will be able to be constructed on time. The estimated schedule can be found in Table 22 and Table 23.

Table 22 Estimated construction schedule for Solatrium house (each block represents 5 man hours)

	Materials	Equipment	Total Man Hours
Foundation	1,7,8	1	30
Kitchen module	kitchen	1,5	10
Floor Panels	4	5,6,7	39
Floor connections	1,2,3	1,2	36
Columns	5	1	10
Interior Walls	1,4	1,4,5,6,7	27
Exterior Walls	1,4	1,4,5,6,7,8	50
Roof Panel prep	2,3,4,9,14	1,2,5,6,7	18
Roof Panel placement	1,4,9	1,3,4,5,6,7,8	60
Atrium construction	4,10,14	1,2,5,6,7	18
Atrium placement	4,10	9	30
Finishing	1,2,13	1,2,15	30
Electronics	11		60
Plumbing	12	1,2	30
Total Man Hours			448

Table 23 Estimated construction schedule for Solatrium house (each block represents 5 man hours) [continued]

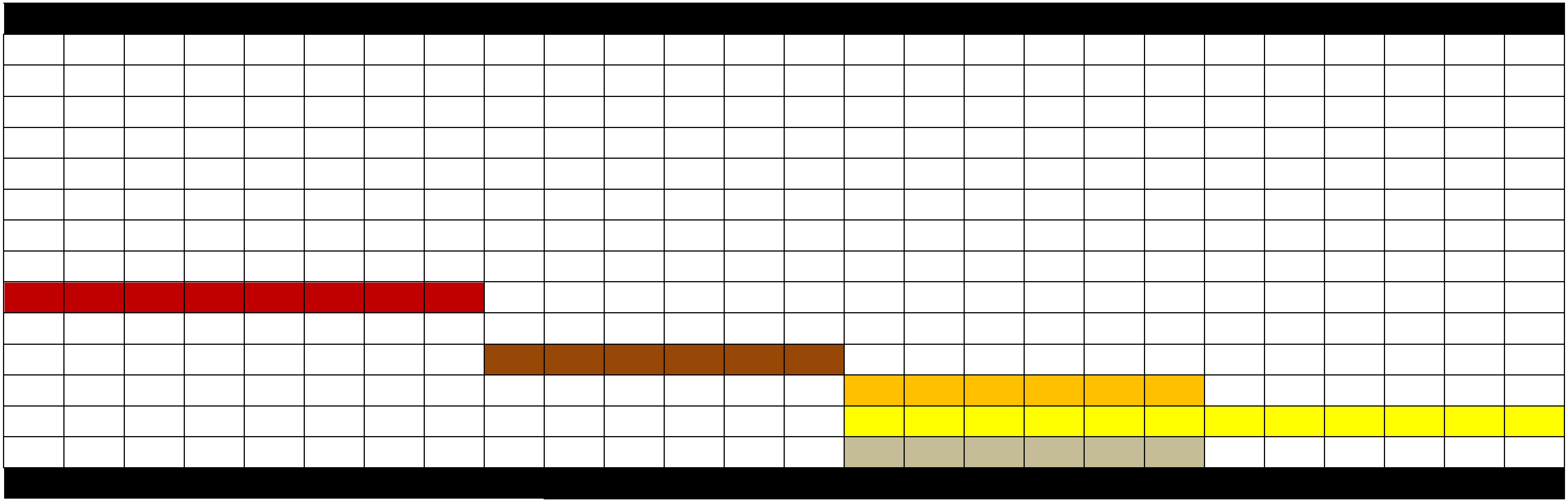


Table 24 Equipment List for Table 22 and Table 23

Equipment List	
1	Wrench
2	Screwdriver
3	Ladder
4	Bracing
5	Forklift
6	Vacuum Lift
7	Generator/Power source
8	Safety Stands
9	Crane

Table 25 Materials list for Table 22 and Table 23

Materials List	
1	Bolts, Nuts, Washers
2	Screws
3	Connection boxes
4	Transonite Panels
5	3.5"x3.5" FRP beam
6	Re-enforced FRP beam
7	4"x6" FRP beam
8	Steel Plates
9	Wide flange FRP beam
10	Steel Truss
11	Wiring
12	Plumbing
13	Concrete Tiles
14	FRP angles
15	Bamboo ceiling

13 Conclusion

The Solar Decathlon project has brought three institutes of higher learning and over 40 students and faculty to compete with 22 other universities from around the world. The ultimate goal is promoting construction design and technology application to produce net zero-energy houses that are appealing and affordable. The team members involved in this project have a broad multi-disciplinary background including architectural, civil, electrical and computing, fire protection mechanical, lighting and acoustical engineering

The use of the FRP elements in the Solatrium presented some interesting challenges during the design process due to the lack of code guidance for the relatively new material and the low stiffness of the material compared to traditional construction materials. Column placement and a cable stayed truss were used to overcome the low stiffness and industry standards were used in lieu of code requirements for composite materials.

The construction phase of the Solar Decathlon China is only 2 weeks long and the construction will be completed by students, faculty and other volunteers. And therefore, the decision to use a prefabricated house that would facilitate the quick construction time constraints during the competition in Datong China.

Sustainability was a major focus in the Solatrium design. The Solatrium is a net zero energy house designed to create a feeling of connection with the outdoors, through the large windowed surfaces and the open central atrium.

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Appendix A

1 Transonite Lab Report

1.1 Introduction

This lab report is for the testing of the Transonite™ panels at WPI. These panels will be used in the construction of the BE-MA-NY team house for the Solar Decathlon China competition in August 2013. Transonite™ panels are custom made by Creative Pultrusions, Inc. This report will begin with a short overview of the structure and application of Transonite™ panels.

