12-1-2022

Measuring Impacts and Vibrations on a Volumetric Modular House During Transportation

Seung Ho Song

MEASURING IMPACTS AND VIBRATIONS ON A VOLUMETRIC MODULAR HOUSE DURING TRANSPORTATION

By

Seung Ho Song

Bachelor of Engineering – Civil Engineering
University of Nevada, Las Vegas
2021

A thesis submitted in partial fulfillment
of the requirements for the

Master of Science in Engineering – Civil & Environmental Engineering

Department of Civil and Environmental Engineering and Construction
Howard R. Hughes College of Engineering
The Graduate College

University of Nevada, Las Vegas
December 2022

Thesis Approval

The Graduate College
The University of Nevada, Las Vegas

October 13, 2022

This thesis prepared by

Seung Ho Song

entitled

Measuring Impacts and Vibrations on a Volumetric Modular House During Transportation

is approved in partial fulfillment of the requirements for the degree of

Master of Science in Engineering – Civil & Environmental Engineering
Department of Civil and Environmental Engineering and Construction

Jin Ouk Choi, Ph.D.
Examination Committee Chair

Jee Woong Park, Ph.D.
Examination Committee Member

Moses Karakouzian, Ph.D.
Examination Committee Member

Jaewon Lim, Ph.D.
Graduate College Faculty Representative

Alyssa Crittenden, Ph.D.
Vice Provost for Graduate Education &
Dean of the Graduate College

ABSTRACT

The U.S. construction industry is experiencing an increase in demand for further implementation of modular construction due to the significant productivity and project cost-reducing benefits it provides. However, there exist challenges with the modular method, and many of them are well covered by previous studies, except for the effects of transportation-induced impact/vibration on volumetric modules. A previous study examined the effects of transportation-induced impact/vibration on a timber-framed module and identified some valuable findings. But, it did not explore other types of modules, height considerations, and the differences in the magnitude of impact/vibration due to different module maneuvers on the road. Therefore, this case study attempts to validate and develop from the findings of the previous study and explore other aspects of volumetric module transportation that the previous study did not consider. For the case study, an impact/vibration sensor and several cameras were installed on the Mojave Bloom modular house with Steel Structure (HSS) framing, which was designed and constructed by UNLV's Team Las Vegas for the 2021 Solar Decathlon Design Challenge. The sensor and cameras collected numerical and visual data throughout the Lifting, Transportation, and Offloading phases of module transportation. From analyzing the Front-to-Back Tilt and Left-to-Right Roll data, the use of synchronized hydraulic jacks for lifting and the potential preference of a bogey support system for projects with limited Jobsite laydown space were validated, and the damaged solar panel on the roof of the modular house validated the need for the module height considerations. Moreover, it was observed that making wide turns lead to high Roll values and high speeds lead to high Tilt values. Given the module's front-to-back secured configuration by the truck and the bogey support system, limiting high Roll values appears to be a higher priority than limiting high

Tilt values in minimizing module damage. This case study contributes to the body of knowledge by validating the previous research findings and addressing their limitations by introducing other means for module transportation, the need for further dimensional considerations, and the effects of different module maneuvers. Also, a future research opportunity with an object-tracking method to monitor module interiors has been identified. Consequently, it will help the practitioners rationalize the optimal approaches suited for various volumetric module transportation projects.

Keywords: Modular Construction, Modular Construction Constraints, Module Transportation

ACKNOWLEDGEMENT

First and foremost, I would like to express my deepest appreciation for my academic advisor, Dr. Jin Ouk Choi. I am extremely grateful for his guidance and thoughtful advice throughout the course of my graduate studies and research.

I am grateful to my advisory committee members, Dr. Moses Karakouzian, Dr. Jaewon Lim, and Dr. Jee Woong Park, for their willingness to provide invaluable feedback and an abundance of support.

I would like to thank UNLV's 2021 Solar Decathlon Team for providing the necessary documents and allowing the implementation of the Mojave Bloom modular house as the case study.

I am thankful to my undergraduate senior design project team members, Manfreht Anicacio and Alfonso Gonzalez, for having initiated the case study and data collection with me. I am thankful to Dr. Seungtaek Lee and Cristian Arteaga for their advice and help in structuring and writing the thesis paper. I would like to express my gratitude to my parents, Il Kwon Song and Boo Ja Park, and my brother, Kyu Ho Song. I would also like to thank my relatives for caring for me for 12 years in this still foreign land. I feel indebted for their unrelenting love, support, and encouragement. Lastly, I thank God for giving me the necessary strength and perseverance.

I am most certain that I would not have been able to finish this case study without the support of the individuals above.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1 Background

By exporting much of the site-based construction tasks to the sophisticated and controlled off-site fabrication facilities, the modular construction method can provide opportunities for capitalizing on plentiful productivity and economic benefits over the traditional stick-built method (Choi et al., 2017; Choi et al., 2019; McGraw et al., 2011; O'Connor et al., 2013, 2014). Over the years, the countries with leading modular construction companies, such as the European countries and Japan, produced many successful cases of the implementation of modular construction that incurred considerable overall cost savings and project schedule reductions (Azhar et al., 2013; Lawson et al., 2012, 2014; Thompson, 2019). In the U.S. construction industry, there is a growing demand and motivation for the adoption of modular construction to a greater extent due to those cases of successful implementation, as well as the other modular drivers, such as the nationwide skilled labor shortage, increasing housing demand, and safety and quality demands (Bertram et al., 2019; Blankinship, 2008; Choi et al., 2017; Faiz Musa et al., 2016; Lawson et al., 2014). In response to these needs, more U.S.-based construction companies are adopting modular construction and investing in the relatively unfamiliar construction method that has proven to lead to substantial benefits (Choi et al., 2017; Lawson et al., 2014; MBI, 2019; O'Connor et al., 2013).

However, as it is with any other attempts at implementing a relatively foreign technic or method, challenges often arise when the stick-built method-accustomed U.S. construction stakeholders implement modular construction. Namely, lack of experience, higher initial project costs compared to the stick-built method, demand for compressive coordination among stakeholders, logistical barriers, and module transportation limitations are critical challenges (Choi et al., 2017; Gan et al., 2018; Hwang et al., 2018a; O'Connor et al., 2014; Polat, 2008; Sun et al., 2020; Wuni et al., 2019). The challenges require complex decisions like the project's percent modularization, means of hoisting, transportation/offloading, and extent of coordination appropriate among stakeholders to consider the environmental and social impacts of the project to be made (Choi et al., 2017). A failure to properly address them can and will result in significantly reduced modular benefits.

1.2 Research Needs

Choi et al. (2017) refers to such challenges as the modular barriers, and among the list of barriers, 'Transportation/logistics' ranked the second highest at 2.44 on a 4.0 scale impact score. Also, among the high-impact Critical Success Factors (CSFs), the factors that dictate the success of a modular project determined by (O'Connor et al., 2014), 'Module Envelope Limitations' relating to the transportation evaluation ranked as the most influential CSF above the other 20 CSFs with a score of 3.83 on a 4.0 scale. Furthermore, out of 18 Prefabricated Prefinished Volumetric Construction (PPVC) constraints recognized by Hwang et al. (2018b), 'Increased transportation and logistics considerations' and 'Limitations to Design due to transportation restrictions' ranked third and sixth in significance, and scored 4.10 and 3.9, respectively on a 5.0 scale. Module transportation is an added step necessary in delivering a construction project in modular construction as it uses a non-Jobsite location for module manufacturing.

The other modular barriers are relatively well covered, and 'Owner Commitment,' 'Early-Engagement/Decision,' and 'Minimum Changes' are identified as effective measures to address them (O'Connor et al., 2013). A few studies, recognizing necessity due to the growth of modular methods in the U.S. construction industry, have examined the impact and vibration that affect the volumetric module during lifting, transportation, and offloading, and discovered some valuable findings. Yet, further research is demanding as they have limitations.

1.3 Research Objectives

Therefore, this paper conducts a case study with the modular house constructed by UNLV's Team Las Vegas for the Solar Decathlon 2021 design challenge. The study, using an impact sensor and several cameras, will numerically and visually examine the effects of impacts and vibration on the module during three phases of transportation (Lifting, Transportation, and Offloading). A data analysis conducted will address and validate the limitations and findings of the previous study, and, as a result, help the industry better understand how the truck's maneuvers affect the volumetric module and the difference in magnitudes of impact in the three phases. Consequently, industry officials can rationalize their approaches to minimize the module damage during transportation.

1.4 Thesis Structure

The study is organized into six chapters. CHAPTER 1 introduces modular construction as a promising alternative to the traditional stick-built method and presents challenges that need to be addressed to help attain the full benefits of modular construction. Among many challenges, this chapter narrows down to the transportation of volumetric modules as the focal point of the study. In CHAPTER 2, relevant literature regarding the currently employed module types, uses, specifications, and transportation (lifting/offloading and transporting) practices, as well as the past research that examined the effects of transportation-induced impacts/vibrations on the volumetric modules, are reviewed, and their limitations are identified. CHAPTER 3 outlines the study's approach to gathering impact/vibration data utilizing the transportation of UNLV's 2021 Solar Decathlon Modular House as a case study and the different duties of the parties involved in transporting the module. CHAPTER 4 analyzes the impact/vibration data gathered throughout the module transportation. The analysis is complemented with numerous figures and graphs. CHAPTER 5 refers to the analysis conducted from CHAPTER 4 and discusses interesting and relevant findings from the case study in comparison to CHAPTER 2, states the limitations of the case study and introduces potential future research possibilities. CHAPTER 6 summarizes the case study conducted and states the main beneficiary of the case study conducted. The thesis concludes with a list of references.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

In this section, a review of the common types, uses and specifications of modules adopted in the U.S., as well as the current volumetric modules transportation practices and past research works that examined the effects of impact and vibration acting on volumetric modules during transportation is conducted, to identify the key findings and the gaps in the existing knowledge.

2.2 Common Types, Uses and Specifications

In the U.S., wood-frame modules are the most general types, but steel and concrete are also adopted, and they are used in many sectors, including, but not limited to, housing, hospitality, education, healthcare, office/admin, commercial/retail, and institutional/assembly, and are being implemented at a greater scale (Lawson et al., 2014; MBI, 2019). Moreover, Ghannad et al. (2020) suggest the use of modular methods to accelerate post-disaster housing recovery processes. The modules typically weigh up to a couple of tens of thousands of pounds and have widths ranging from 10 ~ 16 ft., with 12 and 14 ft. being the most common. The length spans up to 70 ft. with 2 ft. increments and the height ranges from 11 ft. to 13 ft. (Azari et al., 2013; MBI, 2019). For instance, according to MBI (2019) , total multi-family modules more than doubled from 1,136 units in 2017 to 2,314 units in 2018.

2.3 Current Practices

Modules are primarily lifted/hoisted and offloaded using a crane with a lifting beam or a frame that mitigate inward force due to inclined cables (Lacey et al., 2018; Lawson et al., 2014). Different forms of lifting systems are employed depending on the types, dimensions, and weights of the modules, and modules' designs include different types and numbers of ceiling or bottom points accordingly to the lifting system chosen. For instance, steel-framed modules have lifting points at their corner posts whereas concrete modules have lifting points cast into them. The four regularly used lifting systems are: 1) lifting from the corner posts (no lifting beam), 2) lifting with a main beam + crossbeams, 3) lifting with a rectangular frame, and 4) lifting with a protective cage. Some constraints of crane lifting include 1) Limited Jobsite access, 2) overhead power lines, and 3) public safety concerns (Lawson et al., 2014). Lifting via a crane is a common practice, but forklifts could also be used due to the crane's constraints, economic efficiency, etc. (Lacey et al., 2018). For lifting and offloading multi-module structures, it is optimal to use the crane (Cameron, 2007). But, for single modules with relatively smaller overall project sizes, using a crane might overturn the economic benefits of going modular (Mao et al., 2016). According to Bachelor (2012), the cost of crane operation is \$3,500 to \$4,500 per day, and it is the most expensive part of module installation. Thus, forklifts or other more economical substitute means of lifting techniques can more desirable.

The modular construction industry does not have federally-regulated building codes such as HUD-Code (MBI, 2019). Therefore, as discussed in the introduction, the module's dimensions, as well as its weight, can vary, and they are mainly dictated by the respective states' building codes from which the modules are being manufactured and delivered. The regulated or enforced dimension and weight limits are labeled as the 'maximum allowable travel width, length, height, and weight.' In other words, depending on the transportation distance and the number of states on its route, the number of state regulations the module must comply with may vary. Consequently, successful and seamless module transportation requires a thorough module design and transportation route considerations (Hwang et al., 2018a; Li et al., 2016). The complexity of these issues regarding transportation logistics increases as the transportation distance increases, which will inevitably increase the number of regional road restrictions the module has to abide by (Bachelor, 2012; Cameron, 2007; Rippon, 2011) and the chances of damaging the module from the unavoidable loads it will be exposed to on the road. Thus, the typical maximum transportation distance is between 250 to 600 miles (Bachelor, 2012; Cameron, 2007), and anything beyond that is considered impractical.

