

BUILDING THERMAL EFFICIENCY
PROJECT ID: CEEN_CPST_014

by

J & C Engineering
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A Capstone Project Final Report

Submitted to

Andrew South
Brigham Young University

Department of Civil and Construction Engineering
Brigham Young University

April 19, 2023

Executive Summary

PROJECT TITLE: BUILDING THERMAL EFFICIENCY
PROJECT ID: CEEEn_CPST_014
PROJECT SPONSOR: Andrew South
TEAM NAME: J&C Engineering

The objective of this project was to conduct thermal performance modeling and dynamic energy consumption forecasting on a monolithic concrete dome structure of a defined size and shape. The model results were compared with the results of a “traditional building envelope” by installing sensors in a test structure and analyzing its thermal performance. These results assisted in determining how to accurately model thermal efficiency of monolithic concrete domes in order to predict their efficiency and sustainability.

A model was produced using SolidWorks modeling software and Simscale thermal analysis software. This model was accurate (within one standard deviation) in comparison to the information recorded by the sensors in and around the structure. This model is replicable, and the processes contained herein may be used to perform similar analysis on complex structures of similar material composition. Because Simscale is initially a free software and BYU owns a comprehensive license for Solidworks, there were no costs required to create the model or perform the thermal analysis. The only cost associated with the project was the cost to purchase the sensors installed in the concrete; this amount was not disclosed to us as the purchasing and installation were performed by the Solar Decathlon team.

When constructed for humanitarian efforts, these concrete domes can greatly impact the cultures and landscapes of foreign countries. Because they are relatively cheap to construct, durable, and thermally efficient, they can provide safe shelters and places of gathering for communities at a low cost to the residents. The concrete domes

are environmentally sustainable and, while they require carbon emitting materials at the time of construction, they last far longer than similar structures of other materials. Additionally, their increased thermal efficiency requires less carbon emissions to heat and cool the building. This thermal efficiency also makes the structure a more economic home for consumers to maintain throughout the years. We recommend that these structures continue to be built and that further thermal studies are performed to better understand their long-term sustainability.

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Introduction

Monolithic concrete domes are a relatively new technology that is becoming more popular, especially among homeowners. Dome structures have been built for centuries, and many are still around today. Dr. Andrew South and his partners at the Monolithic Dome Institute have revolutionized a methodology for building domes that rival anything that has been done in the past. The domes are more efficient than traditional wood framed homes in several aspects including cost, durability, and lifespan (Hamed 2011). In this project specifically analyzed the thermal efficiency of a monolithic concrete dome constructed by the solar decathlon team. The dome was made with a PVC coated nylon that was blown up and then sprayed with a three-inch layer of reinforced concrete and a three-inch layer of polyurethane foam insulation.

In this project, our goal was to conduct thermal performance modeling and dynamic energy consumption forecasting on a monolithic concrete dome structure of a defined size and shape. We compared the results of these models with the results of a “traditional building envelope” by installing sensors in the test structures that the BYU Sustainability Decathlon team built in Fall 2022 and analyzing its thermal performance. These results assisted in determining how to accurately model thermal efficiency of monolithic concrete domes in order to predict their efficiency and sustainability.

The biggest limitation to this project was knowledge. We had relatively zero knowledge of thermal modeling and heat transfer and so much of our time was spent learning all we could about it. This included gathering knowledge about the topic in general and looking at potential software and testing it. Another limitation was our model and the software itself. We tried to remain as true to the structure as we could, but the thermal modeling software we were using struggled handling such a complex structure. We had to find ways to overcome those obstacles.

Schedule

17 November 2022 – Begin research of possible analysis software suited for heat transfer thermal study with appropriate construction materials.

13 January 2023 – Modeling software selected and downloaded.

14 February 2023 – Concrete dome building completed, thermal sensors to be installed.

02 March 2023 – Data from thermal sensors collected and organized.

17 March 2023 – Model completed in Rhino3D.

20 March 2023 – Thermal efficiency analysis unsuccessfully performed in SimScale using model created in Rhino3D due to discontinuities in mesh because of incompatibilities between file type and SimScale.

31 March 2023 – Created a simplified model in Solidworks .

03 April 2023 – Thermal efficiency analysis successfully performed in SimScale using simplified model created in Solidworks.