1.1.1 Solar Decathlon

The US Department of Energy has held the Solar Decathlon competition biennially since 2002. The US Department of Energy states that Solar Decathlon has “collegiate teams design and build energy-efficient houses powered by the sun,” (2012). The Solar Decathlon China (SD China) competition is the most recent expansion of Solar Decathlon program. 2013 will be the first year the SD China Competition is held and it will take place in Datong, PRC. The Competition is the result of a US-PRC agreement that stipulates:

> … the Governments of the United States of America and the People's Republic of China have a common goal in fostering sustainable economic and social development while encouraging the use of renewable energy sources and recognize that solar energy development and use is an important part of their collaboration …

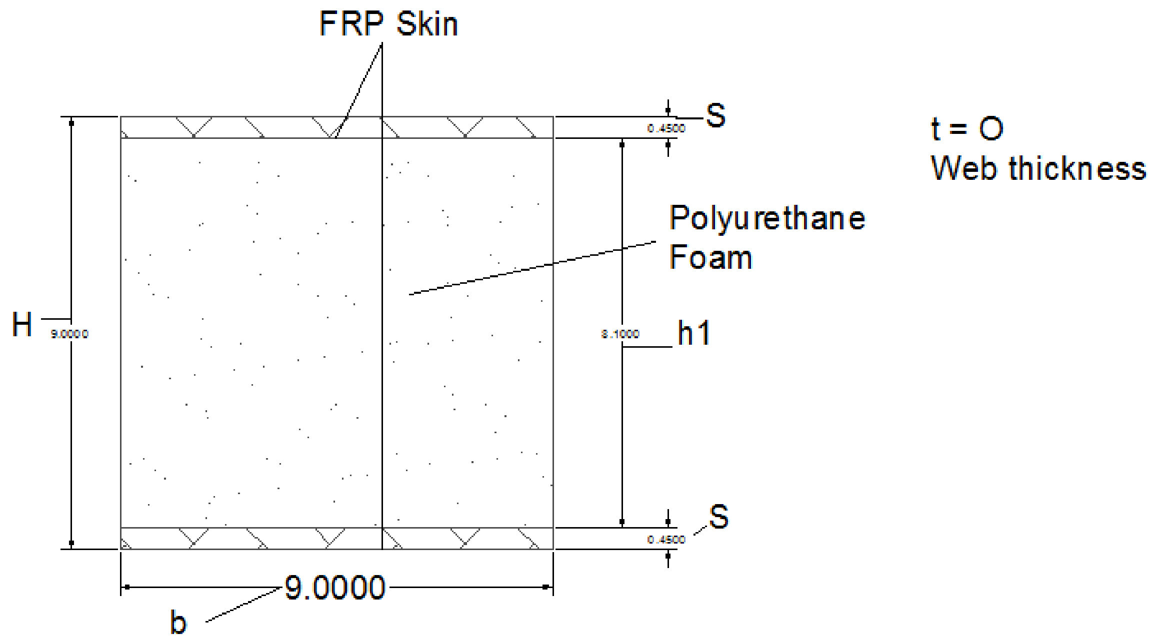
US-PRC memorandum signed Jan 18, 2009.

There are 23 teams made up of universities, from China, the US, Belgium, and other places around the world competing in SD China. The goal of each of these teams is to design and build a single family home that conforms to regulatory standards and is powered by the sun. The BE-MA-NY team is using the Transonite™ material extensively in the design of their entry into this contest, as such it is necessary to understand the properties of the material.

1.1.2 Fiber Reinforced Polymers

The primary material being used in the construction of the structure is Fiber Reinforced Polymer (FRP) panels manufactured by Creative Pultrusions, Inc. Creative Pultrusions is a manufacturer of fiber reinforced polymer composites and use the pultrusion manufacturing method to create FRP products.

Fiber reinforced polymers are plastics with fiber matrixes within the material. The material being used Creative Pultrusions 60% glass fiber by weight in a system that Creative Pultrusions calls Transonite™. Creative Pultrusions’ transonite are custom made to customer specifications for every order. The Transonite™ system is a panel with two skins separated by a foam core with the skin connected by glass fibers. Our custom Transonite™ panels are 90mm thick with 4.5mm thickness FRP skin, thus a foam core of Polyurethane is 81mm thick.



The major benefit of using FRP elements is that they are lightweight compared to equivalent elements of traditional materials such as concrete. The density of the transonite panels for example is about 25 kg/m^2 where as a concrete panel of similar dimensions would be over 200 kg/m^2.

1.1.3 Solar House

The Transonite™ system is not commonly used as a building material, but the BE-MA-NY team is using the Transonite™ panels as structural roof elements, structural floor elements and structural walls. The lightweight nature of the material greatly decreases the dead loading on the vertical elements of the structure. The downside is that the material deflects much more than other standard building materials, so the while we are looking for the critical strength of the material, we are also observing its behavior under stress. The material will be under shear, bending, compression, and buckling conditions in the current design.

1.2 Creative Pultrusions, Inc Testing

Creative Pultursions, Inc performed some tests on the custom designed panels before WPI received their shipment. This section will go through their results. Only testing relevant to the design of the Competition house will be analyzed.

1.2.1 Bending

The determination of the bending properties of the panel system is necessary to determine the behavior of the roof and floor panels of the competition house. Creative Pultrusions used a simple 3 point bending test to determine the flexural strength of the panel, as shown in figure 1-1. The sample was one foot wide and the span length was 70 inches. Additional details of the testing are found in Table 1-1.