2.4 Summary of Current Practices

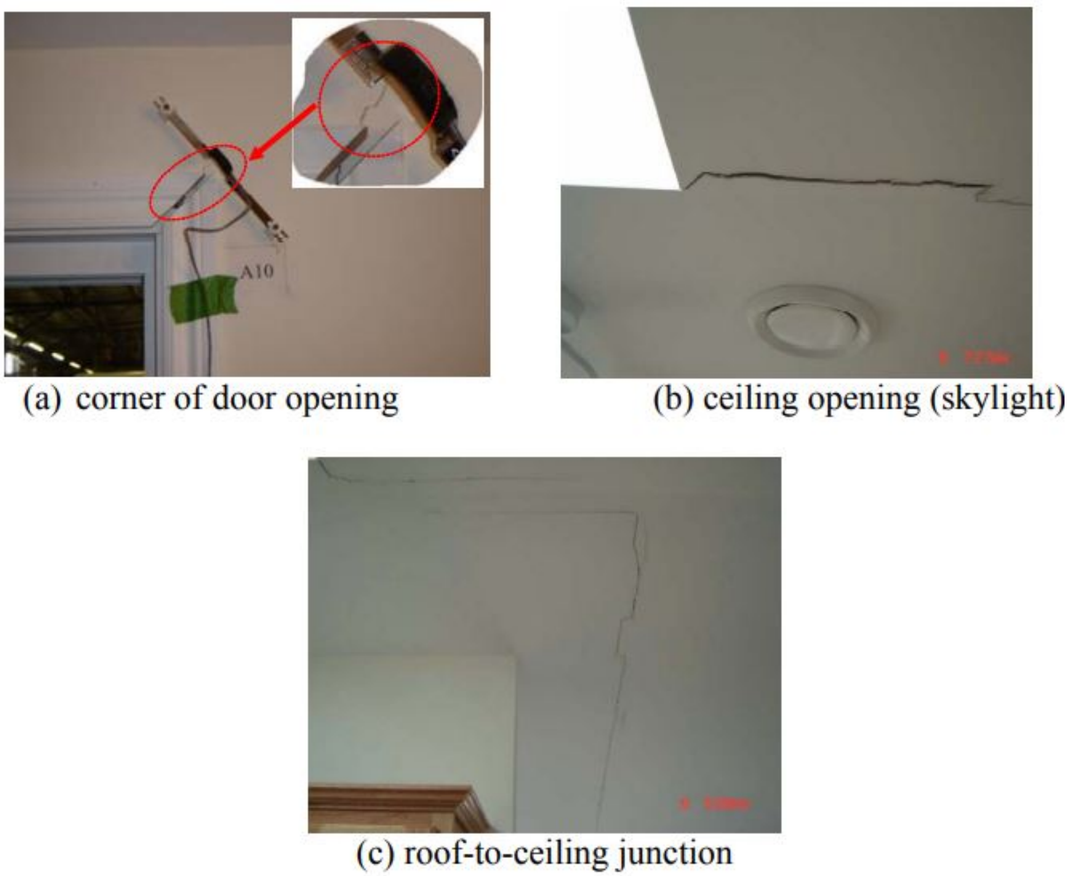
Volumetric modules are vulnerable to damage incurring from the high impact and vibration when lifting/hoisting to attach them to their means of transportation, transporting them on the roads, and offloading the modules to their final installation location at the Jobsite (Godbole et al., 2018; Gustafsson et al., 2011; Hu et al., 2007; Innella et al., 2020; Liu et al., 2018; Wang et al., 2019). The module damage can range from simple dents in the installed furniture to cracks in the modules themselves. Any transportation-induced damage to the module, regardless of its magnitude, can compromise its performance by compromising its durability via air leakage and moisture deposition that leads to molding and heat loss (Smith et al., 2007). Moreover, depending on the severity of the damage, the module's structural integrity could also be impaired. Consequently, the importance of an immediate and timely restoration of the module is paramount if any damage has occurred to the module to prevent it from developing into a more serious problem and minimize overall project schedule loss and additional costs incurred (Valinejadshoubi et al., 2022).

2.5 Research Works

Smith et al. (2007) examined the behavior of a prefabricated modular house under load during lifting/offloading and transportation using four accelerometers, eleven deformation sensors, and eighteen pressure taps installed. The author referred to the modular house as a ‘mini home.’ The mini home was a typical wood frame modular house with the longest and widest dimensions a prefabricated unit can have to be driven on the U.S. public roads of 4.88 m (W) x 22.6 m (L) (16 ft. x 74 ft.) at that time. The field test was conducted in four phases: 1) Lifting the mini home inside the factory, 2) Moving the mini home on top of the temporary supports consisting of six steel saddles (three on each side) at the factory yard, 3) Lifting the mini home from the temporary supports to a flatbed of a tractor-trailer, and 4) road test. Three switch-activated electro-hydraulic jacks were used on either side of the mini home to lift it in phases (1) and (3).

The transportation route included three road types: rural, provincial, and expressed highway. The total distance of travel was not specified. As a result of the field tests, the author reported that the impacts translated into actual module damage mainly due to three reasons during its lifting and offloading phases that occurred at the factory and factory yard. First, each of the six hydraulic jacks required manual switch-on activation, thus slight delays among the jacks' movements were inevitable, creating a twisting moment to the mini home about its longitudinal axis. Second, the mini home's temporary location at the factory yard was unpaved, causing the temporary supports to be unevenly leveled and leading to an amplification of module damage.

Third, according to the comparison of Von Mises stresses among different lifting scenarios conducted by the author, the usage of three lifting points also contributed to module damage, as four lifting points would have resulted in a 53% reduction in peak stress. Figure 1 includes the mini home damages identified.



(a) corner of door opening (b) ceiling opening (skylight)

(c) roof-to-ceiling junction

Figure 1. Damages occurred to the mini home (Smith et al., 2007).

The damage occurred in the patterns of long horizontal cracks on the plasterboard linings of the side walls, vertical cracks on the kitchen ceiling, and 45-degree cracks on the corners of the frames of the windows and doors. According to the author, lifting/offloading-induced impact initiated the damage in the form of various types of cracks within the module, and vibration, impact, and wind pressure affected the module during transportation and further developed those existing cracks.

Valinejadshoubi et al. (2022) also recognized the significance of assessing the volumetric module damage from impact during transportation. The author developed a monitoring system consisting of an acceleration-sensor-based data acquisition (DAQ) module, a storage module, and an automated data analysis module for the detection of module damage during transportation. The dimensions of a bigger module were 42 ft. (L) x 11 ft. 6.5 in. (W), and the modules were transported via a tractor-trailer to the Jobsite location 186 miles away (dimensions for a smaller module were not specified). The author installed the sensors and monitoring systems near the openings of the modules, which are stress-prone locations as identified by (Smith et al., 2007). The vibration sensors collected 1.7 million raw data points, which indicated relatively higher impacts at the beginning (local road) and end (city road) compared to the middle (highways) of the transportation, showing the differences in the qualities of the roads. Regardless, the modules did not experience any damage throughout the transportation.

2.6 Summary and Limitations

It is evident, from the completion of the literature review, that the importance of an adequate assessment of volumetric module damage due to transportation-induced impacts is recognized. The first research work by Smith et al. (2007) thoroughly explored the effects of transportation-induced impacts on a volumetric wooden module. The author identified a few shortcomings of the practices and tools adopted for the field test that could lead to significantly improved volumetric module transportation practices in the future by addressing them. The second research work by Valinejadshoubi et al. (2022) adopted recommendations from the first research work and conducted another competent field test utilizing the transportation of two volumetric wooden modules. However, the two studies were not without any limitations.

Firstly, the two studies did not consider the heights of the volumetric modules, which is another aspect that might need to be considered in planning the module transportation route as it can be one of the possible module dimension constraints. For instance, some routes might include bridges and overpasses that mandate certain clearance limits. The module height, combined with the height of the truck's wheels, do often go over the clearance limits of some overpasses. Secondly, the limitation was only considering one type of volumetric module (wooden frame), and it was recognized as one of the limitations in both studies. Lastly, the two studies did not examine the potential effects of different module maneuvers on the road or the speed at which the module is traveling to the module.

CHAPTER 3: METHODOLOGY

3.1 Introduction

The Methodology covers the detailed background of the module transportation project, as well as the responsibilities of one indirectly and three directly involved parties for each of the three phases (lifting, transportation, and offloading) of the project. A timeline of the module transportation is included at the end of this chapter.

3.2 Background

The Solar Decathlon 2021 competition was planned to be held at the National Mall in Washington, D.C. For Team Las Vegas, this meant the modular house (Mojave Bloom) would have to be ground transported for a minimum of 2,417 miles, according to the Google map. It is inevitable for the modular house to cross the borders of multiple states during its transportation. Given each state has its codes for regulating maximum allowable travel width (Arizona, Nebraska, Ohio, Missouri, and New Mexico), height (Missouri and Arkansas), and weight (Ohio, Arkansas, and Missouri) for mobile home transportation, the Team Las Vegas had to design the modular house to be smaller than 14 feet in width and height, and lighter than 120,000 lbs. in weight. Moreover, the modular house had to be smaller than 60 feet in length to comply with the competition rules. As a result, the completed modular house has dimensions of 12 feet (W) x 12 feet (H) x 58 feet (L) and weighs about 27,000 lbs. (Khodabandelu et al., 2020, 2022). Figure 2 shows prospective transportation routes from Las Vegas, NV, to Washington, D.C.

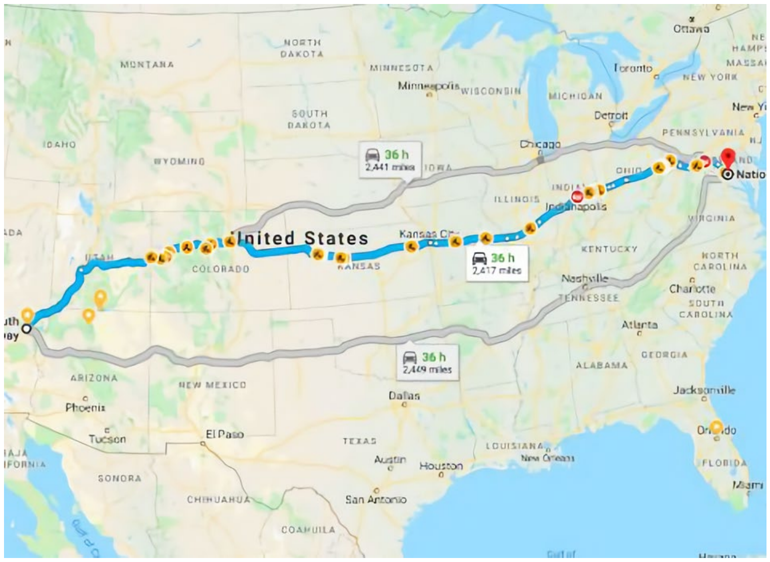
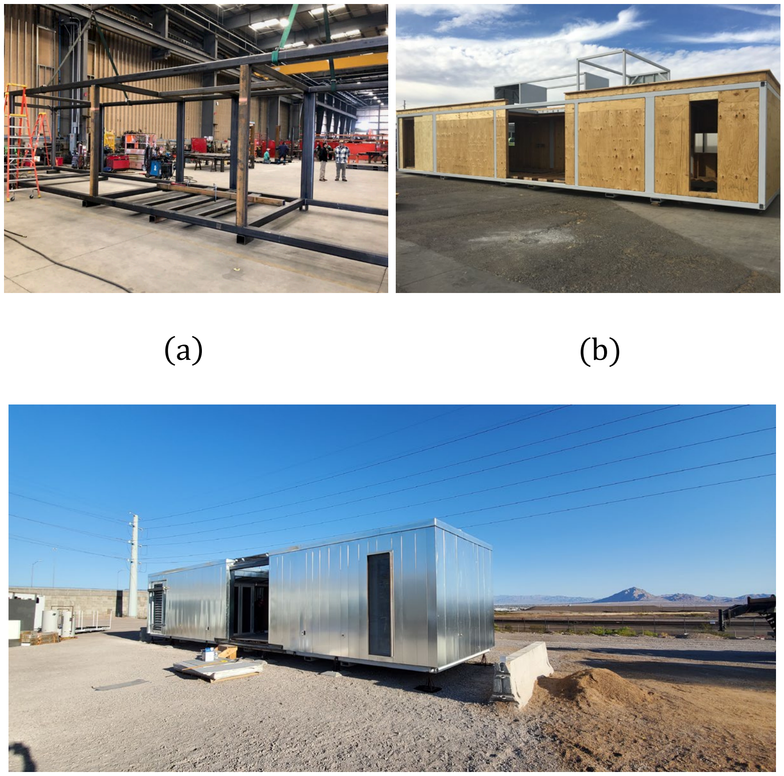


Figure 2. Proposed Modular House Transportation Routes

Since the originally anticipated transport distance was far beyond the typical mobile home transport distances, the team adopted 6 in. X 6 X. ¼ in. square Hollow Structural Sections (HSS) for the framing of the modular house to help maintain its structural integrity throughout the extended trip. Figure 3 shows distinct stages of modular house construction, denoted as structural components finished, exterior walls finished, and the modular house completed.



(a) (b)

(c)

Figure 3. Structural Components (a), Exterior Walls (b), Finished Modular House (c)

The teams participating in the competition were required to submit as-built projects by February 2020 according to the initial schedules. However, all projects had to come to a sudden halt due to the global pandemic, which led to an inevitable postponing of the overall competition schedule. On May 22nd, 2020, the organizer of the competition, the Department of Energy, announced that the competition schedule had been adjusted to take place between April 16-18, 2021, and the change of location from the National Mall, Washington D.C., to the Department of Energy's (DOE) National Renewable Energy Laboratory in Golden, Colorado. The actual assessment of Mojave Bloom happened on March 30th, 2021, at its prefabricated location, Xtreme Cubes Corp. at Henderson, LV, NV. Consequently, the modular house's final installation location also changed to Las Vegas Community Healing Garden, thereby reducing the prospective transportation distance from 2,417 miles to only about 13.2 miles. Figure 4 includes the transportation route to the adjusted final installation location.

Figure 4. Xtreme Cubes to Las Vegas Community Healing Garden

The modular house transportation commenced on March 31st, 2021, and it involved three cooperating parties: (1) two contractors, (2) two subcontractors, and (3) a truck driver. Contractors and subcontractors were responsible for lifting and offloading the module and connecting/securing the module to the truck. The driver was responsible for transporting the modular house from its prefabricated location to the final location. The author utilized this transportation as a case study and were not directly involved. The case study considered transportation in three phases: modular house lifting, transportation, and offloading/installation. Lifting consists of all the procedures required to ready the modular house to 'hit the road' from lifting the modular house to be leveled with and connected to the truck's 5th wheel hitch. Transportation starts from the moment the modular house is on the road to when it arrives at its final location. Offloading/Installing is when the modular house is offloaded/installed.

The transportation route excluded highways due to higher speed limits and included as few turns as possible. In total, the modular house made 6 turns to arrive at the Jobsite (NOT the final location). First, the modular house made a right turn to exit the fabrication yard and drove on Eastgate Rd. Second, it made a right turn from Eastgate Rd. to W. Sunset Rd. Third, it made a left turn from W. Sunset Rd. to N. Boulder Hwy. Fourth, the modular house continued N. Boulder Hwy. and onto E. Fremont St., then made a left turn into E. Charleston Blvd. Fifth, it made a right turn into S. Casino Center Blvd. then made another right turn at Coolidge Ave to arrive at the Jobsite.