05 April 2023 – Poster finished and submitted to be printed.

Design, Analysis & Results

The first step in creating a thermal analysis of the monolithic dome was to create a virtual model using the specifications provided by our sponsor. This information was contained in a three-dimensional Revit file that other teams used for this structure. We used these specifications to create our three-dimensional models in two different modeling software: Rhino 3D and Solidworks.

First, we began working in Rhino 3D with hopes to output a clean mesh to use in a thermal analysis software. We started trying to make our own model using the information we had. Relatively quickly, however, we discovered that a Rhino model had already been created by another team for a structural analysis of the concrete dome. After getting in contact with them, we received a few versions of the Rhino file to use for our own analysis.

We ran into many problems with these Rhino files. A smooth mesh was not easily created from the files we received, and much time was spent trying to unite edges and make it all continuous. The thermal analysis software SimScale would not run anything without having a clean input mesh. So, our plan was to make a mesh, run it through the software, and see if it was valid or not. Unfortunately, even once we obtained a clean mesh in Rhino, the thermal analysis software couldn't interpret the data file into something it could work with. We tried exporting various filetypes (.step, .3dh, etc.), but to no avail. Fortunately, we had more luck with the other 3D modeling software.

When starting to work in Solidworks, we spent a substantial amount of time learning how the program works and creating a simple geometric layout of the concrete domes. Once a two-dimensional model was created, we extruded the element to create a three-dimensional model and created a hollow shell with varying thicknesses to represent the dimensions of the polyurethan foam and concrete layer as specified by the architectural drawings created by the Solar Decathlon team.

After assigning each layer the appropriate material and their associated thermal properties, we downloaded the model as an .sldprt file and imported it to SimScale to run the heat transfer analysis. However, our analysis was unsuccessful because the software treated the entire body as one solid with a uniform temperature throughout its thickness. In order to fix this, we decided to modify the model so it would be composed of three distinct solid bodies, with the innermost solid defined as "air" material, accompanied by its correct thermal properties. After implementing these changes, we ran the heat transfer analysis in SimScale and successfully obtained varying thermal values at different depths inside of the dome, as well as at different points in each material (see Figure 1).

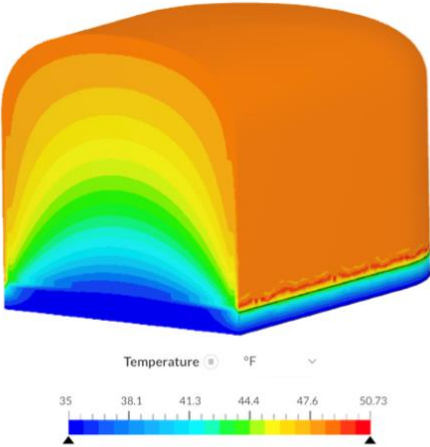


Figure 1. SimScale Simulation Results

While we were creating our model of the dome, we were able to successfully record the temperature information from the embedded sensors in collaboration with the other groups analyzing the domes. We collected data for each of the eight sensors for the days of February 7, 9, 11, 13, 15, 17, 19, 21, 23, and 25. We also collected data for the days of March 14,15, 16, and 17 (see Table 1 & Figure 2).

Sensor	Daily Averages										
	9-Feb	12-Feb	14-Feb	15-Feb	17-Feb	21-Feb	24-Feb	14-Mar	15-Mar	16-Mar	17-Mar
TC1	55.1	49.3	53.2	54.0	54.5	58.7	56.4	56.8	57.4	54.7	69.0
TC2	52.6	48.1	51.4	52.5	54.6	58.7	56.8	56.8	52.8	45.5	51.1
TC3	40.4	40.6	40.6	40.7	40.3	42.2	40.6	56.8	44.8	44.1	43.8
TC4	58.0	48.9	56.9	57.2	57.7	61.9	60.8	56.8	57.4	51.1	62.3
TC5	31.1	33.6	34.6	23.9	43.0	43.0	43.0	56.8	43.1	35.7	34.7
TC6	48.8	48.7	48.4	48.5	48.7	48.9	48.6	56.8	49.2	48.9	48.7
TC7	34.5	35.9	36.2	32.9	33.8	36.9	34.2	56.8	43.8	37.7	42.0
TC8	49.9	47.1	50.5	49.9	49.6	54.4	60.7	56.8	52.7	48.8	55.7