Before the testing, Creative Pultrusions, Inc. informed us that the panels would most likely deflection past the ultimate service limits before they would reach their ultimate strength limit. This behavior was confirmed by this test. Using Equation 1-1, we can see that the panel deflected at a ratio of about 1:70 which is much larger than the ultimate service limit of the floor, 1:360. This suggests that if we can limit the deflections to the 1:360 mandated, the panels will not fail thru bending.

$$Ratio = \frac{\Delta}{L}$$

Using Equation 1-2 the young's modulus was determined.

$$E = \frac{PL}{48\, I\Delta}$$

Using equation 1-3, the flexural strength was determined

$$\sigma = \frac{PL}{4} * \frac{\frac{t}{2}}{I}$$

The test resulted in a max young's modulus of 5.6 x 10^5 psi before failure. The Young's modulus combined with the Moment of inertia of 12.387 in^4 that gives panel stiffness (EI) of 6.93 x 10^7 lbs per $inch^6$. The loading, deflections, and Young's modulus measured during the test are found in table 1-2. What is of interest about this test is that the beam did not fail by bending but rather through shear failure. The beam failed began to fail by shear at 1340 lbs. That loading created a bending stress of 3313 psi and a shear stress of 16 psi. These results are found at table 1-3.

Figure 1-1 Creative Pultrusions Bending Test configuration with failed sample

Table 1-1 Creative Pultrusions Bending test specimen details.

Part Id:	PA535
Description:	Transonite Panel 3.5" thick 3/16" Face

Date Produced:	n/a
Direction Tested:	Crosswise
Footprint size:	1" Full Panel Width
Span (inches):	70
Thickness (inches):	3.50
Width (inches):	12
Skin Thickness (in):	0.188
Moment of Inertia:	12.387
Sheet:	1 of 5

Table 1-2 Creative Pultrusions Bending Test Data

Sample #1	PA535	
Date Tested:	9/26/2012	
Load	Deflection	Modulus of Elasticity
505	0.521	5.6E+05
1005	1.057	5.5E+05
1505	1.954	4.4E+05
1995	5.394	2.1E+05
Foam Shear Failure began at 1340lb		

Table 1-3 Creative Pultrusions Bending test Results

Failure Load:	1340	Lb
Flexural Stress	3313	Psi
Shear Stress	16	Psi

1.2.2 Shear

Under horizontal loading on the competition house, it was assumed in the design phase that, the panel walls would act as shear walls and resist the horizontal shear. Creative Pultrusions, Inc performed a short beam 3 point bending test to determine the shear strength of the panel; the configuration is shown in figure 1-2. The sample was 1 foot wide, and the support span was not given. The sample details provided by Creative Pultrusions, Inc. are found in Table 1-4

Using equation 1-3:

$$\tau = \frac{P}{2tw}$$

Creative Pultrusions determined the shear strength. After 3 samples (data found in Table 1-5) the average shear strength was 22 psi. Of significant note is that the note for this test which says "Load recorded at first significant crack of foam." In the results section, it will be shown that the testing at WPI determined that the cracking of the foam was not indicative of structural failure or of local failure.

Figure 1-2 Creative Pultrusions Shear Test

Table 1-4Creative Pultrusions Shear Test detials

Date Manufactured:		**Panel Thickness (in):**	**3.5**
Date Tested:	See Below	**Specimen Width (in):**	**12**
Tested By:			
Construction:	Ref: Spec. Sheet		

Table 1-5 Creative Pultrusions Shear Test Data and Results

Crosswise			
Sample #	**Date Tested**	**Ultimate Load (lbs)**	**Shear Stress (psi)**
1	**9/26/2012**	**1,795**	**21.37**
2	**9/26/2012**	**1,710**	**20.36**
3	**9/26/2012**	**2,140**	**25.48**
		STDEV =	**3**

		Average =	**22**
		COV % =	**12.10%**

1.2.3 Pin Bearing

The competition house is held together with bolts, so the bearing strength of the panels is necessary to establish the strength of the connections. The details of Creative Pultrusions test setup were not given to us, but the configuration shown in figure 1-3 shows a panel sample (3.75” by 3.75”) with a rod (diameter 9/16”) and they applied a force downwards into the panel.

Using equation 1-4 below, Creative Pultrusions measured the bearing strength of the panel. The bearing strength comes from the strength of the skin, so the thickness used the skin thickness, not the panel thickness.

$$\sigma = \frac{P}{2td}$$

The average bearing strength was 9872 psi, shown in table 1-7. The failed samples are shown in figure 1-4..

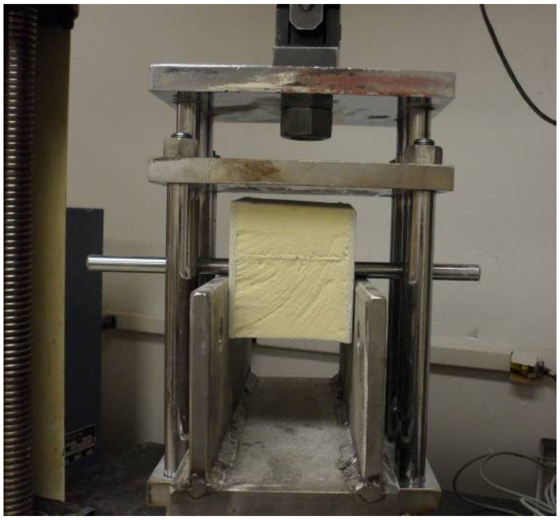


Figure 1-3 Creative Pltrusions Pin Bearing test configuration

Table 1-6 Creative Pultrusions Pin Bearing test Details

Specimen Size (in)	3.75" x 3.75" square

Hole Diameter (in)	9/16
Pin Diameter (in)	0.5
Laminate Thickness (in)	0.1875
Load Direction	Machine Direction

Table 1-7 Creative Pultrusions Pin Bearing Data and Results

Sample	Load (lbs)	Bearing Stress (psi)
1	1890	10080
2	1812	9664
3	1880	10027
	Average (psi)	**9872**
	STD DEV	**294**
	3X STD DEV	**882**
	3 std-mean	**8990**
	COV	**3%**

Figure 1-4 Creative Pultrusions Pin Bearing Failed Test Samples

1.2.4 In-Plane Compression

The in-plane compression is the type of compression that the walls of the competition house will experience. Creative Pultrusions applied a uniform loading a panel sample such that the interface consisted of the 2 panel skins and the foam core, as per ASTM C365, as shown in figure 1-5.