3.3 Sensor and Camera Installation

On March 31st, the Senior Design Team members arrived at the prefabricated location before the start of Lifting phase at around 7:00 AM to install the impact sensor and cameras inside the modular house. For the impact sensor, SpotSee's ShockLog 298 was adopted, and for cameras, one Samsung Gear 360 and two sets of DR750s-2ch from the BlackVue dashcam were used. ShockLog 298 measures impact in G and tilt and roll in degrees, and it was set to record the data every 10 seconds. According to the ShockLog 298 user manual, tilt represents a front-to-back movement in degree and roll represents left-to-right movement in degree, and the data is displayed in a range of ±180 degrees. It would mean the modular house experienced a complete turnover if either of the tilt and roll data displayed 180 degrees, and 0 degrees would mean the modular house is upright/centered. Given the sensor's orientation for this case study, a negative value in tilt and roll would mean a tilt or roll towards the front or right, and a positive value towards the back or left. Also, the sensor records the maximum and the minimum values of tilt and roll in one slot, meaning there would be two columns of tilt and roll data when extracted into an excel file. The numerical data orientation based on ShockLog 298 installation location is represented with the 2D view of the modular house in Figure 5.

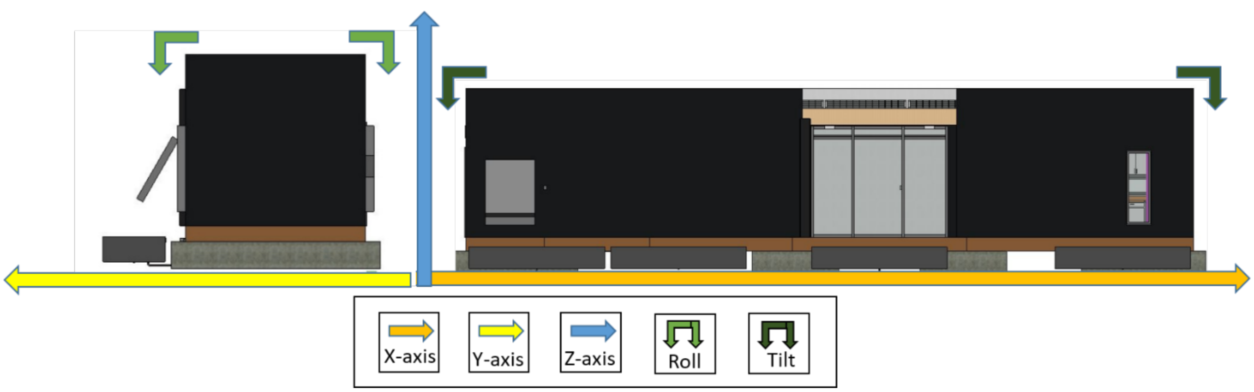


Figure 5. Numerical data orientation

Samsung Gear 360 and BlackVue dashcams record footage in 1080p quality and display the time of recording in UTC and the speed at which the vehicle was traveling. The installation location for ShockLog 298 was considered in terms of the modular house's vulnerability to impact/vibration-induced damage. As previously stated, damage most prevalently occurs in the patterns of cracks along the long horizontal plasterboards and near window openings and door corners. Therefore, the ShockLog 298 was installed on the floor at the 'Hallway' area between the modular house's longest horizontal wall and the glass wall panel. Samsung Gear 360 was attached to the horizontal wall at the 'Hallway.' The dashcams were installed in locations that allowed them to capture the widest angles. One set of dashcams (front/rear dashcam) was installed in the 'Kitchen/Living' area, and their angle of view was adjusted to capture both the inside view of the modular house and the outside view through the glass wall panels and doors at the 'Entrance' area. The other set was installed in the 'Bathroom' and 'Bedroom' areas and captured the views of their respective installed areas. Figure 6 shows the prospective installation locations of the sensor and cameras.

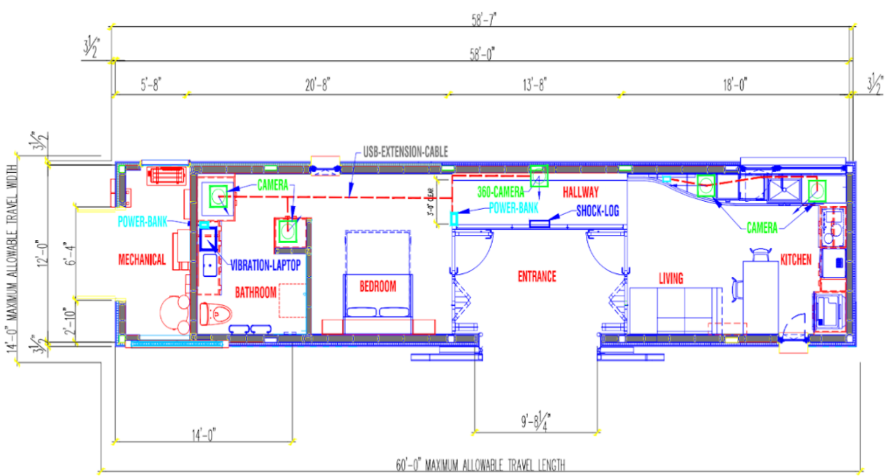
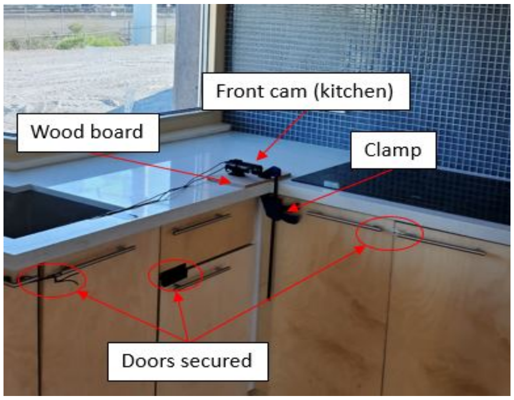
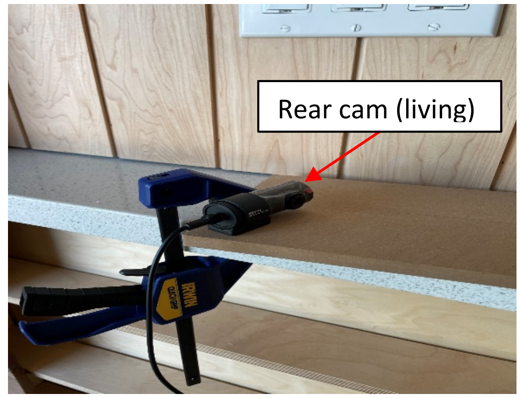


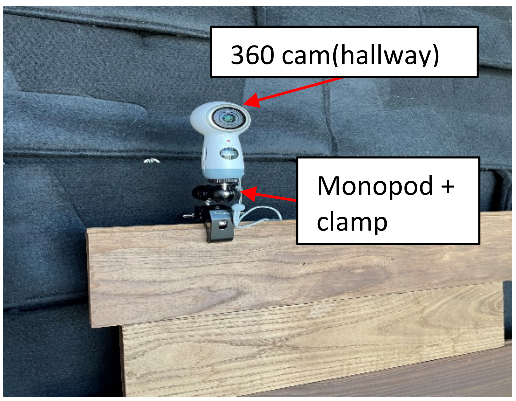
Figure 6. Sensor & Cameras layout

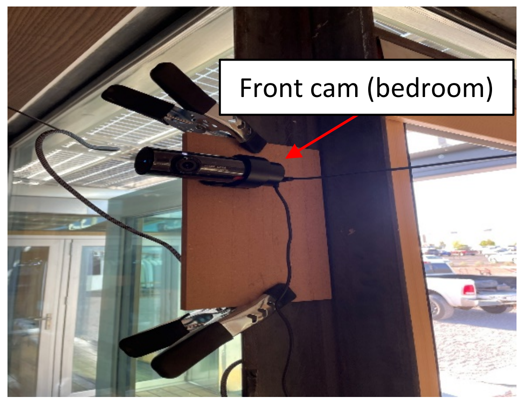
The author intended the impact sensor and cameras to gather numerical and visual data throughout all three phases of the transportation, which was expected to take about 10 hours to complete. The ShockLog 298 has more than enough storage and battery life to remain selfsufficient for 10 hours. However, the cameras do not have batteries. They require a connection to a separate power source at all times of their operation. Accordingly, three power banks were installed to power the cameras. The author used duck tapes to install and secure the ShockLog 298 sensor. The Samsung Gear 360 was attached to the wall via the monopod and clamp, and the dashcams were first attached to the wooden boards, then secured to their respective installation locations using clamps to avoid damaging the furniture. The author used duck tapes and/or iron wires to secure the cabinet doors to prevent them from bursting open during transportation due to impact. The actual installation locations for the sensor and cameras are shown in Figure 7.



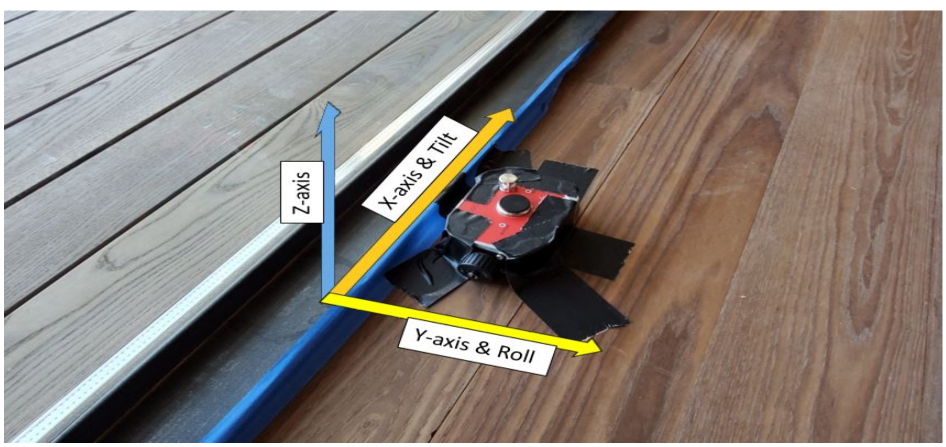


(a) (b)





(c) (d)



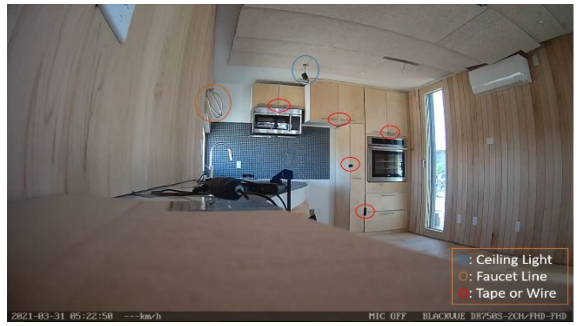
(e)

Figure 7. Front & Rear dashcams (Kitchen/Living) (a & b), 360 cam (Hallway) (c), (Front dashcam (Bedroom) (d), ShockLog sensor (Hallway) (e)

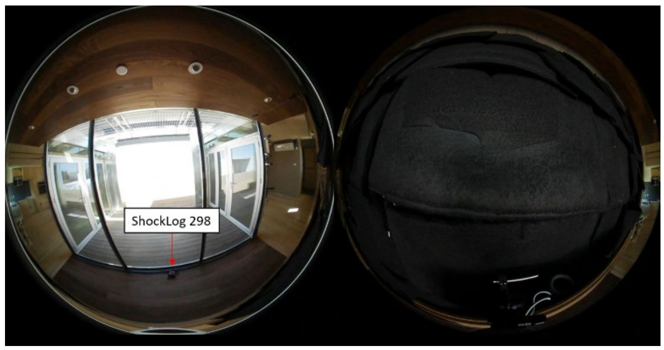
Connections to power banks are not shown in Figure 7. However, all cameras had a power bank allocated to them. Contrary to the original layout plan pictured in Figure 6, a front dashcam was installed to the structural component that serves as a frame for the glass panel instead of installing both front and rear dashcams in the ‘Bathroom’ area. The author was not only unable to determine an ideal location for its installation in the ‘Bathroom’ area but also believed installing it to the structural component would allow it to capture both the ‘Bedroom’ area and a portion of the ‘Bathroom’ area more effectively. In the ‘Bathroom’ area, the rear dashcam was installed on top of the cabinet to capture the widest view. However, its vision was significantly obstructed by the cabinet top due to not having a proper elevation required to locate the lens high enough to prevent the cabinet top from taking up much of the frame. By this time, all three parties had arrived, and it was inevitable for the author to evacuate the modular house to let them proceed with the transportation. Unfortunately, the author had to disregard using rear dashcam (Bathroom) data for the case study. It was around 8:30 AM when the author left the modular house.

Views captured by the two dashcams and a 360 camera in the ‘Kitchen/Living’ and ‘Hallway’ areas are presented in Figure 8.

(a)



(b)



(c)

Figure 8. Front dashcam (living) (a), Rear dashcam (living) (b), 360 cam (hallway) (c)

Only the BlackVue dashcams provide the date, time (UTC), and speed (km/h), as shown in the bottom left corner of Figures 8 (a) and (b). Adding four hours to the displayed time would give out its respective PST. Figure 8 (a) displays '5:22:50', which means it is 9:22:50 AM in PST. Dashcams do not display whether the time is in AM or PM. However, it can be easily distinguished by simply observing the recorded footage. When the modular house was traveling, its speed gets measured and displayed next to the time. In Figures 8 (a) and (b), the dashcams display '--- km/h' as the speed, indicating the modular house is not moving, which was true as it was stationed at the fabrication yard at the time of recording. Figure 8 (b) shows various kitchen equipment and furniture. Notably, a ceiling light is dislocated from its socket and hanging in the air, a faucet line is tied to the wall, and cabinet doors are secured via either duct tapes or wires. Figure 8 (c) is a view from the Samsung Gear 360 camera at ‘Hallway.’ From this view, the left side is the ‘Kitchen/Living’ area, and the right-side leads to the ‘Bedroom’ and ‘Bathroom’ areas, and on the floor is a ShockLog 298 sensor.

3.4 Modular House Lifting

At default, the modular house was positioned 19” + above the ground on top of the C.P. Seismic/Standard Piers. Each pier has 6,000 lbs. capacity, and seven piers were on either side, as shown in Figure 9. In total, fourteen piers supported the modular house.