Table 1. Daily Average Temperature, °F

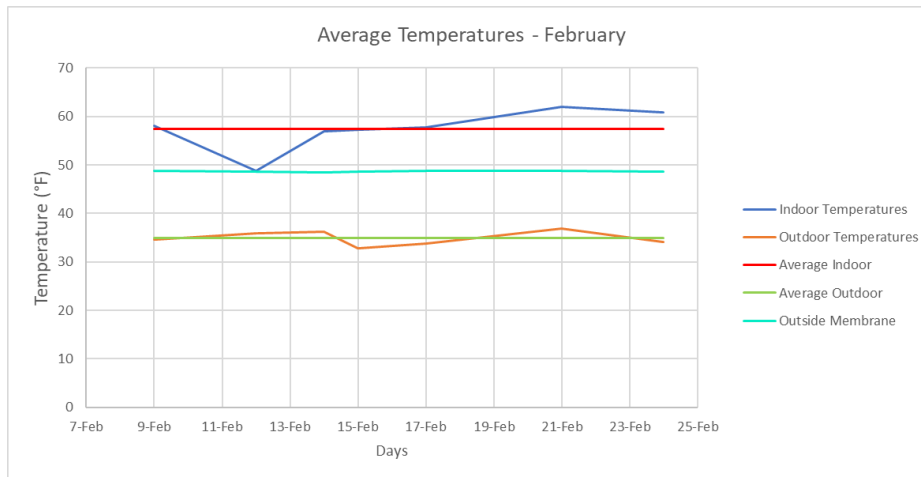


Figure 2. Average Temperatures in February

We used the data shown above in our heat transfer analysis to directly compare our results with those recorded by the sensors. Table 2 indicates the average temperature values of the data we collected from the sensors and used in our thermal study.

Outside Ground Temperature (°F)	34.9
Outside Membrane (°F)	48.7
Outside air (°F)	36.0
Inside concrete surface average (°F)	51.7

Table 2. Overall Average Temperature, °F

Through a series of heat transfer simulations in SimScale, we found that our model produced results well within one standard deviation of the recorded data specified in Table 2. The outside edge of the concrete dome was measured to be between 47.6 and 50.7 °F. As expected, the average value we found for the outside edge of the dome in our model was 48.6 °F. Similarly, we found that the temperature varied depending on the

precise location of interest. Table 3 specifies the location of each sensor used on the actual domes and Figure 3 shows the temperature variation by embedded sensor.

Sensor	Location
TC1	Roof, in between concrete and insulation
TC2	Side, in between concrete and insulation
TC3	On insulation under the wood floor
TC4	Roof inside concrete surface
TC5	Outside of dome – side
TC6	Outside membrane
TC7	In the ground – asphalt outside
TC8	Side, inside concrete surface

Table 3. Embedded Sensor locations

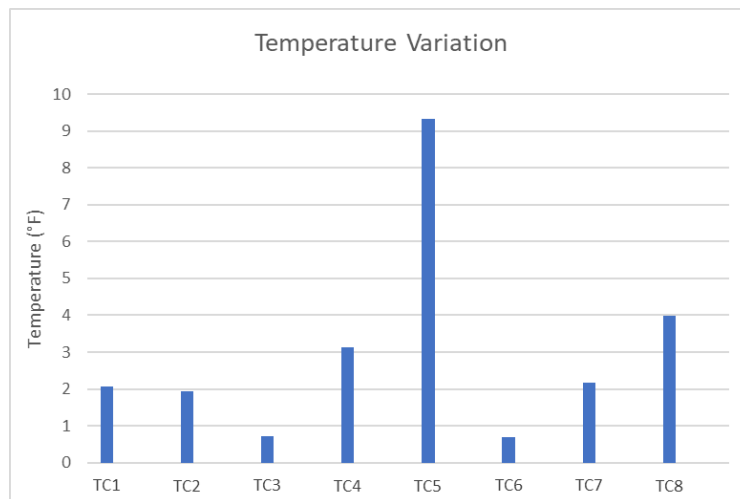


Figure 3. Average Temperature Variation by Sensor.

As shown above, the temperature decreased further inside the dome, with the minimum temperature occurring closest to the ground. This is very similar to the results we obtained as shown in Figure 1. We also observed that the polyurethane foam provided greater insulation than the 3” concrete layer. Although this is what we expected, the

concrete performed surprisingly well as a barrier to the more extreme temperature of the air outside of the dome.