Using equation 1-5, Creative Pultrusions determined the Compressive strength of the 3” x 3” x 1” panel (table 1-8), again the strength of the materials is considered to be the skin, so thickness means skin thickness:

$$\sigma = \frac{P}{2tw}$$

The average strength of the material was determined to be 6667 psi (table 1-9). Creative Pultrusions noted “Typical failure was the result of interlaminar buckling of the facesheet, and typically occurred near the endcut of the sample. “ Because of the slimness of the material and the panel skin, the panel actually failed thru buckling even though the samples were so short. But using Equation 1-6 for buckling (Euler buckling equation), indicates that the skin should buckle at 633450 lbs at a length of 3 inches, not the 3052 lbs that it failed at (if pin boundaries are assumed).

$$P = \frac{\pi^2 EI}{L^2}$$

Table 1-8 Creative Pultrusions In Plane Compression test detials

Specimen Length (in)	3
Specimen Width (in)	1
Facesheet Thickness (in)	0.1875
Load Direction	Machine Direction

Table 1-9 Creative Pultrusions inPlane Compression test Data and Results

Trial Number	Load (lbs)	Compression strength (psi)
1	1920	5120
2	3052	8139
3	2528	6741
	Average (psi)	**6667**
	STD DEV	**1511**
	3X STD DEV	**4532**
	3 std-mean	**2135**
	COV	**23%**

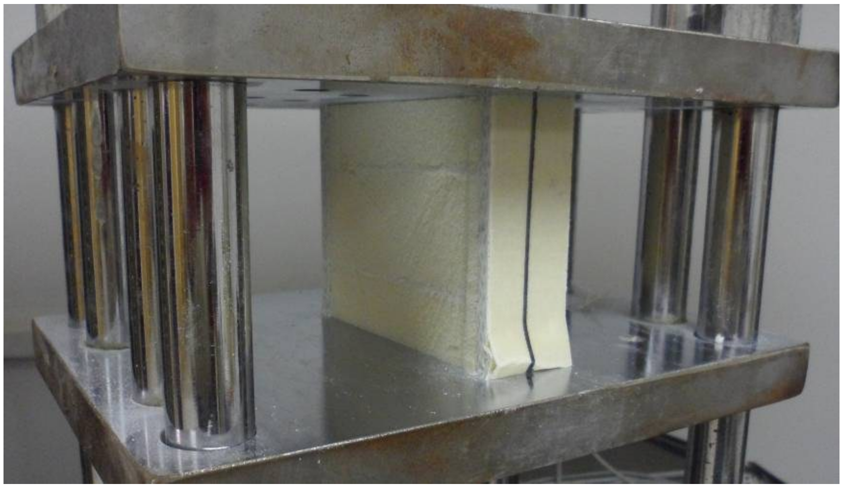


Figure 1-5 Creative Pultrusions InPlane Compression configuration and failed test specimen

1.2.5 6" Footprint

The roof is supported by 3"x3" columns and the panels must be strong enough to resist the column pushing thru the panel. Creative Pultrusions performed a 6"x 6" footprint as shown in figure 1-6.

Using Equation 1-7, Creative Pultrusions determined what the Compressive strength in this loading direction. The area in this formula is the area of the 6" by 6" plate.

$$\sigma = \frac{P}{A}$$

The average strength determined was 236 psi, in table 1-11. Since the actual loading area in the structure is one quarter of the testing area, the max loading is one quarter of the loading in the test, about 2000 pounds.

Table 1-10 Creative Pultrusions 6" footprint test Details

Specimen Size	12" x 12"
Footprint Size	6" x 6"
Compression Area (in^2)	36

Table 1-11 Creative Pultrusions 6" footprint test Data and results

Trial Number	Load (lbs)	Compression strength (psi)
1	8135	226

2	8640	240
3	8720	242
	Average (psi)	**236**
	STD DEV	**9**
	3X STD DEV	**26**
	3 std-mean	**210**
	COV	**4%**

Figure 1-6 Creative Pultrusions 6" footprint configuration and Failed Sample

1.2.6 Edge Loading

If the panels are eccentrically loaded, most or all of the loads may go through only one skin. Creative Pultrusions put on concentrated load on one skin of the panel system as shown in figure 1-7.

No calculations were done for this test. Only the max concentrated loading given in the table 1-13. The average max loading is 1078 lbs. The table 1-13 from Creative Pultrusions erroneous marks it as psi, when it is actually pounds. The failure method for this test was the skin beginning to separate from itself. This means the design of the competition house needs to avoid concentrated loads of about 1000 lbs on the end of the skin of the panel system.

Table 1-12 Creative Pultrusions Edge Loading Details

Specimen Size (in):	3" Width
Flange Length (in):	1.75
Load width (in):	0.75"

Table 1-13 CREATIVE PULTRUSIONS EDGE LOADING Data and results

Trial Number	Load (lbs)

1	1087
2	785
3	1190
4	1251
Average (psi)	**1078**
STD DEV	**207**
3X STD DEV	**621**
3 std-mean	**458**
COV	**19%**