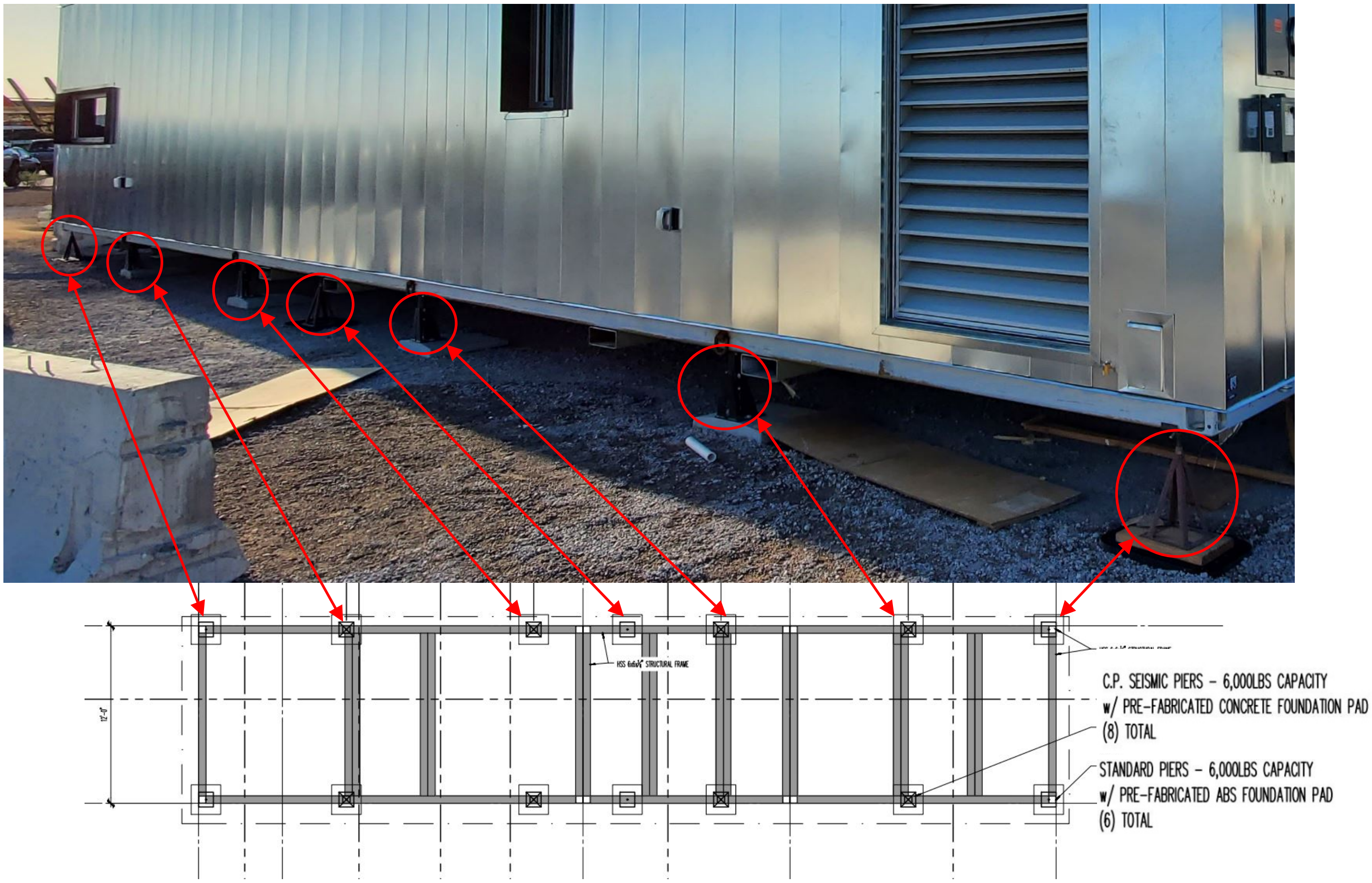


Figure 9. C.P. Seismic/Standard Piers supporting the modular house

Despite being positioned 19" + above the ground, the modular house had to be lifted further up to attach two tandem axle dollies to the rear and level the front with the truck's 5th wheel to establish a connection between the modular house and the truck. The contractors and subcontractors began lifting at around 8:34 AM using four hydraulic jacks.

Step 1, two steel beams have been attached to the bottom of the modular house, one to its rear side and the other to its front side. Step 2, four hydraulic jacks have been attached to the either side of the two steel beams, as shown in Figure 10 (the beams have long enough spans to establish hydraulic jacks' attachment to their sides underneath the modular house).

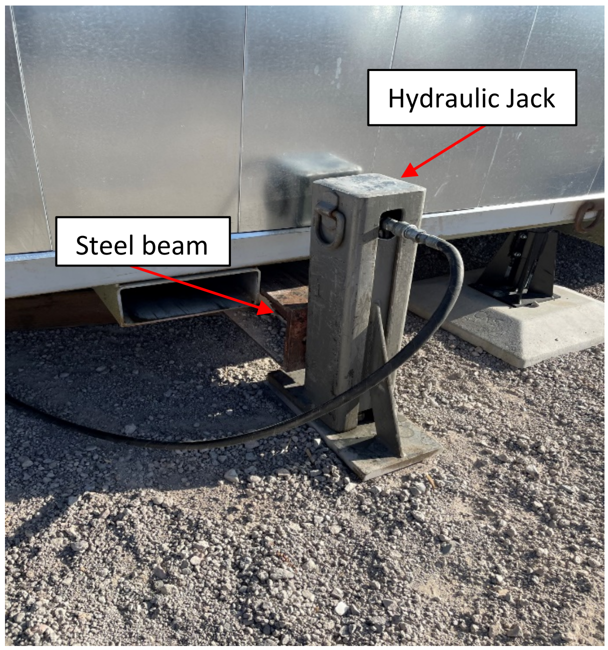
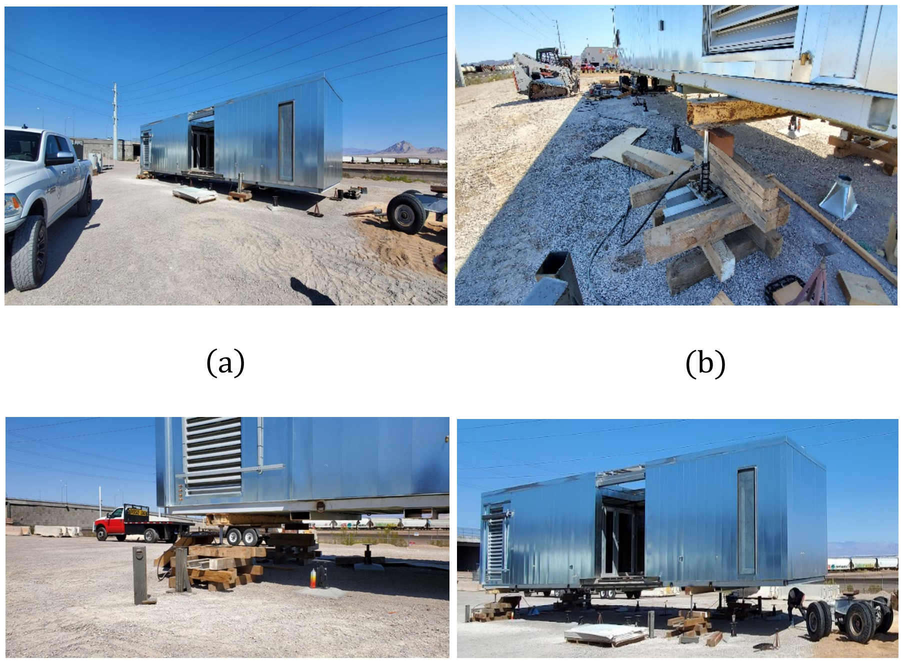


Figure 10. View of one of four hydraulic jacks (rear)

Step 3, all four hydraulic jacks were activated at the same time to lift the modular house. Step 4, once the hydraulic jacks lifted the modular house to their maximum lifting range, square lumber stacks were made around each hydraulic jack. Step 5, hydraulic jacks were temporarily removed, and two steel I-beams are placed on top of each lumber stack. Step 6, the hydraulic jacks were placed on top of the steel I-beams and lifted the modular house to their maximum lifting range. Step 7, once the modular house was positioned high enough, the piers were removed. Steps

3 to 6 were repeated to lift the modular house in small increments. Figure 11 depicts a summary of the modular house lifting steps.



(a) (b) (c) (d)

Figure 11. First lumber stacks made (a), more lumber being stacked (b), several lumber stacks made (c), lifted high enough for tandem axle dollies (d)

When the modular house was at the level shown in Figure 11. (d), the subcontractors attached the two tandem axle dollies to the steel beam attached to the rear side of the modular house. The steel beams, like an I-beam, have a top and bottom flange, and the axle dollies have flange clamps. The attachment of the axle dollies to the steel beam was a simple work of sliding and clamping. The axle dollies were inserted from one side of the steel beam, attached to a Bobcat utility vehicle on the opposite side via a chain, and the vehicle pulled the chains backward to adjust the axle dollies to the desired position. After the two tandem axle dollies were installed, the two hydraulic jacks were removed, and their axle arms were attached to either side of a wooden beam and secured with mechanical tie downs. As a result, the axle dollies' attachments were further strengthened, and uniform movements between the axle dollies were established. Moreover, chains and wrenches have been used on either side of both frontal/rear steel beams to tighten their attachments to the modular house. The above attachment of axle dollies is depicted in Figure 12.

(a)

(b)

(c)

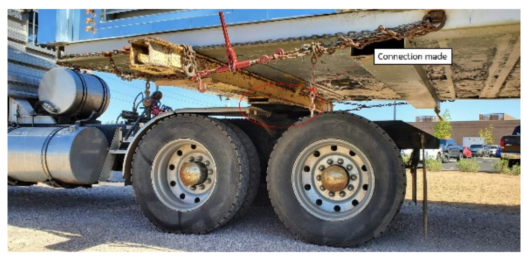
(d)

(e)

Figure 12. Tandem Axle Dollies (no clamp) (a), Tandem Axle Dolly (clamp) (b), Bobcat pulling axle dolly (c), two axle dollies attached (d), left side view of a completed rear wheel system (e)

The lifting of the rear side of the modular house was completed with the attachment of the two tandem axle dollies. The steel beam on the front side has a trailer kingpin, and it was going to be attached to the truck's 5th wheel hitch to establish a connection between the modular house and the truck. However, the truck was at a slightly higher level than the modular house, so the modular house was lifted once again by a small increment to be leveled with the truck. After leveling the modular house to the truck, the driver carefully pulled back to connect the 5th wheel hitch to the kingpin. The process of connecting the modular house to the truck is shown in Figure 13.

(a)



(b)

(c)

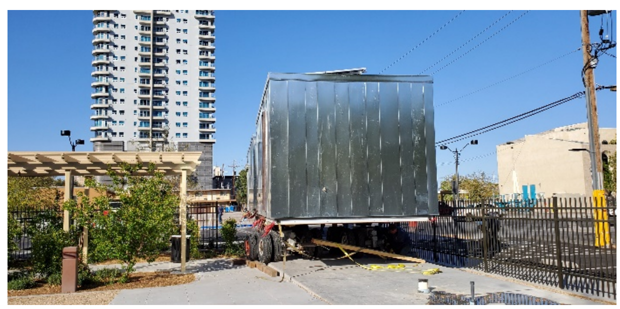
Figure 13. Modular house lifting for leveling (a), Modular house connected to the truck (b), Modular housing leaving jobsite (c)

3.5 Modular House Transportation

The driver drove the modular house on the pre-planned transportation route as shown in Figure 4, and delivered the modular house from its fabrication yard, Xtreme Manufacturing, to its Jobsite/installation location in Las Vegas Community Healing Garden. Inside the healing garden is a 6.2-inch-thick concrete slab, where the modular house was planned to be offloaded. The garden was surrounded by fences and plants. A narrow entrance was created by temporarily removing a part of the fences to incorporate modular house installation. Still, the space inside the garden was extremely limited. Any modular house maneuver would be impossible once it makes the initial movement to enter the garden. In other words, the truck must be driven in rear gear to enter the garden and offload the modular house on top of the concrete slab. The modular house made a right turn to arrive at the road next to the garden, meaning the garden was on the right side of the modular house. Making an immediate right turn into the garden would not have worked as there is not any extra space in the garden to allow the modular house to adjust its positions. Thus, the driver made a left turn into the empty lot across the garden. From there, the driver pulled back in rear gear into the garden. Figure 14 shows the summary of the described truck maneuvers.

(a) (b)

(c) (d)



(e) (f)

Figure 14. concrete slab (fences removed) (a), Modular housing driving in (b), Modular housing into empty lot (c), Modular housing pulling out (d), Two steel plates as driveway (e), Modular house into the garden (f)

Temporary traffic barriers appear in Figure 14 (a) ~ (d). The contractors installed them to keep both the pedestrians and vehicles away from the Jobsite throughout the transportation and installation or offloading phases. The road restricted was Coolidge Ave. between S. Casino Center Blvd. and S. 3rd St. When the modular house was pulling in rear gear, two steel plates (Figure 13 (e)) were adopted to serve as a driveway. Figure 14 (f) shows that a wooden beam connection between two tandem axle dollies was made at the rear of the two dollies to help keep the wheels stable as they overcome 6-inch curbs.

3.6 Modular House Offloading/Installing

The contractors and the subcontractors began offloading the modular house using a similar technique they used to lift the modular house. First, they removed fences adjacent to the truck's wheels and axle dollies to create sufficient working spaces. Second, they established four lumber stacks on either side of the front and rear attached steel beams. Third, a connection between the truck's 5th wheel and a front steel beam's kingpin had been loosened, and the driver pulled out the truck. Fourth, four hydraulic jacks had been installed on either side of the two steel beams. Fifth, the uppermost layers had been removed from the lumber stacks. Sixth, hydraulic jacks had been leveled down to match the height of the lumber stacks. Seventh, the axle dollies had been removed. Eighth, the fifth, and sixth steps had been repeated until the modular house was lowered enough to be rested on top of the piers. Ninth, the modular house rested on top of the fourteen piers. Each pier was screwed to a concrete plate. Last, the two steel beams were removed. The above modular house offloading steps are summarized in Figure 15.



(a) (b) (c)


(d) (e)

Figure 15. Fence removed (a), Truck removed (b), Axle dollies removed (c), Modular house rested on piers (d), Offloading completed, and walkway attached (e)

Upon completion of the modular house transportation project, Team Las Vegas came to the installation site and attached a walkway, as displayed in Figure 15 (e).

3.7 Transportation Timeline

As stated, contractors and subcontractors began lifting phase of the modular house transportation project at 8:34 AM. There was a lunch break at around noon, and by 12:56 PM, the modular house was attached to the truck, and at 2:09 PM, the modular house left the fabrication yard. A gap of 1 hour and 13 minutes between the modular house's attachment to the truck and its departure time occurred due to an additional time required to adjust the bogey support connection. In total, lifting phase took 5 hours and 35 minutes to complete, which means the ShockLog 298 sensor recorded 2,016 slots of data, given the sensor recorded the data every 10 seconds.