Related Issues

While this project focused on assessing the thermal efficiency of monolithic concrete domes for future purposes, these structures have already been proven to have a significant impact on a myriad of issues, several of which are described below.

Cultural & Social Impacts

Building these domes can drastically impact various cultures and societies by changing the landscape of the communities in which they are built. Their unique architectural style invites a new feeling and attitude towards built infrastructure as it changes the landscape and adds to the cultural diversity of a community; subdivisions built in rural areas in Southeast Asia have already demonstrated that monolithic domes bring changes to cultural identity. Used mostly for personal dwellings in this instance, the monolithic dome became a template for other types of infrastructure such as libraries and civic centers. Consequently, there is an increase in access to resources and education acquisition that can benefit those involved and allow them to gain the required skills to improve their livelihood. Furthermore, monolithic dome construction can be a community-based endeavor as it brings people together to build the structures. As a result, this can foster a sense of community and shared ownership, which promotes a culture of collaboration, interdependency, and social development. Due to monolithic domes extreme durability, they can promote a culture of safety and preparedness, especially among those most susceptible to natural disasters such as hurricanes, earthquakes, and tornadoes.

Environmental and Sustainability Impacts

There are several potential environmental and sustainability impacts that monolithic domes can have on communities. This project demonstrated that these

structures exhibit high thermal efficiency and can maintain ambient air temperature without additional heating or cooling sources. This means that they require less energy to regulate air temperature, leading to less energy consumption and reduced carbon emissions. Although the dome itself is made from materials that required much energy consumption during fabrication, their durability and lifespan provide impressive sustainability in the long term. Steel, concrete, and foam insulation have a very long lifespan, and can all be recycled or reused, making them excellent materials to invest in; their durability also means that there is less need for repairs or replacement. Concrete is one of the world's greatest sources of carbon emissions which is terrible for our planet. But, because reinforced concrete is so strong, it can last for much longer than traditional light frame structures. This means that even though monolithic concrete domes have a greater initial carbon footprint than light frame structures, that footprint is offset because they can stick around for longer time. Also, because they require less maintenance than typical light frame structures, they have less carbon emissions after they are built. Overall, monolithic concrete domes can be extremely sustainable because of how durable they are, how well they perform, and how well they conserve energy.

Economic Impacts

In addition, the construction of these monolithic domes also provides significant economic benefit. As mentioned previously, their thermal efficiency allows its users to minimize their energy consumption and, as a result, lowers utility costs over time. Their durability requires less need for repairs, which makes their construction more affordable over its long lifespan. Due to the simplicity of their construction, monolithic domes are a cost-effective alternative to traditional building methods as they require less material and minimal labor. Because of its shape, significantly less concrete needs to be used in monolithic concrete domes than in CMU or ICF construction. Because of the minimal amount of material that is required in monolithic concrete domes, they are even more

cost effective than wood framed homes. It is estimated that the monolithic concrete domes are around 50% the cost of a traditional wood framed home of the same size.

In addition to the amount of material benefitting the cost of a monolithic concrete dome, other factors include labor and time. Much of the cost of a wood framed home is attributed to labor. The average time to construct a simple wood framed home is around seven months. The average time to construct a simple monolithic dome is around two to three months. Because they take much less time to build, monolithic concrete domes require less labor and, therefore, less money. Consequently, these characteristics make monolithic domes more accessible to individuals and communities with limited financial resources. In addition, the construction of these domes can create jobs in the local community, particularly jobs in construction, manufacturing, and design. As a result, these employment opportunities stimulate economic growth and provide communities with skills that can be of use in future settings.

Lessons Learned

Simplification: The geometry and modeling processes are very complex for our concrete dome structure. We uncovered many problems with complex geometries, especially when transferring files between software. We learned that thermal analysis results can still be meaningful even when the structure is simplified. The one-unit structure that we ended up modeling was still largely representative of how the entire structure behaved. Information was still gained about how heat is transferred between materials and how efficient they are.

Using all your resources: Over the course of this project, we spoke with various professors and worked with many different groups to create a successful thermal analysis model. Since none of our university courses have instructed us on 3D modeling or thermal analysis concepts, we needed to rely on the knowledge and expertise of others. Dr. Shepherd helped us learn about modeling software and thermal analysis software.