Figure 1-7 Creative Pultrusions Edge Loading configuration

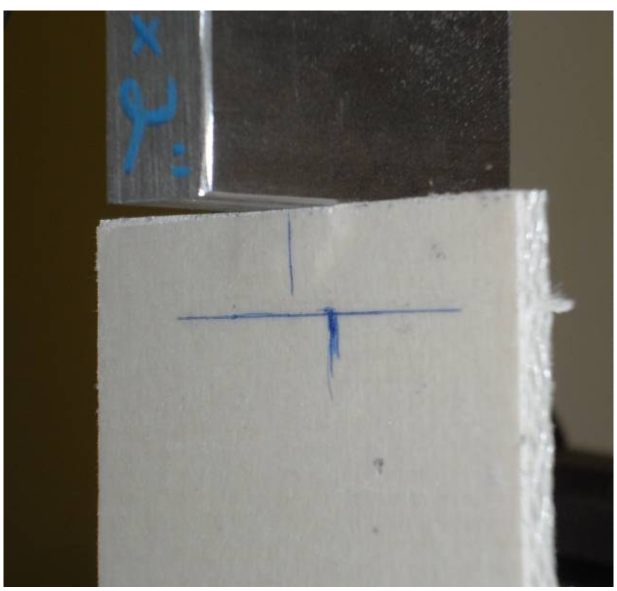


Figure 1-8 CREATIVE PULTRUSIONS EDGE LOADING failed sample

1.2.7 Coupons Testing

In addition to all the testing listed above, Creative Pultrusions performed standard ASTM testing. The results of which are found in table 1-14. No more information about this testing was received. The results of all the testing in this table indicate that the panel's mechanical properties are almost isotropic. The cross and lengthwise results are within a percent difference of 10%, with the exception of the tensile modulus and In-Plane shear, as seen in table 1-15.

Table 1-14 Creative Pultrusions ASTM mechinal properties testing results

	ASTM	Results	
Mechanical Properties	Test	Average	Units
Tensile Strength Lengthwise	D638	24,468	psi
Tensile Modulus Lengthwise	D638	2.82E+06	psi
Tensile Strength Crosswise	D638	22,073	psi
Tensile Modulus Crosswise	D638	2.38E+06	psi
Compressive Strength Lengthwise	D695	8,611	psi
Compressive Modulus Lengthwise	D695	2.97E+06	psi
Compressive Strength Crosswise	D695	8,605	psi
Compressive Modulus Crosswise	D695	3.21E+06	psi
Interlaminar Shear Lengthwise	D2344	2,095	psi
Interlaminar Shear Crosswise	D2344	1,956	psi
In-Plane Shear Lengthwise	D5379	5,056	psi
In-Plane Shear Crosswise	D5379	3,650	psi

Table 1-15 Percent differences between the Crosswise and Lengthwise test results for the mechincal properties of the Transonite Panels

	% difference in crosswise and lengthwise results
Tensile Strength	9.79
Tensile Modulus	15.46
Compressive Strength	0.07
Compressive Modulus	-7.97
Interlaminar Shear	6.63
In-Plane Shear	27.81

The In-Plane Shear results of a 5056 psi lengthwise and 3650 psi crosswise indicate that the panels are much stronger in shear than the Creative Pultrusions Bending and shear tests indicated (16 psi and 22 psi respectively). In the competition house, the panels while generally be under In-Plane shear from the seismic and wind loadings. The out of plane shear only becomes a structural issue at deflections past the allowable deflections, so the in-Plane resistance becomes the critical shear strength in the current design of the competition house.

1.3 Methodology

This section will relay the reasons for additional testing, the procedures for that additional testing, and the excepted results. One of the most important differences between this set of testing and the Creative Pultrusions testing, is that in this testing, the tests continues past the first appearance of shear cracks in the foams.

1.3.1 Reasons for Additional Testing

After a review of the Creative Pultrusions testing, the behavior of the Transonite Panel was not fully understand, especially its compression, bending, and buckling behaviors. The need to better understand the behavior of this materials is twofold; to determine if the computer model of the structure was correctly simulating its behavior, and supply the graduate students with more data for their thesis on computer modeling.

The shear failure during the bending test indicated that the results from the bending test were not the true flexure strength of the material.

1.3.2 Compression testing

The compression test done by Creative Pultrusions failed thru buckling at a loading that could not be explained by the Euler buckling equation (equation 1-6), so a different in-plane compression test following the ASTM testing procedure . ASTM 364/C364M calls for the testing samples to have a face of 7”x 7” instead of the 3” x 1” used by Creative Pultrusions. The sample is then placed in a compression testing machine that measures deflection and the force applied to the sample. Originally there was a fear of the glass fibers getting into the air during testing so for the first 2 tests a plastic covering was placed on the samples to contain any airborne debris. After the first two tests, it became clear that the fear was unfounded and no more of the test samples were covered by plastic.

Using equation 1-5 again, the compressive strength of the material is determined:

$$\sigma = \frac{P}{2tw}$$

By rearranging equation 1-5 and assuming the sample will behave similarly to the Creative Pultrusion test, we can estimate the excepted failure loading of the compression test using this equation 1-8

$$P = 2\sigma tw$$

The excepted failure load is 17,501 lbs.

Using Euler's buckling equation (1-6) we can also estimate what the fail loading will be thru buckling. The Euler buckling loading of the sample should be 814,440 lbs. It is very import to note that the Creative Pultrusions sample did not conform to Euler buckling behavior.

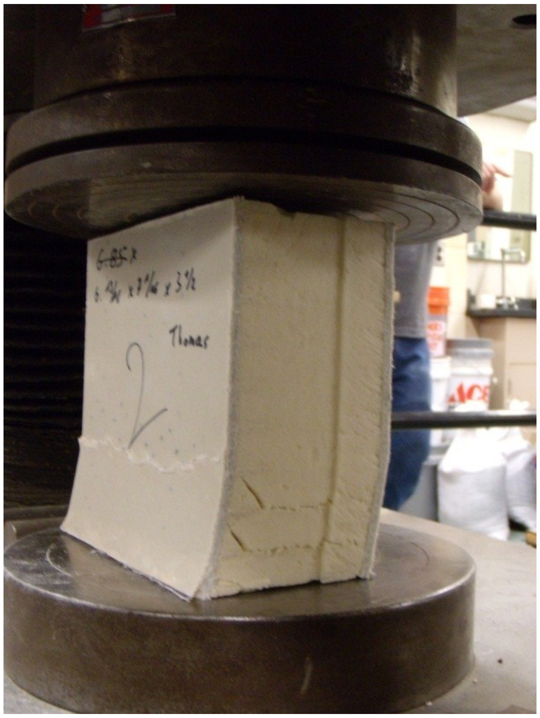


Figure 1-9 Compression test configuration with failed sample

1.3.3 Short bending

The short bending test consists of 8" samples with a 7" support span consistent with ASTM D7250/D7250M, which is a testing procedure specifically for sandwich panel materials. The samples were 3" wide. The shortness of the beam should force the panel to fail through shear. There were 3 samples, and each sample underwent both 3 point bending and 4 point bending tests.