Transportation (Road) immediately followed upon the completion of Lifting phase, and it took 1 hour and 8 minutes, and the sensor recorded 414 slots of data. This is the actual time the modular house was being delivered on the road based on its fabrication yard departure time and the Jobsite arrival time, which were 2:10 PM and 3:18 PM, respectively. Transportation (Jobsite) began from the modular house's arrival at the Jobsite and finished when it was located on top of its final installation location and was completed at 5:32 PM. Calculating from its arrival time of 3:18 PM, it took 2 hours and 14 minutes to locate the modular house on top of its final installation location inside the garden, and the sensor recorded 804 slots of data.

A dashcam in the 'Kitchen/Living' area capturing the outside view caught a construction glove falling off the roof 6 minutes after Transportation (Road). The glove sat in the 'Entrance' area through all three phases. 2 minutes after, the wooden beam failed, and there was a delay of 10-minute to re-adjust the wooden beam. 44 minutes into Transportation (Road), the modular house was on Boulder Hwy. under an overpass on Great Basin Hwy., and one of the solar panels on the roof of the modular house got damaged due to the modular house exceeding the clearance by a small margin. Modular house offloading did start right after Transportation (Jobsite), but sunset occurred before its completion. The work came to a halt and resumed on the following day, April 1st, at around 8:50 AM. The author arrived at the Jobsite at 11:53 AM and removed the sensor and cameras from the modular house at 12:13 PM. The approximate time of the completion of Offloading is 3:20 PM. Calculating from the time the work resumed to the time the sensor and cameras were removed, the sensor recorded 1,224 slots of data. Table 1 includes time stamps for all the procedures/events that occurred during all three phases of the modular house transportation project.

Table 1. Transportation Procedures & Events

Phase	Procedures/Events	(3/31)
Lifting	Started Lifting	8:34 AM
	Attached to Truck	12:56 PM
	Leaving Offsite	2:09 PM
Trnspt. (Road)	On the road (departure)	2:10 PM
	Glove Falling	2:16 PM
	Wooden Beam Failure	2:18 PM
	Transportation Resumed	2:28 PM
	Solar Panel Damaged	2:54 PM
	Jobsite Arrival	3:18 PM
Trnspt. (Jobsite)	Moving to Final Location	3:18 PM
	At the Final Location	5:32 PM
Offloading/Installing	Started Offloading/Installing	5:33 PM
	Procedures/Events	**(4/1)**
Offloading/Installing	Work resumed	8:50 AM
	Author arrived	11:53 AM
	Sensor & Cameras Removed	12:13 PM
	Approximate completion	3:20 PM

The above timeline of events shows that Lifting and Transportation phases took 8 hours and 58 minutes to complete, and Offloading phase got pushed back to the next day and took more than 6 hours to complete, resulting in 4,458 slots of data recorded. In other words, the modular house transportation project took more than 15 hours to complete, excluding the idle time when the work was halted, which is about 5 hours longer than the expected 10 hours.

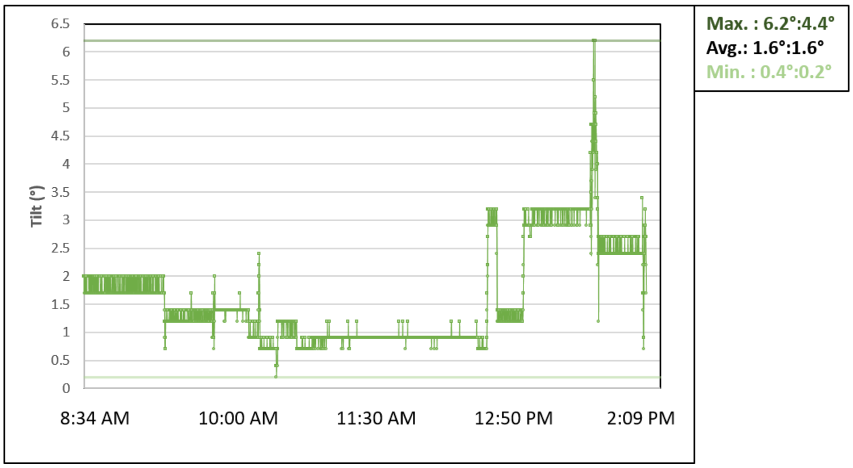
CHAPTER 4: RESULTS

4.1 Introduction

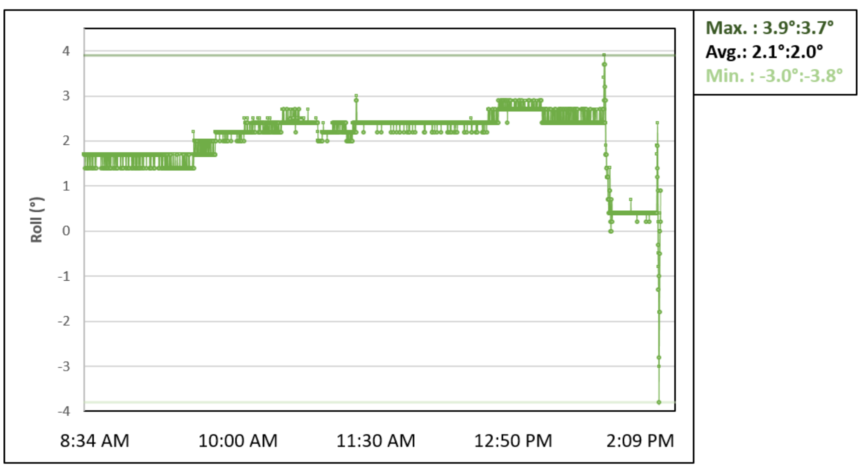
Results follow the same structure as the Methodology. In general, collected numerical and visual data are divided into three phases (Lifting, Transportation, and Offloading), except Transportation. The transportation spans from the instance the module was on the road to the moment it was located on top of its installation location. After the module arrived at the Jobsite, it took some time for the module to be located at its installation location. The data gathered during that time were significantly different in magnitude compared to the data gathered while the module was on the road. Therefore, the Transportation phase is further divided into two sub-phases, Transportation (Road) and Transportation (Jobsite). Only the visual data recorded during the Transportation (Road) will be referred to as the data collected in Lifting and Offloading can be substituted with the pictures taken by the author.

4.2 Modular House Lifting

Given an approximate modular house weight of 27,000 lbs., which can be converted to 12,247 kg, acceleration due to gravity or 1 G of impact is equivalent to 120,143 N. For 5 hours and 35 minutes long Lifting phase, no impact was recorded in the X, Y, and Z axes. ‘No impact was recorded’ may lead to a false impression that the lifting phase was uneventful. But tilt and roll data reflect the contrary and help to depict a clearer picture of what happened and how the modular house was affected. Figure 16 includes the Front-to-Back tilt and Left-to-Right roll graphs based on the data recorded during Lifting.



(a)



(b)

Figure 16. Lifting phase: Front-to-Back tilt (a), Left-to-Right roll (b)

The overall maximum Front-to-Back tilt recorded was 6.2 degrees and occurred at 1:38 PM. The minimum tilt at this instance was 4.4 degrees. The average of maximum/minimum Front-to-Back tilts were 1.6 degrees to 1.6 degrees. The overall minimum tilt recorded for Front-to-Back movements was 0.2 degrees, and the maximum tilt at this instance was 0.4 degrees. The overall minimum tilt occurred between 8:34 AM and 12:34 PM when the contractors and subcontractors finished attaching the two tandem axle dollies and were beginning to lift the front side of the modular house to level it to the truck. From then on, it can be seen in the graph that the tilt values go up significantly. The overall maximum tilt occurred when the modular house was turning left to leave the fabrication yard. (As shown in figure 12 (a), the front side of the modular house was facing the opposite direction from the exit. Making a U-turn was prohibited due to its size and the limited space, so the modular house had to drive around the fabrication yard). The view of the modular house making a left turn is shown in Figure 17.

(a)

(b)

(c)

Figure 17. Modular housing turning left (1:37 PM) (a), Modular house turning left cont. (1:38 PM) (b), Modular house turning left cont. (1:38 PM ~) (c)

It can be difficult to discern from the figure, but the modular house was not only titled backward but also got rolled to the right side as it was making a wide left turn. The disorientation becomes more distinguishable by looking at the wooden beam underneath the modular house and the left tandem axle dollies. In figure 17 (a), it is noticeable that the left tandem axle dollies are not directly underneath the modular house and are exposed outward. In Figures 17 (b) and (c), the wooden beam is rolled upward towards the right side and is off balance.

For Left-to-Right roll movements, the overall maximum values were recorded about 1 minute before the overall maximum Front-to-Back tilt at 1:37 PM, as shown in Figure 16 (b), and it was 3.9 degrees. The minimum value at this instance was 3.7 degrees. The average of maximum/minimum Left-to-Right roll movements was 2.1 degrees to 2.0 degrees. Like Front-to-Back tilts, Left-to-Right roll movements between 8:34 AM to 12:28 PM were uneventful with a few spikes. The overall minimum Left-to-Right roll was -3.8 degrees, with a maximum of -3.0 degrees, and they occurred at 2:08 PM while the modular house was making a wide right turn after completing the left turn to exit the fabrication yard. The view of the modular house making a right turn is captured in Figure 18 (left) (the modular house maneuver in Figure 12 (c) followed upon the completion of the right turn).

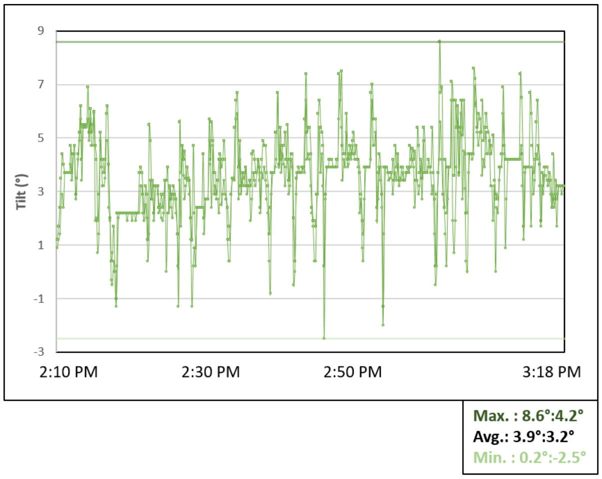
Figure 18. Modular House Making a right turn (left), Modular House completing a right turn (right)

Contrary to what is shown in Figure 17 (b), Figure 18 (left) indicates the wooden beam rolled upward towards the left, hence causing an off-balance between the tandem axle dollies in the opposite direction from Figure 17 (b). The overall minimum Left-to-Right roll, as well as a moderate spike in Front-to-Back tilts, occurred at this point. Both Figure 16 (a) and (b) imply that the modular house was stabilized moments after such an off-balance occurred, and Figure 18 (right) depicts the wooden beam back at a balanced position, proving the alignment of the tilt and roll data recorded with the actual events occurred.

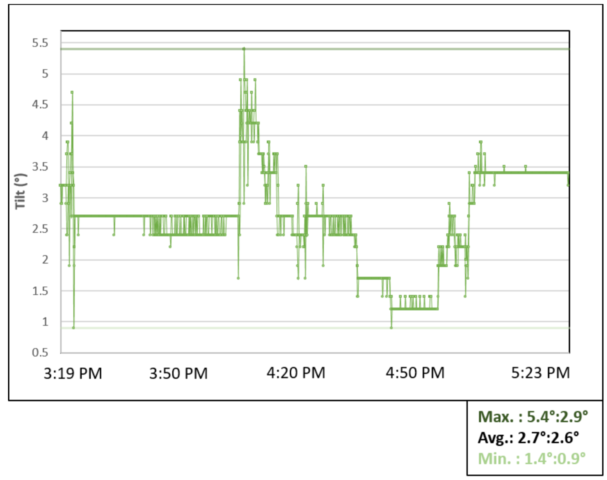
4.3 Modular House Transportation (numerical data)

The speed limits for the roads used ranged from 30, 35, and 45 mi/h. At its fastest, the modular house was being transported at 49 km/h (30.4 mi/h), going barely over the slowest speed limit. Acceleration from and deceleration to a full stop, making wide (left) turns, and road conditions affected the modular house to experience high degrees of Front-to-Back tilt and Left-to-Right roll.

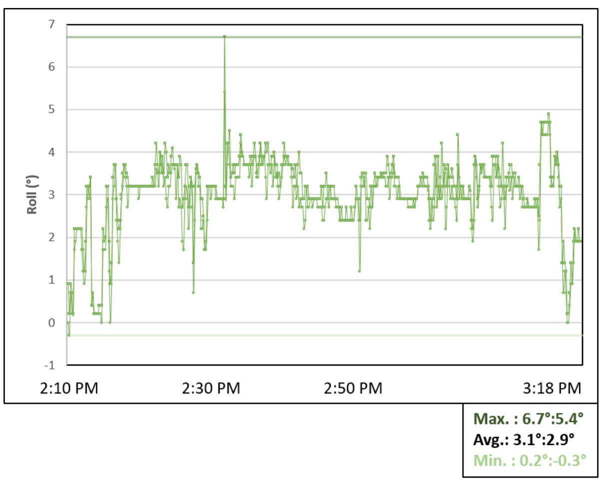
Despite all events or accidents that occurred that are denoted in Table 1, no impact was recorded in the X, Y, and Z axes according to the ShockLog sensor during the Transportation phase. Although the two phases (Lifting and Transportation) can be said to be equivalent in terms of impact recorded, Front-to-Back tilt and Left-to-Right roll data show how the transportation and being on the road affected the modular house to a greater extent than it was on the fabrication yard getting lifted. Tilt and roll graphs have been constructed using the data recorded and are represented in Figure 19.