James Niedens gave us his 3D Rhino model that he had made for structural analysis. Sofi Velasco Vega measured the temperatures around the dome structure and shared with us all the data she recorded. By using the resources that were already available, we were able to accomplish much more than we would have without.

Conclusions/Recommendations

We looked into various software programs for 3D modeling. Of all the modeling software we investigated, it is our opinion that SolidWorks is the best platform to model a structure if thermal analysis is the end goal. The files exported from SolidWorks were the easiest to integrate into the SimScale program. It is also a good program to work with to accurately model the geometry of a structure. Layers were easy to create, simulating the various materials in a structure. If the reader desires to run future analysis on other structures, SolidWorks is the recommended platform.

An accurate model was obtained using SimScale as the thermal analysis program. Using the sensors in and around the dome, we were able to compare our simulation data to the actual recorded data. Assumptions were made in the thermal analysis: steady-state analysis, inside air not convective, no windows. Despite numerous assumptions, the model matched the temperatures that were recorded. With similar assumptions, this model is replicable and could be used in future projects to know the strain on the interior air conditioning and heating systems. It can also be used to compare against similar structures of different material makeup to show efficiency of these insulated concrete domes.

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Education

Brigham Young University - Provo, UT

Graduation: Apr 2023

BS Civil Engineering (emphasis on Structures), Minor in Italian

GPA: 3.88

Ira A. Fulton College of Engineering Dean's List (Winter 2021 through Winter 2022)

University Academic Scholarship (2021-2022, 2022-2023)

Skills

- Strong command of AutoCAD, Excel, Revit, Risa 3D, SAP2000, ArcGIS Pro
- Familiar with building codes and design specifications: ASCE 7-22, IRC, AISC, ACI, NDS, and SPWDS
- Proficient drafting skills
- 2 years of architectural design

Engineering Related Experience

Student Engineer, Acute Engineering - Orem, UT

Mar 2021 - Present

- Managed and performed in-depth analysis of over 150 projects of light-frame structures built in accordance with codes and building preferences in over 6 different states
- Created over 400 addenda for the revision and development of engineering projects
- Developed and maintained a spreadsheet to analyze the effects of holes and notches in wood beams
- Communicate daily with colleagues and clients to address specific concerns and carry out modifications to design

Research Assistant, Brigham Young University - Provo, UT

May 2022 - Sep 2022

- Surveyed structural analysis programs such as Risa 3D and evaluated their functional compatibility with BIM systems such as Revit
- Analyzed how various structural components are represented in said programs
- Identified computational methods that can improve workflow between architects, engineers, and contractors

CHASE H. MOSS

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EDUCATION

- Brigham Young University studying Civil Engineering with 3.54 G.P.A. Expected Graduation: 04/24
- Graduated top in class from Lehi High School in 2016 with 4.0 G.P.A.
- 31 ACT Score

WORK

- Acute Engineering Orem, Utah 11/18 – Current
Engineer in Training
- Brigham Young University Provo, Utah 12/18 – 11/20
Test Prep Coordinator
- Brigham Young University Provo, Utah 08/18 – 05/19
EFY Counselor
- UPS Orem, Utah 11/18 – 01/19
Peak Season Driver Assistant
- Hadco Construction Lehi, Utah 07/16 – 10/16
Residential Construction Worker

SERVICE

- BYU ASCE Student Chapter Treasurer 12/21 – 12/22
- Full-time Volunteer Representative for two years in Argentina 11/16 – 10/18
- Volunteer work for St. George Half Marathon and Iron Man, Ivins Animal Shelter, Utah Food Bank, Homeless Shelter, and other service projects benefitting the community

SCHOLARSHIPS/AWARDS

- Half tuition Henrietta P. Clyde scholarship: Fall 2022, Winter 2023
- Half tuition Neil & Velma Stewart scholarship: Fall 2022, Winter 2023
- Half tuition Regents Scholar Award: Winter 2019, Fall 2019, Winter 2020, Fall 2020
- Full tuition BYU scholarship: Winter 2019, Fall 2019
- 2nd in State in DECA Marketing Competition - 2016
- Science Sterling Scholar - 2016
- Eagle Scout - 2014
- Snow Canyon High School Leadership Award – 2013