1.3.3.1 3 point bending

Creative Pultrusions performed 3 point bending tests so 3 point bending tests were done so a direct comparison between the results of both could be made. The support span for the 3 point bending was 7" and the contact point for the loading was places directly at mid-span. This configuration is shown in

Figure 1-10 short Beam testing configuration with sample under loading

figure 1-9.

Reordering equation 1-3 into equation 1-9, the excepted failure load can be determined.

$$P = 2\tau t w$$

The estimated failure load is 1848 lbs.

1.3.3.2 4 point bending

4 point bending tests were performed because the additional loading point spreads the shear between the contact points. The support span is again 7" and the contact points for the loading are 4" apart. This configuration is shown in figure 1-10.

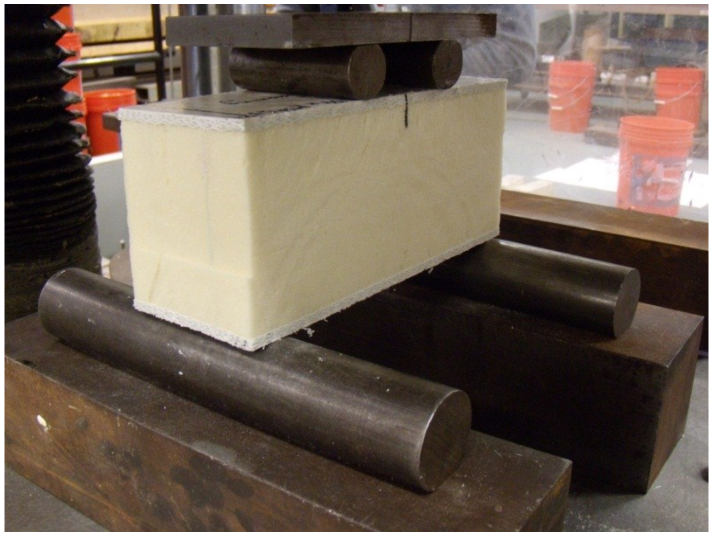


Figure 1-11 Short Beam 4 point bending test Configuration

Since the loading i[illegible] changes to equation 1-11

$$P = 4\tau t w$$

The estimated shear failure load is now 3696 lbs.

1.3.4 Long bending

The long bending test consists of 24” samples with a support span of 22” consistent with ASTM D7249/D7249M, which (Like ASTM D7250/D7250M) is a procedure specially for sandwich panels. The samples were 3” wide. The length of the beam should make it easier for the beam to fail through bending. There were 3 samples, and each sample underwent both 3 point bending and 4 point bending tests.

1.3.4.1 3 Point bending

Creative Pultrusions performed 3 point bending tests so 3 point bending tests were done so a direct comparison between the results of both could be made. The support span for the 3 point bending was 22” and the contact point for the loading was places directly at mid-span. This configuration is shown in figure 1-11

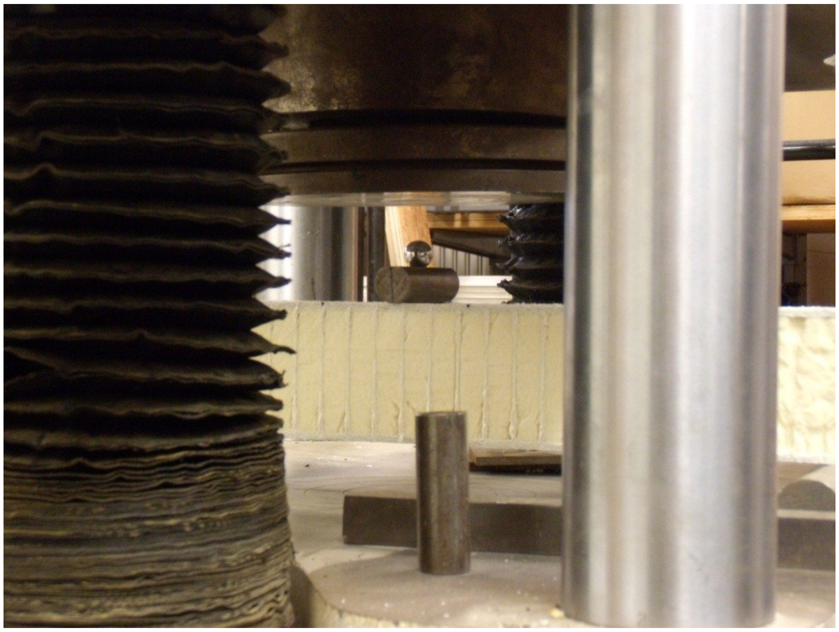


Figure 1-12 Long Beam 3 point bending test configuration

Reordering equation 1-3 into equation 1-9, the excepted failure load can be determined.

$$P = \frac{\frac{4\sigma I}{Lt}}{2}$$

The estimated failure load is 1065.9lbs.