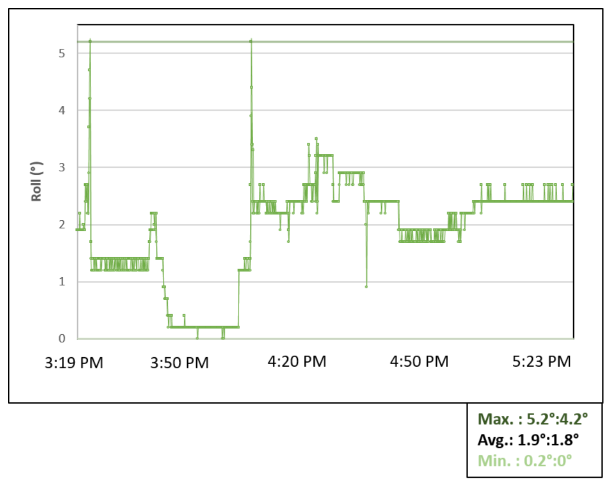
(a)



(b)



(c)



(d)

Figure 19. Phase (Road): Front-to-Back tilt (a), Phase (Jobsite): Front-to-Back tilt (b) Phase (Road): Left-to-Right roll (c), Phase (Jobsite): Left-to-Right roll (d)

As shown in Figures 19 (a) ~ (d), the effects of being on the road are illustrated via overwhelmingly prevalent spikes in Figures 19 (a) and (c), whereas Figures 19 (b) and (d) indicate a moderate modular house state in terms of tilt and roll.

4.3.1 Transportation (Road & Jobsite): Front-to-Back tilt

For Transportation (Road), the overall maximum and minimum (at this instance) Front-to-Back tilts were 8.6 degrees to 4.2 degrees, and they occurred at 3:02 PM. The modular house was on E. Fremont St., and on its right side was a Lowe's mall. At this point, the Left-to-Right rolls were 3.2 degrees to 2.7 degrees. The modular house was driving in a straight line and made no noticeable maneuvers such as a wide turn or a sudden stop that may have caused the high tilts. However, according to the dashcams, the modular house was driving at 49 km/h (30.4 mi/h), which was a lot faster than the usual range of 25km/h (16mi/h) to 30 km/h (19 mi/h). In the dashcam footage, it was also noticeable that the ceiling light and faucet line were swaying a lot, implying a high vibration. The average Front-to-Back tilts were 3.9 degrees to 3.2 degrees. The overall minimum and maximum (at this instance) tilts were -2.5 degrees and 0.2 degrees, and it occurred at 2:46 PM when the modular house was traveling at 31 km/h (19.3mi/h) on the Boulder Hwy going past the Las Vegas Gambling Hall on its right side.

For Transportation (Jobsite), moments after modular house's arrival at the Jobsite, there was a spike of 4.7 degrees to 3.7 degrees tilts at 3:22 PM when the modular house was making a wide left turn into an empty lot to pull back in a straight line into the garden (Figure 13 (a)). As the modular house was turning, it went over a 6-inch curb. Therefore, after the turn, the misalignment between the modular house and the two tandem axle dollies was easily distinguishable and is depicted in Figure 20.

Figure 20. Misaligned axle dollies

In Figure 19 (b), the spike is followed by a sudden drop, which maintains and forms a straight line-like trajectory or a 'stable state.' The stable state lasted from 3:22 PM to 4:05 PM. During this time, the wooden beam was removed and installed it in the rear of the two axle dollies to help them maintain stability while the modular house pulled back into the garden and re-aligned the axle dollies to the modular house. Immediately upon finishing the re-alignment, the driver pulled back and came down the curb (Figure 12 (d)), and directly caused another spike (overall maximum tilt and minimum) of 5.4 degrees to 2.9 degrees that occurred at 4:07 PM. From that point onward, the graph makes a moderate trajectory despite the troublesome processes of placing the modular house at its installation location. As shown in Figure 13 (f), the concrete platform was not wide enough for the two axle dollies. Thus, a stack of wooden beams was made adjacent to it to provide extra space for the axle dollies. Also, it is visible that the axle dollies are misaligned from the modular house due to having gone over two consecutive 6-inch curbs in rear motion.

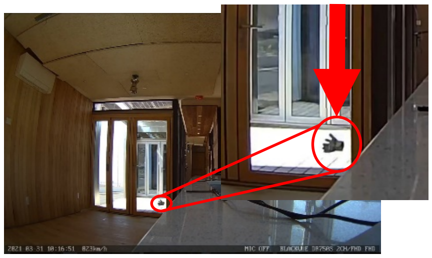
4.3.2 Transportation (Road & Jobsite): Left-to-Right roll

For roll during Transportation (Road), the overall maximum and minimum Left-to-Right rolls were 6.7 degrees to 5.4 degrees. The overall maximum roll happened at 2:31 PM when the modular house was making a wide left turn from W. Sunset Rd. to N. Boulder Hwy. at 16 km/h (10 mi/h). Despite the low speed, the ceiling light and faucet line movements were very pronounced in the dashcam footage. The maximum and minimum Front-to-Back tilts at this instance were 5.6 degrees to 2.4 degrees. The average Left-to-Right rolls were 2.3 degrees to 2.2 degrees, and the overall minimum and maximum rolls of -0.3 degrees and 0.2 degrees were recorded moments after the modular house made a right turn to exit the fabrication yard at 2:10 PM.

For roll during Transportation (Jobsite), like tilt, spike of 5.2 degrees to 4.2 degrees rolls were observed at 3:22 PM before the stable state. Another spike occurred moments before the second spike in the tilt graph occurred at 4:06 PM due to the same cause. The roll graph makes an even more moderate trajectory after the second spike occurred.

4.4 Modular House Transportation (visual data)

The other events/accidents denoted in Table 1 are depicted in Figure 21.



(a) (b)

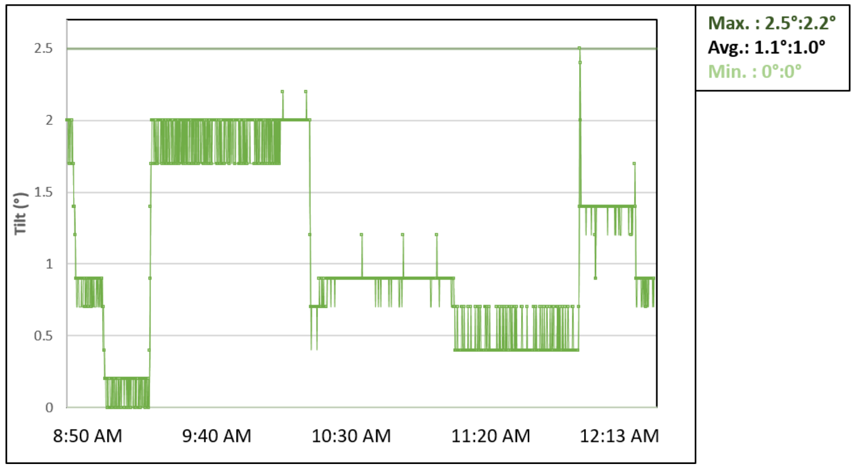
(c)

Figure 21. Transportation Phase: Glove falling (a), Wooden beam failure (b), Solar panel damaged (c)

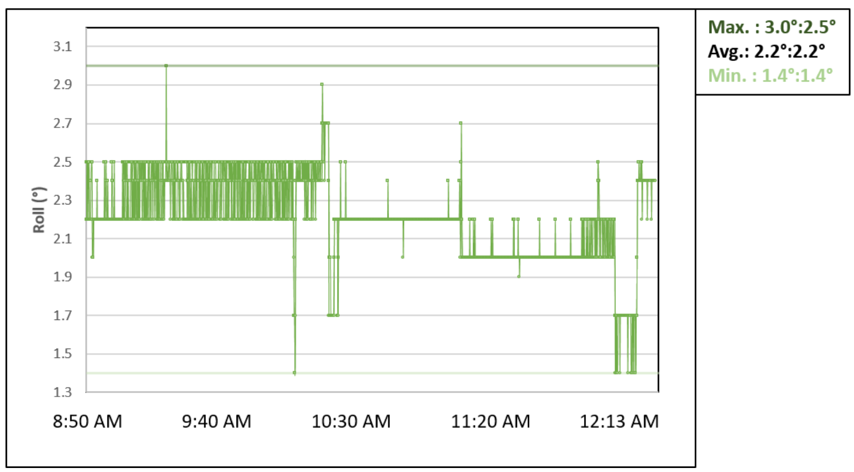
As one could expect, both tilt and roll graphs did not reflect the fallen glove in Figure 21 (a) due to its relative insignificance compared to the modular house. Wooden beam failure shown in Figure 21 (b) holds much greater significance, and both graphs did reflect wooden beam failure. The tilts recorded were -1 degrees to -1.3 degrees, and the rolls were 3.4 degrees to 2.7 degrees. These values can be valuable in themselves. However, when they are put into the graphs and placed next to other values recorded, they do not stand out. Surprisingly, this was also true for the damaged solar panel. The modular house was driving at 42 km/h (26 mi/h) as it went under the overpass and resulted in 3.9 degrees to 3.4 degrees Front-to-Back tilts and 3.4 degrees to 3.2 degrees rolls, which were not noticeably different from the values recorded before and after the accident. Moreover, dashcam footage also did not provide any visual evidence of the unusual impact that can be associated with the damaged solar panel.

4.5 Modular House Offloading/Installing

The modular house offloading process took approximately 6 hours and 30 minutes to complete, and its first 3 hours and 23 minutes were recorded with no impact in all three axes, meaning all the impacts the modular house felt throughout all three phases of the transportation were below the minimum impact threshold of 1G. The Front-to-Back tilt and Left-to-Right roll graphs for Offloading phase are presented in Figure 22.



(a)



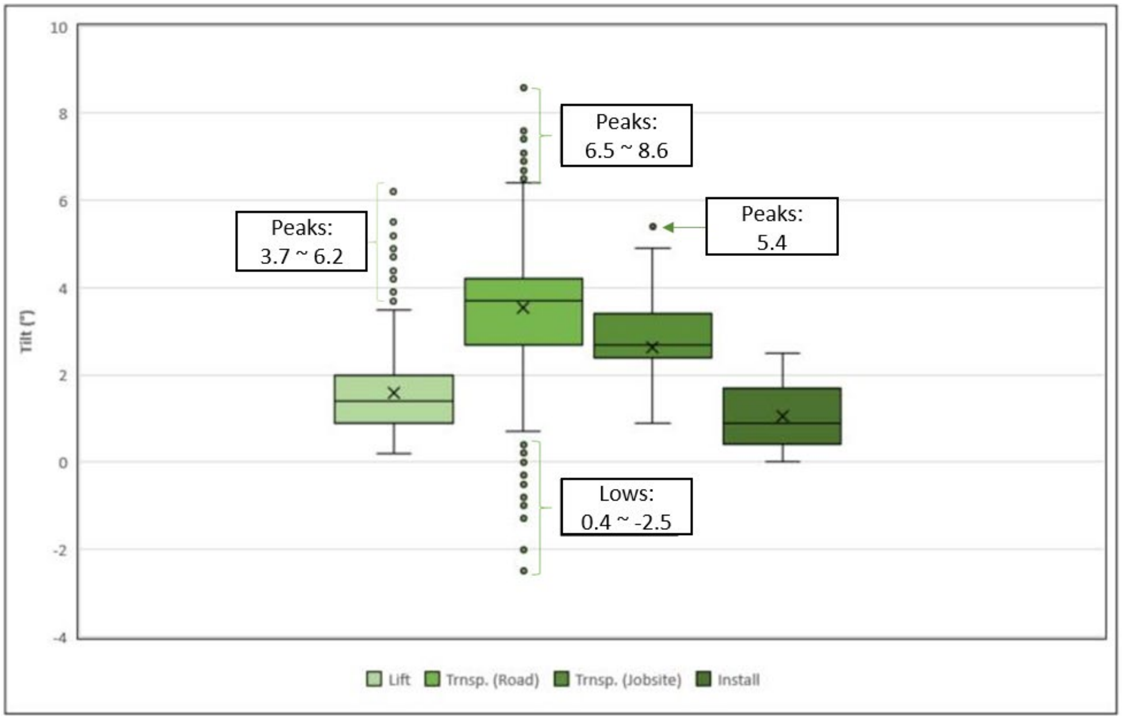
(b)

Figure 22. Offloading Phase: Front-to-Back tilt (a), Left-to-Right roll (b)

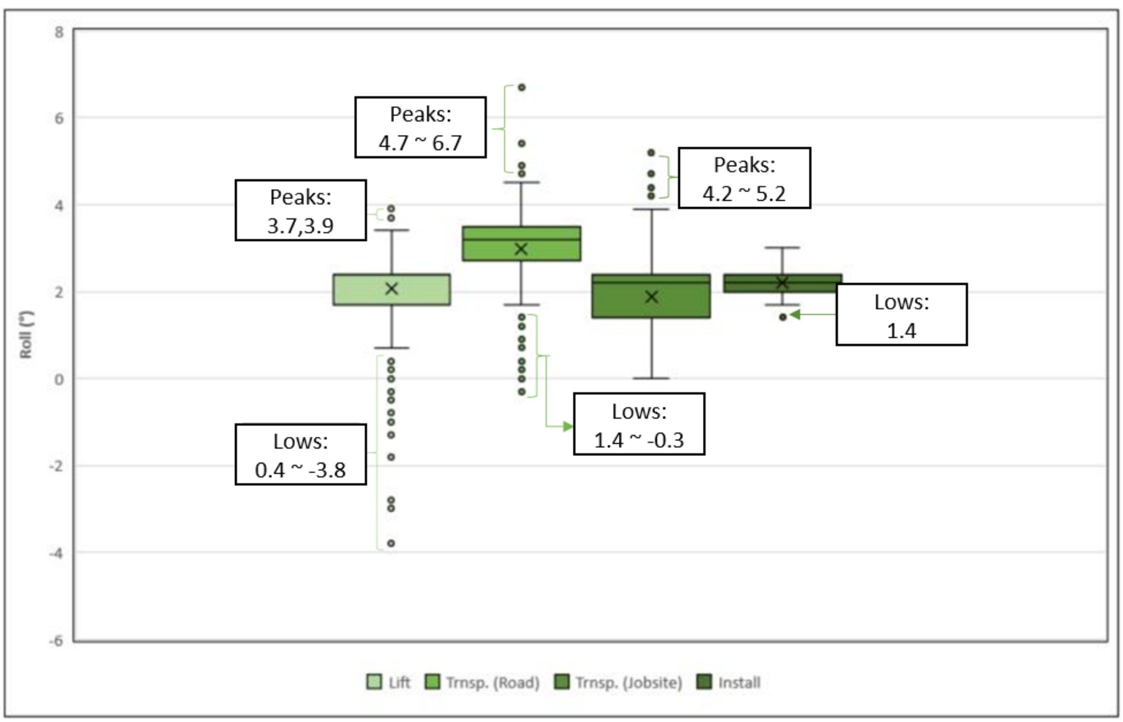
The overall maximum and minimum Front-to-Back tilt recorded were 2.5 degrees to 2.2 degrees at 11:48 AM. The average tilts were 1.1 degrees to 1.0 degrees. The overall minimum tilts of 0 degrees to 0 degrees were recorded between 9:03 AM and 9:18 AM, and during that period the modular house was upright. The overall maximum Left-to-Right rolls were 3.0 degrees to 2.5 degrees recorded at 9:18 AM. The average roll were 2.2 degrees to 2.2 degrees, and the overall minimum roll were 1.4 degrees to 1.4 degrees at 10:04 AM and 12:06 PM. In summary, in comparison to the other two phases, the lowest values of tilt were recorded during the Offloading phase, and considering the average values, the rolls recorded were similar to the Lifting phase. However, there were a lot more peaks in the Lifting phase towards the end, when the modular house was leaving the fabrication yard.