SKILLS

- Extensive drafting work in AutoCAD with structural drawings including taking measurements, drawing up plans and details, editing client drawings, and printing/exporting
- Substantial use in Excel including writing functions, using macros, VBA programming, troubleshooting, and resolving errors
- Proficiency in Word, PowerPoint, and Bluebeam
- Considerable use in the use of several Simpson Strong-Tie software applications such as Hanger Selector, Anchor Designer, and Strong-Wall Shear Wall Selector
- Experience in Risa 2D and 3D performing analysis of moment frames, steel beams, collar ties, and timber frames
- Familiarity with Revit and Civil 3D
- Advanced level in the Spanish language for reading, writing, speaking, and listening

James Estes

Provo UT 84604

702-462-4652

jestes5@byu.edu

- EDUCATION** Civil Engineering Major, Brigham Young University, Provo, UT, Projected graduation date: Dec 2023.
- GPA: 3.13
- WORK EXPERIENCE**
- Sales Representative**, Aptive Environmental, Cincinnati OH, April-August 2019 and Indianapolis IN, April-August 2020
- Initiated and secured 369 year-long contracts
 - Participated in trainings and workshops to improve sales tactics and soft skills
- Resident Assistant**, BYU Residence Life, Provo UT, August 2019 – December 2020
- Took charge of 36 freshmen residents
 - Coordinated and executed training meetings on a weekly basis
 - Organized group activities to become familiarized with campus resource
- Structural Engineering Intern**, Acute Engineering, Orem UT, January 2021- Present
- Trained for 1 month in AutoCAD and spreadsheet proficiency
 - Designed all structural elements in over 150 residential light-frame structures
 - Addressed concerns and needs of builders by modifying structural elements on the plans of 50 houses
- OTHER EXPERIENCE**
- Volunteer Representative**, The Church of Jesus Christ of Latter-day Saints, Cochabamba Bolivia, Dec 2016– Dec 2018
- Provided leadership, development, and training for 160 volunteer representatives
 - Completed service projects in construction, excavation, and maintenance for Bolivians in need
- Ecclesiastical Mission Leader**, The Church of Jesus Christ of Latter-day Saints, Provo, UT, August 2019 - Present
- Instructed a course on missionary preparation to 15 – 20 prospective missionaries
- Organization of missionary-related events and trainings for over 150 members
- SKILLS**
- Technical:**
- CADD applications
 - Proficiency in Visual Basic, R, and Python languages
 - Calculus and linear algebra proficiency
 - Statics in Engineering
 - Geomatics and ArcGIS
- Foreign Language:**
- Fluent Spanish speaker

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Education

BS in Civil and Environmental Engineering
Brigham Young University

April 2023
Provo, Utah

- GPA – 3.55
- Relevant courses: Reinforced Concrete Design, Foundation Engineering, Structural Analysis, Material Sciences, Soil Mechanics, Fluid Mechanics
- Clubs: ASCE Student Chapter and National membership, Family History Club, Refugee Club, BYU College Republicans, Phi Beta Lambda Portuguese Honors Society
- Scholarships: Brigham Young Scholarship (2019, 2020, 2021), Wells Fargo Foundation Scholarship (2021), Regents Scholarship (2019, 2020)

Skills

- AutoCAD
- Risa 2D
- Simpson Cold-Formed Steel Designer
- Simpson Anchor Designer
- Enercalc Structural Engineering Library

Experience

Student Engineer

Acute Engineering inc.

May 2020-Present

- Experience in light-frame construction
- Projects include cold-formed steel design, retaining walls, timber frame design.
- Member of the training development team to help new engineers understand the design and implementation of intermediate to more complicated topics. Topics included precast concrete floor panels, cold-formed steel structures, drill-and-epoxy hold-downs in anchor designer.

Research Assistant

Transportation Research Lab, BYU

April 2022-June 2022

Provo, Utah

- Performed weekly field studies to determine roads conditions in Provo
- Tested 30% of the roads in Provo in 3 months – this amount had taken previous students 9 months to test

Notable Projects

Cold Formed Steel (CFS)

- The only current student engineer to work on a CFS framing project for a residential structure at Acute Engineering.
- Was selected to work on more CFS framing projects received because of experience
- Created custom wood-steel hybrid detailing based on client preferences
- Developed a guided training for new engineers that was used by more experienced engineers who were unfamiliar with CFS framing for residencies.

Cantilever Steel Columns

- Recently completed 2 projects in September 2022 that required steel cantilever columns