This test was also necessary for the calculations to

1.3.4.2 4 Point Bending

4 point bending tests were performed because the additional loading point spreads the shear between the contact points. The support span is again 22” and the contact points for the loading are 4” apart. This configuration is shown in figure 1-12. The expected loading was determined by the equation where S_l is the span of the loading.

$$P = \frac{4wt^2\sigma}{3(L - S_l)}$$

The max expected loading is 26 lbs from this equation for the max bending stress given by Creative Pultrusions.

1.3.5 Buckling

The buckling test is the test that is most directly related to the competition house. There are no easily available references to how a FRP sandwich panel wall should behave under in-plane vertical loading. This test is the only test performed that does not have a ASTM standard attached to it. The test was conceived to be as close to the actual conditions of the building as possible. There was one sample of 54” in height and 14” wide. The width of 14” was selected to insure that the panel would resist buckling along one axis just as it would if it was a full size wall. The height is the largest size the testing equipment could fit. A wooden frame was created to hold the bottom of the sample and prevent the sample was sliding out of place.

There are no pictures of the buckling test in the report at this time because the student that documented this test has not uploaded the pictures the community file share.

Using Equation 1-6, the estimated failure load was determined.

$$P = \frac{\pi^2 EI}{L^2}$$

The estimated failure load is 27,371 lbs, assumed the boundary conditions are pin connected.

1.4 Results

One of the most important results of the testing was common across all the bending tests. After the loading was removed from each test, the panel beam deformation was almost completely elastic. Figure 1-12 shows a long beam under loading, and Figure 1-13 shows the same beam after the loading is removed. You can see where the foam was cracked from the shear effects of the bending, but there is no permanent deformation of the curvature of that beam.

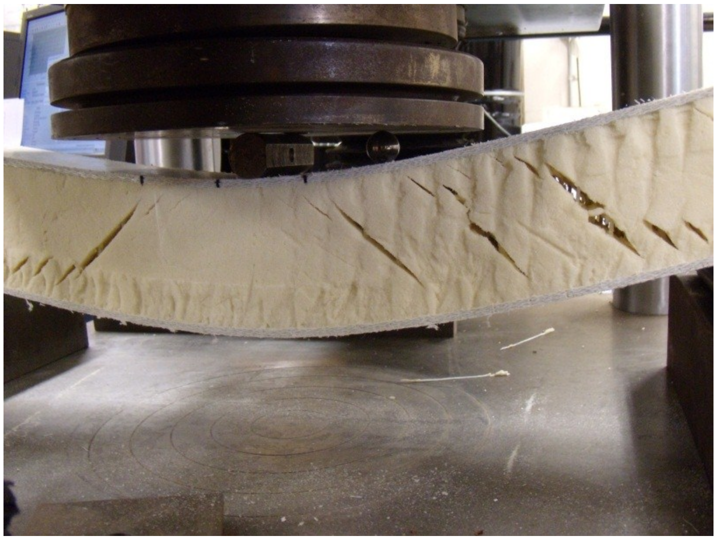


Figure 1-13 Long bending 3 point under loading.

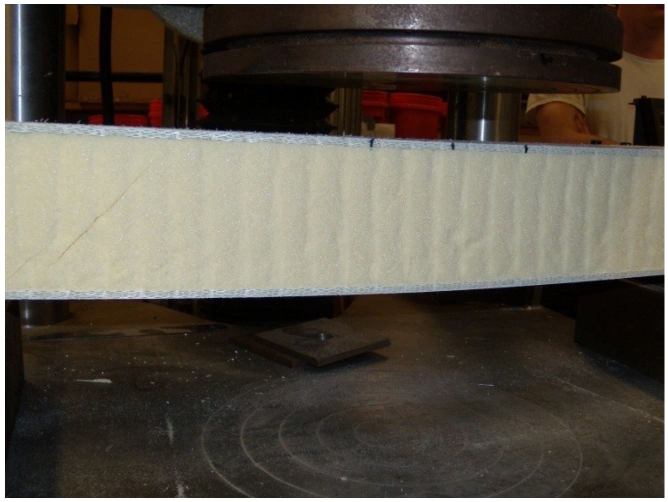


Figure 1-14 Long Beam after undergoing 3 point bending

Also, as you can see in Figure 1-12, the foam core cracks along the shear lines caused by bending, but through the cracks the glass fibers holding the skins together. There was no visible failure of the inner glass fibers.

1.4.1 Short Bending

The loadings in these beams were attempted to take to failure, but the first test sample dislodged from the testing apparatus so testing was continued to the point before the the sample would slip instead of failure

1.4.1.1 3 point Bending

We got a max load of 1042 lbs which is much lower than the expected 1848lbs

1.4.1.2 4 Point Bending

We got a max loading of 411, which was both lower than the excepted results of 3696, and the 3 point bending loading, which was against expectations.

1.4.2 Long Bending

The deflections of the long bending tests was so large that eventually the contact plate seen in figure 1-13, started to contact the beam in addition to the contact point. When that occur the testing was stopped.

1.4.2.1 3 point Bending

The max loading for long beam 3 point bending was 547 lbs, which was about half of the expected loading of 1065.9lbs. the stress given by this loading was 91.4 psi.

1.4.2.2 4 Point Bending

The max loading for 4 point bending was 570 lbs is much higher than the estimated 26 lbs. When the equation that estimated a loading of 26 lbs is reconfigured to determine the stress of panel, the stress for the loading of 547 is 772,000 psi which is much higher than the 3313 psi given by the Creative Pultrusions testing.

1.4.3 Compression

The compression samples failed in two ways; the skin starts to delaminate, and the skin buckles near the end cut, just as the Creative Pultrusions testing suggested. Figure 1-9 in methodology shows the buckling cracks the skin. Table 1-16 shows that the failure accorded at a load that was on average 60% of the excepted failure load by compression.