4.6 Transportation Summary

Tilt and roll data gathered from modular house Lifting, Transportation, and Offloading revealed the modular house, at its default position, was slightly titled backward and rolled to the left. The data suggested that the modular house was at its most stable state while it was getting lifted at the fabrication yard and when it was getting placed on top of the concrete slab inside the garden and offloaded/installed. Under the above conditions, the peaks in data, if there were any, incurred from distinctive and unordinary module maneuvers. When the modular house was on the road, the number of peaks increased with lesser distinctiveness, meaning it was more difficult to pin down one module maneuver that caused the peaks. The box plots of tilt and roll data recorded are shown in Figure 23.



(a)



(b)

Figure 23. Tilt data from transportation (a), Roll data from transportation (b)

For the Lifting phase, two different module maneuvers caused all the peaks and lows for tilt and roll data illustrated in Figures 23 (a) and (b). Given tilt, all peaks and lows, including the overall maximum peakof 6.2 degrees, occurred as the modular house was making a left turn at 1:37 PM (Figure 17). The peaks for the roll of 3.9 degrees and 3.7 degrees occurred about a minute before. The lows ranged from 0.4 degrees to -3.8 degrees and occurred when the modular house was making a wide right turn to exit the fabrication yard at 2:08 PM (Figure 18). For the Transportation (Road) phase, the overall maximum peak for tilt and roll were 8.6 degrees and 6.7 degrees, respectively. The overall maximum peak for tilt occurred at 3:02 PM when the modular house was driving at a relatively faster speed of 49 km/h in a straight line. The roll occurred at 2:31 PM when the modular house was making a wide left turn. As stated, the tilt and roll peaks and lows recorded in the Transportation (Road) phase were incurred from sources independent from each other. For the Transportation (Jobsite) phase, while not apeak, a spike of 4.7 degrees occurred at 3:22 PM as the module went over the 6-inch curb. Another peak of 5.4 degrees for tilt occurred at 4:07 PM due to the impact the module felt as it came down the 6-inch curb. The maximum peak of 5.2 degrees for the roll and other peaks also occurred at or around 3:22 PM and 4:07 PM. The number of peaks and lows and other notable values from box plots are included in Tables 2~5.

Table 2. Numbers and Distribution of Peaks & Lows: Tilt

	Tilt			
	# Peaks/Lows	Back (+°)	Upright (0°)	Front (-°)
Lift (a)	42	**42**	0	0
Trnsp. (b: Road)	57	**39**	6	12
Trnsp. (b: Jobsite)	1	**1**	0	0
Offloading (c)	0	0	1	0

The numbers of peaks and lows from the data points gathered for tilt during the Lifting phase, Transportation (Road), Transportation (Jobsite), and Offloading phases were 42, 57, 1, and 0, respectively. For Lifting phase, all peaks were positive, and there were no instances of the modular house being positioned upright. For Transportation (Road) phase, 39 of 57 peaks and lows were positive, and 12 were negative. There were 6 instances of the modular house being upright, which were also counted as lows. For Transportation (Jobsite) phase, only 1 positive peak was recorded with no instance of the modular house being upright positioned. For Offloading phase, no peaks and lows were recorded. There was one instance of the modular house being upright.

Table 3. Specification of Boxplot Data Points: Tilt

	Tilt					
	Max. (°)	Q3 (°)	Median (°)	Mean (°)	Q1 (°)	Min. (°)
Lift (a)	3.5	2.0	1.4	1.6	0.9	0.2
Trnsp. (b: Road)	6.4	4.2	3.7	3.6	2.7	0.7
Trnsp. (b: Jobsite)	4.9	3.4	2.7	2.6	2.4	0.9
Offloading (c)	2.5	1.7	0.9	1.1	0.4	0

The maximum, third quartile, median, mean, first quartile, and minimum tilt values recorded during Lifting phase were 3.5, 2.0,1.4,1.6,0.9, and 0.2 degrees, respectively. For Transportation (Road) phase, the values were 6.4,4.2,3.7,3.6,2.7 and 0.7, respectively. For Transportation (Jobsite) phase, the values were 4.9,3.4,2.7,2.6,2.4, and 0.9, respectively. For Offloading phase, the values were 2.5,1.7,0.9,1.1,0.4, and 0, respectively. Overall, the values recorded during Transportation (Road) phase were the highest, and the magnitude of values recorded increases from Offloading to Lifting to Transportation (Jobsite) to Transportation (Road).

Table 4. Numbers and Distribution of Peaks & Lows: Roll

	Roll			
	# Peaks/Lows	Left (+°)	Centered (0°)	Right (-°)
Lift (a)	346	**329**	5	12
Trnsp. (b: Road)	70	**64**	5	1
Trnsp. (b: Jobsite)	6	**6**	3	0
Offloading (c)	14	**14**	0	0

The numbers of peaks and lows from the data points gathered for roll during the Lifting, Transportation (Road), Transportation (Jobsite), and Offloading phases were 346, 70, 6, and 14, respectively. For Lifting phase, 329 of 346 peaks and lows were positive, and 12 were negative. There were 5 instances of the modular house being positioned centered, which were also peaks. For Transportation (Road) phase, 64 of the 70 peaks and lows were positive, and 1 was negative. There were 5 instances of the modular house being centered, which were also calculated as peaks. For Transportation (Jobsite), 6 positive peaks were recorded, with 3 instances of the modular house being centered. No negative lows were recorded. For Lifting phase, 14 positive peaks were recorded. There was no instance of the modular house being centered.

Table 5. Specification of Boxplot Data Points: Roll

	Roll					
	Max. (°)	Q3 (°)	Median (°)	Mean (°)	Q1 (°)	Min. (°)
Lift (a)	3.4	2.4	2.1	2.1	1.7	0.7
Trnsp. (b: Road)	4.5	3.5	3.2	3.0	2.7	1.7
Trnsp. (b: Jobsite)	3.9	2.4	2.2	1.9	1.4	0
Offloading (c)	3.0	2.4	2.2	2.2	2.0	1.7

The maximum, third quartile, median, mean, first quartile, and minimum roll values recorded during Lifting phase were 3.4,2.4,2.1,2.1,1.7 and 0.7 degrees, respectively. For Transportation (Road) phase, the values were 4.5,3.5,3.2,3.0,2.7 and 1.7, respectively. For Transportation (Jobsite) phase, the values were 3.9,2.4,2.2,1.9,1.4 and 0, respectively. For Offloading phase, the values were 3.0,2.4,2.2,2.2,2.0 and 1.7, respectively. The roll values recorded increase from phase Offloading to Lifting to Transportation (Jobsite) to Transportation (Road), given maximum values. However, when considering median and mean values, all phases were similar except for Transportation (Road).

CHAPTER 5: DISCUSSION

5.1 Introduction

The Discussion presents interesting and relevant findings discovered from the Mojave Bloom transportation project, as well as the limitations of the case study conducted. The findings validate and address the work and limitations of previous research. This section concludes with a recommendation on future research opportunities utilizing an object tracking method.

5.2 Changes in Mojave Bloom Transportation Project

In UNLV's Mojave Bloom modular house transportation project, a few changes in planning and tool selection occurred. First and most critically, its final installation location changed from Washington D.C. to the local Community Healing Garden, moving approximately 2,400 miles closer to the fabrication shop where the modular house was manufactured. Second, the modular house was originally planned to be lifted using forklifts, hence the reason why it had several built-in holes to fit the forks. However, as shown in previous chapters, four hydraulic lifts were adopted to lift the modular house. Third, according to the original plan, a flatbed tractor-trailer was going to be used as the means of transporting the modular house. Instead, the modular house simply got attached to the truck with two tandem axle dollies attached to its rear side, forming a bogey support system. It seems reasonable to suspect such changes incurred from extensively shortened transportation distances.

5.3 Mojave Bloom and the Research Works Reviewed

As stated, (Smith et al., 2007), similar to this case study project (the lifting method adopted for (Valinejadshoubi et al., 2022) was not specified), adopted hydraulic jacks to lift the mini home. (Smith et al., 2007) reported all of the module damages originated from its lifting process, and the transportation-induced impacts/vibrations propagated those lifting-borne damages. However, for this case study, the tilt and roll data and the dashcam and 360 camera footage recorded indicated that the modular house experienced significantly less impact/vibration during the lifting process compared to the transporting process. There are a few differences in both projects regarding the module characteristics and the measures taken that might have separately or collectively caused such distinctions.

First, the mini home is a wooden modular home, whereas the Mojave Bloom adopts HSS framing. Consequently, the Mojave Bloom will have greater resistance to stresses and deformation. Second, unlike the mini home, there were no delays among the hydraulic jacks. All four hydraulic jacks were connected to one pump, which allowed synchronized lifting. Third, as mentioned, the two case studies reviewed were transported via flatbed tractor-trailers, whereas the Mojave Bloom was transported via a bogey support system. The connection between the modular house, bogey support system, and the truck was insecure, therefore the stability of the modular house was considerably compromised.

5.4 The Default Module Configuration

The wheel diameters of the adopted tandem axle dollies were not level with the 5th wheel of the truck, which caused a slight backward tilt towards the rear side of the modular house. Such a tilted orientation of the modular house inflated the Front-to-Back tilt values. As shown in Figure 23 (a), the boxplots are formed above the 0-degree line (upright), illustrating the modular house's tendency to tilt backward, and only a few peaks and lows recorded during the phase (b: Road) depict instances of forwarding tilt. It was not as visually obvious as the tilt, but the boxplots for the Left-to-Right roll movements illustrated in Figure 23 (b) are also formed above the 0-degree line (centered), indicating the modular house's tendency to roll to the left side more. A noticeable instance of the modular house rolling to the right side occurred when the modular house made a wide right turn to exit the fabrication yard. The modular house's tendencies shown in the two graphs prove that the modular house, at default, was tilted backward and rolled to the left side, which, combined with the already unstable bogey support system, exacerbated the tilt and roll movements, especially when the modular house was making big maneuvers such as wide left or right turns. Figures 17 (b), (c), 18 (left), (right), and 21 (b) depict the bogey support system, hence the tandem axle dollies, tilting towards the direction the modular house was turning.

5.5 Bogey Support System

The adjustment requirements of bogey support system incurred meaningful and distinctive transportation project time delays. In the fabrication yard, the transportation was delayed by 1 hour and 13 minutes after a connection between the modular house, bogey support system, and the truck was made. A few minutes after being on the road, the modular house was driving up Eastgate Rd, and the wooden beam portion of the bogey support system failed, causing a temporary transportation halt. Fortunately, the issue was quickly addressed, and the total delay was only 10 minutes. At the Jobsite, another delay of about 43 minutes occurred when the modular house was temporarily located in an empty lot across the installation location to, again, adjust the bogey support system. Calculating the modular house arrival time, it took 2 hours and 14 minutes to put the modular house on top of its installation location.

During this time, the public use of the road Coolidge Ave. between S. Casino Center Blvd. and S. 3rd St. was restricted. After locating the module inside the garden, it was already too late, and the offloading portion of the transportation project got pushed back by one day, and the accumulation of said time delays amounted to 4 hours and 20 minutes, which could have gotten extended by a significant amount if the wooden beam failure led to module damage or was not addressed promptly. The roads restricted were uncongested, so the public disturbance caused seemed negligible.

The less distinctive time delay occurred due to the slow speeds at which the modular house was being driven on the road. At its fastest, it was driving barely over the slowest speed limit since it was thought that if it were to be driven any faster, the risk of module damage would have increased exponentially. The Front-to-Back tilt data also aligned with the above hypothesis, as the maximum peak value of 8.6 degrees to 4.2 degrees was recorded at the instance the modular house was driving at its fastest speed of 30.4 mi/h.

5.6 Likelihood of Module Damage: Tilt vs. Roll

However, given the configuration of the modular house, bogey support system, and truck connection, a question arises regarding the criticality of tilt motions being a bigger driving factor in leading to module damage than the roll motions. In other words, the front and back sides of the modular house were fixed via the truck and the two tandem axle dollies. Therefore, the Front-to-Back tilt motions could be more forgiving than the Left-to-Right roll motions when it comes to incurring module damages because the left and right sides of the module were relatively loose. In that sense, when the modular house was traveling at 30.4 mi/h, the Left-to-Right roll values recorded were 3.2 degrees to 2.7 degrees, which is equal to the median value of all roll values recorded during Transportation (Road).

The maximum peak values recorded through the transportation project were 3.9, 6.7, and 5.2 degrees, respectively. The first peak occurred when the modular house made a left turn at the fabrication yard, the second peak occurred when the modular house made a wide left turn on the road, and the last one occurred when the modular house came down a 6-inch curb. Given these circumstances of occurrences of the maximum peaks in roll, it can be hypothesized that making left/wide turns or direct impact are the main causes of spiking in roll graphs.

5.7 The Effects of Road Conditions on Tilt and Roll

While the modular house was at the fabrication yard getting lifted or Jobsite getting offloaded, correlations between the spikes or even peaks and lows in tilt and roll data and the modular house maneuvers that caused them are perceptible. But, recognizing those relationships become difficult once the modular house is on the road. Though the instance of a maximum peak in tilt and roll and other spikes caused by making wide turns are still recognizable, there were a lot of other peaks and lows or spikes whose cause of occurrence was unforeseen. At many points, the modular house appeared to be traveling at normal speeds without making any big maneuvers, and the peaks and lows in tilt or roll occurred unexpectedly. It is thought that these seemingly random spikes in tilt or roll are caused by the conditions of the roads the modular house is driving on.