Table 1-16 Max loadings and Stress in compression testing

Sample	Max Load (lbs)	Max Stress (psi)
1	9358	3555
2	10824	4054
3	11663	4430
4	9241	3506
5	11323	4302
Avg	10481.8	3969.4

Figure 1-15 shows the stress versus strain graph of one of the samples. It shows that the stress vs strain relationship is bimodal. All 5 samples exhibited localized fails that temporally decreased the loading capacity of the sample, then reached a high point after at least one localized failure. Also shear built up in the foam, and cracked the foam core, as seen in figure 1-17

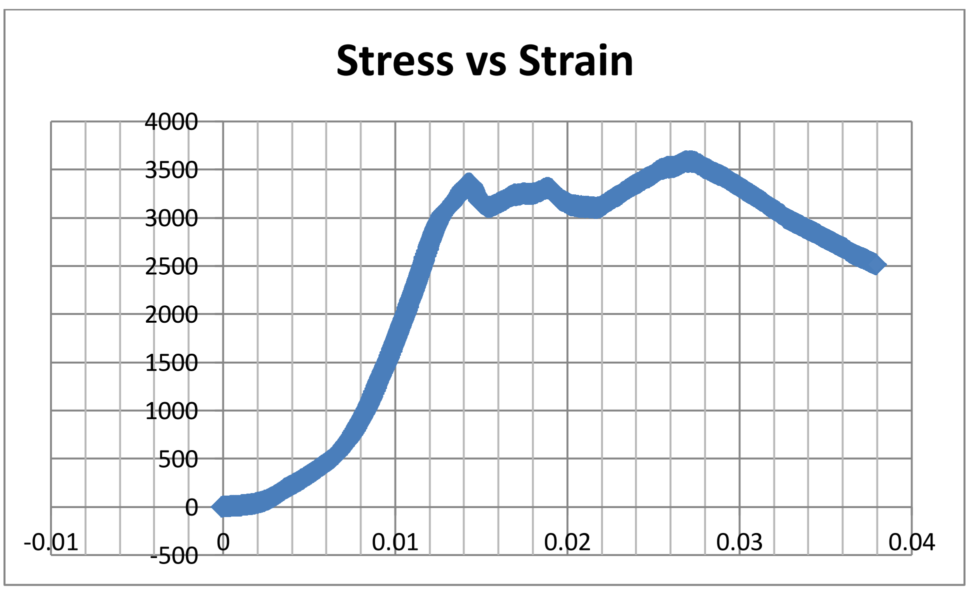


Figure 1-15 Stress vs. Strain graph for sample 1

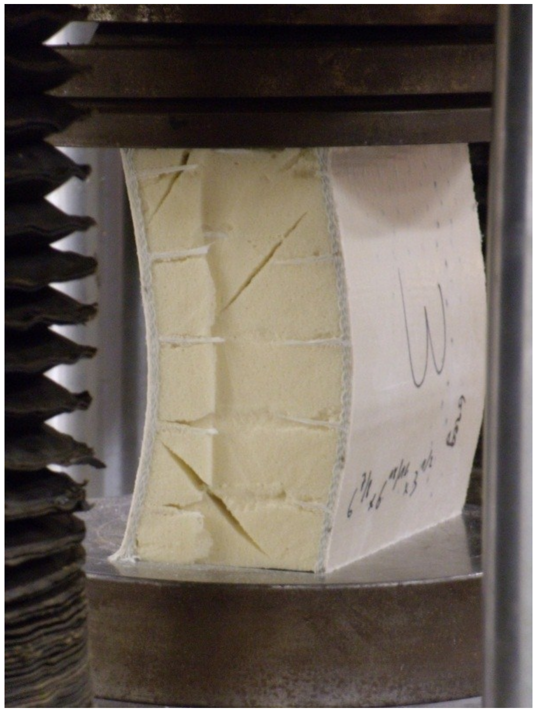


Figure 1-16 Compression tesing sample under loading showing the shear cracking of the foam.

1.4.4 Buckling

The buckling test had the same failure mechanism as the compression testing, namely buckling near the end cut. 2 tests with the same sample were performed but the program recording the loading and deflection failed to record the second test. The second test had a max loading of 18 kips but there is no record of the loading curves of this test A third test was then performed with a shorter sample if 44" left over preparing the samples. The Euler buckling load of the shorter sample is 41,227 lbs. The max loadings are found in Table 1-17.

Table 1-17Max Loadings of samples in Buckling testing

Sample	Max Loading (kips)
1	14.627
2	~18
3 (44" sample)	16

These loads are respectively 13,000 lbs, 9000lbs, and 25,000 lbs less than the estimated Euler buckling loads. Also of note is the fact that the buckling happens near the end cut of each sample, seems to imply that the deflection curve of the panel does not conform to the deflection excepted in materials that conform to Euler buckling.

1.5 Conclusion

The Transonite panels are extremely elastic, after removing the loading from each bending test; the tested beams were virtually the same curvature as the untested beams. The cracking of the foam did not seem to effect the strength of material, though there was some sort of localized failure in the structure after some point. The mechanism of this localized failure was not determined, but during the bending tests, some of the exposed and weakened glass fiber threads failed at their connection with the skin of the panel as shown in figure 1-17. One theory set forth was that the connections of the glass fibers were failing, but the foam within the panel prevented an evaluation of the central glass fibers. The bending tests gave confusing results. One gave a bending stress of less than the Creative Pultrusions testing and another gave a higher stress. More testing needs to be done.

Figure 1-17 a failed connection point of the glass fibers and the FRP skin

Also the buckling tests show that the panels do not follow Euler buckling behavior. This will make it difficult to accurately model how much loading that the walls will be able to hold, though the tests show that the loading will be on the magnitude of about 10 kips of force.

Also the compression testing was unable to get a similar compressive strength to the Creative Pultrusions testing. More testing should be done to attempt to get more consistent compressive strength of the material.