5.8 The Effects of Transportation-Induced Impacts/Vibrations

Despite the above-described instability of the modular house during transportation, no visible damage has occurred to the volumetric module, except for one of the solar panels installed on top of the modular house (Figure 21 (c)). The default backward tilted configuration of the modular house raised its front side by a few inches, making it slightly go over the height clearance of one of the overpasses on the transportation route. However, in this instance, neither the numerical data nor the video footage reflected the impact/vibration. The tilt of 3.9 degrees to 3.4 degrees and the roll of 3.4 degrees to 3.2 degrees were recorded, which are within the interquartile ranges (IQR).

5.9 Is Flat-Bed Tractor Trailer Always Optimal?

So far, the discussions based on the analysis of the results may appear to encourage the use of flatbed tractor-trailers as the means of volumetric module transportation over the bogey support systems for the sake of module stability during transportation. However, given this specific case study, the author recognized one characteristic of using tractor-trailers that might make its use complicated. It is mentioned earlier in the study that the entrance and laydown space inside the Jobsite is limited. The flatbed tractor-trailers might be able to deliver the module more safely to the Jobsite. However, offloading the module in such a tight space could be more challenging as the use of forklifts will be inevitable. With the bogey support system, offloading module within a tight space can be more manageable as it can be offloaded just by removing the bogey support.

5.10 Case Study Limitations

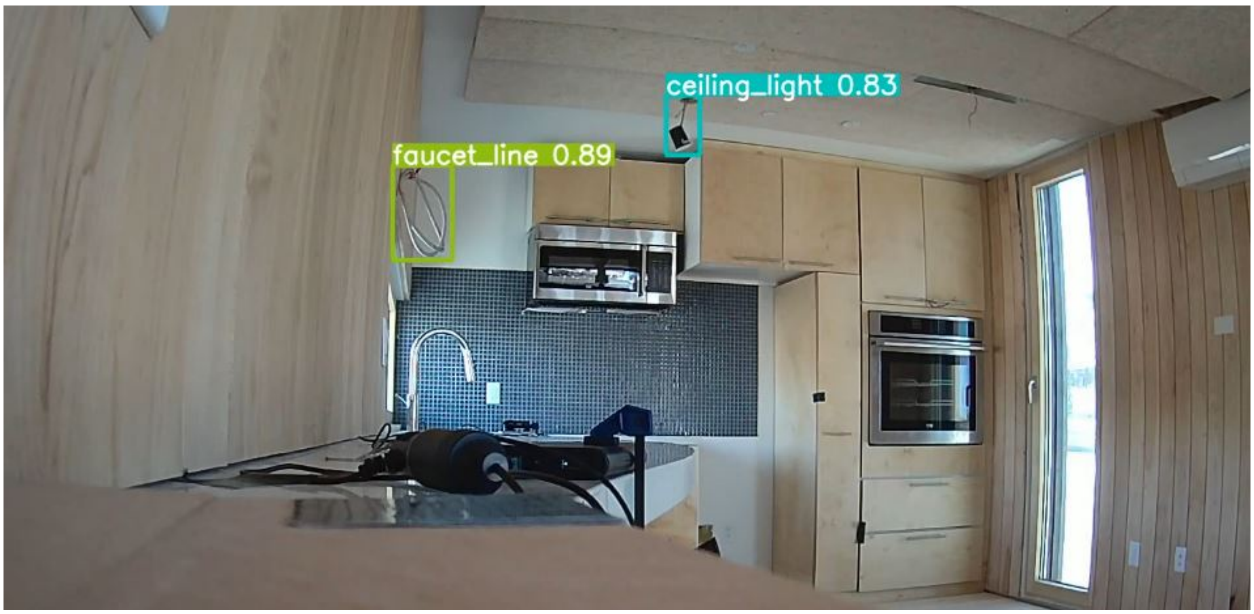
Given the typical maximum volumetric module transpiration distances of 250 to 600 miles, the team UNLV's Mojave Bloom modular house transportation distance was extremely short at only 13.2 miles, which converted to less than one hour spent on the road despite the slow speeds at which the module traveled. In other words, the time the modular house was exposed to the transpiration-induced road impacts/vibrations, and the amount of data recorded during transpiration, were also very limited. On top of that, the case study lacked in terms of the number of tools, equipment, or sensors used. Only one impact/vibration sensor was installed in the corridor of the modular house, and no other numerical data measuring tools, such as the pressure taps and deformation sensors, were used. Lastly, the Mojave Bloom adopted HSS framing, whereas the Mini Home adopted typical wood framing, thus, the use of synchronized hydraulic jacks for module lifting requires further validation. Nevertheless, this case study identified valuable findings that could be adopted by industry practitioners or be further validated in future research.

5.11 Future Research Opportunities

The dashcam and 360 camera footage captured the falling glove and ceiling light swaying. The impact, tilt, and roll data do not reflect these events since the magnitude of impacts they have on the large volumetric module like the Mojave Bloom is trivial. But, because the volumetric modules are often delivered fully furnished, damage occurring to that furniture can also reduce the economic benefits. Also, it was not mainly discussed in this case study, but the other well-renowned advantage of the modular method is the ease of relocation. The modules can be even more full with furniture before the relocation, and removing them all may be of huge inconvenience. Accordingly, it may be beneficial to track the movements of the furniture on top of securing them to minimize the chances of damage occurring to the furniture themselves or cascading damage that the fallen furniture might inflict.

This case study examined the Object Tracking method with a custom-trained object detection model called YOLOv5 to track the movements of the furniture inside the module. Utilizing the dashcam and 360 camera footage, the ceiling light, faucet line, and even a falling glove were detected and tracked as shown in Figure 24.

(a)



(b)

Figure 24. Glove & Faucet line detected (a), Faucet line & Ceiling light detected (b)

Although the object detection and tracking were done using the recorded footage, it is plausible to implement it with a real-time recording camera. And the information regarding the locations of each object is stored while tracking their movements, and a system can be created that can send an alert to the driver when abnormal object movements are detected. As a result, the driver can react accordingly by temporarily stopping the transportation to resolve the issues.

CHAPTER 6: CONCLUSION

In conclusion, while no impacts and damage were observed during the transportation of the UNLV's Mojave Bloom modular house, the analysis of Front-to-Back tilt, Left-to-Right roll, dashcams and 360 camera footage provided led to the recognition of several helpful and interesting findings. Valinejadshoubi et al. (2022)'s claim of stress and module deformation due to twisting motion from desynchronized movements among hydraulic jacks was partially validated. The hydraulic jacks used for this case study had synchronized movements. The lowest amount of Front-to-Back tilt and Left-to-Right roll movements were recorded during lifting/offloading via hydraulic jacks. However, further validation is desirable by testing synchronized hydraulic jacks for the module made out of the same material (Mojave Bloom had HSS framing) on a much longer transportation distance.

There was one instance of exterior module damage (solar panel), numerous potential module damage, and distinctive and subtle project time delays, all caused by additional adjustments required for using a wooden beam for the bogey support system. The damaged solar panel serves as a valuable lesson that the height of the module should also be considered when planning the transportation route. The speeds at which the modular house was traveling seemed to directly cause variances in Front-to-Back tilt values, hence why the majority of transportation commenced at slower speeds than the posted speed limits. Such time delays could be more significant in longer transportation. However, it is hypothesized the contribution of high tilt values might not be as critical as the high roll values at increasing the risks of module damage due to the way the module was connected and secured. Wide turns seemed to directly cause high roll values, not the faster travel speeds. Thus it might be better to focus on minimizing the turn rather than slowing down to eliminate the risks of transportation-induced module damage. The causes of peaks and lows in tilt and roll values recorded during the phases lifting (a) and (b: Jobsite) were easily recognizable, while the seemingly random peaks and lows were observed while the modular house was in phase (b: Road) due to road imperfections.

The adjustment requirements with the bogey support system and more distinctive time delays may appear to encourage the use of a flatbed tractor-trailer over the bogey support system. However, opting for a flatbed tractor-trailer might not always be optimal. The use of forklifts for the laydown of volumetric modules is necessary for the flatbed tractor-trailer. But, in some cases, Jobsites do not have sufficient laydown spaces to incorporate the use of forklifts, making the use of the bogey support system more adequate. Regardless, the bogey support system used for this case study required a lot of expertise from the stakeholders to work with and to be viable for longer and extensive trips, significant improvements are demanding.

All in all, as covered in the discussion, changes in planning in construction projects occur frequently. Therefore, it is in all stakeholders' best interest to acquire as many alternatives as possible to carry out the projects seamlessly through those changes. The findings from this case study contribute by validating previous research findings and addressing their limitations by introducing other alternative means for module transportation, the need for further dimensional considerations, and the effects of different module maneuvers. It is deemed this case study will mainly help industry practitioners deliver timely and safe volumetric module transportation projects.

REFERENCES

Azari, R., Javanifard Naomi, Markert Debra, Strobel Kristen, & Yap Jason. (2013). *Modular Prefabricated Residential Construction: Constraints and Opportunities*.

Azhar, S., Lukkad, M. Y., & Ahmad, I. (2013). An Investigation of Critical Factors and Constraints for Selecting Modular Construction over Conventional Stick-Built Technique. *Http://Dx.Doi.Org/10.1080/15578771.2012.723115*, *9*(3), 203–225. https://doi.org/10.1080/15578771.2012.723115

Bachelor, S. V. (2012). *Feasibility, benefits and challenges of modular construction in high rise development in the United States : a developer's perspective*. https://dspace.mit.edu/handle/1721.1/77129

Bertram, N., Fuchs, S., Mischke, J., Palter, R., Strube, G., & Woetzel, J. (2019). *Modular construction: From projects to products*.

Blankinship, S. (2008). Modular construction gains ground: rising costs, labor shortages, safety and other factors favor modularization for power plant construction projects. With the potential benefits, however, come some risks. *Power Engineering*, *112*(3), 54–59. https://go.gale.com/ps/i.do?p=AONE&sw=w&issn=00325961&v=2.1&it=r&id=GALE%7CA178232739&sid=googleScholar&linkaccess=fulltext

Cameron, P. J. (Peter J., & Di Carlo, N. G. (2007). *Piecing together modular : understanding the benefits and limitations of modular construction methods for multifamily development*. https://dspace.mit.edu/handle/1721.1/42038

Choi, J. O., Asce, A. M., O'connor, J. T., Asce, M., Young, ;, Kwak, H., Shrestha, B. K., & Asce, S. M. (2019). Modularization Business Case Analysis Model for Industrial Projects.

Journal of Management in Engineering, *35*(3), 04019004. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000683

Choi, J. O., Bin, X., Tae, C. &, Kim, W., Chen, X. Bin, & Kim, T. W. (2017). Opportunities and challenges of modular methods in dense urban environment. *Https://Doi.Org/10.1080/15623599.2017.1382093*, *19*(2), 93–105. https://doi.org/10.1080/15623599.2017.1382093

Choi, J. O., Chen, X. Bin, & Kim, T. W. (2017). Opportunities and challenges of modular methods in dense urban environment. *Https://Doi.Org/10.1080/15623599.2017.1382093*, *19*(2), 93–105. https://doi.org/10.1080/15623599.2017.1382093

Faiz Musa, M., Reeza Yusof, M., Fadhil Mohammad, M., & Samsudin, N. (2016). Towards the adoption of modular construction and prefabrication in the construction environment: A case study in Malaysia Disaster Management View project Competence interior design in sustainable refurbishment project View project. *Article in Journal of Engineering and Applied Sciences*, *12*, 749. https://www.researchgate.net/publication/305550264

Gan, X., Chang, R., & Wen, T. (2018). Overcoming barriers to off-site construction through engaging stakeholders: A two-mode social network analysis. *Journal of Cleaner Production*, *201*, 735–747. https://doi.org/10.1016/J.JCLEPRO.2018.07.299

Ghannad, P., Lee, Y.-C., & Choi, J. O. (2020). Feasibility and Implications of the Modular Construction Approach for Rapid Post-Disaster Recovery. *International Journal of Industrialized Construction*, *1*(1), 1. https://doi.org/10.29173/ijic220

Godbole, S., Lam, N., Mafas, M., Fernando, S., Gad, E., & Hashemi, J. (2018). Dynamic loading on a prefabricated modular unit of a building during road transportation. *Journal of Building Engineering*, *18*, 260–269. https://doi.org/10.1016/J.JOBE.2018.03.017

Gustafsson, Å., Vessby, J., & Rask, L.-O. (2011). Identification of potential improvement areas in industrial housing: A case study of waste. *Lean Construction Journal*, 61–71. http://creativecommons.org/licenses/by-nc-nd/3.0/61www.leanconstructionjournal.orgwww.leanconstrutionjournal.org

Hu, C.-S., Li, C.-G., Liao, H.-X., Li, K.-F., & Dai, N.-X. (2007). Load behaviors of a prefabricated wood framing house during lifting and transportation. *For. Stud. China*, *9*(3), 221–224. https://doi.org/10.1007/s11632-007-0036-9

Hwang, B. G., Shan, M., & Looi, K. Y. (2018a). Key constraints and mitigation strategies for prefabricated prefinished volumetric construction. *Journal of Cleaner Production*, *183*, 183–193. https://doi.org/10.1016/J.JCLEPRO.2018.02.136

Hwang, B. G., Shan, M., & Looi, K. Y. (2018b). Knowledge-based decision support system for prefabricated prefinished volumetric construction. *Automation in Construction*, *94*, 168–178. https://doi.org/10.1016/J.AUTCON.2018.06.016

Innella, F., Bai, Y., & Zhu, Z. (2020). Mechanical performance of building modules during road transportation. *Engineering Structures*, *223*. https://doi.org/10.1016/J.ENGSTRUCT.2020.111185

Khodabandelu, A., Choi, J. O., Park, J. W., & Sanei, M. (2020). Developing a Simulation Model for Lifting a Modular House. *Construction Research Congress 2020: Computer Applications - Selected Papers from the Construction Research Congress 2020*, 145–152. https://doi.org/10.1061/9780784482865.016

Khodabandelu, A., Park, J. W., Choi, J. O., & Sanei, M. (2022). Analysis of a Long Volumetric Module Lift Using Single and Multiple Cranes. *9th International Conference on Construction Engineering and Project Management*.

https://digitalscholarship.unlv.edu/fac_articles/932

Lacey, A. W., Chen, W., Hao, H., & Bi, K. (2018). Structural response of modular buildings – An overview. *Journal of Building Engineering*, *16*, 45–56. https://doi.org/10.1016/J.JOBE.2017.12.008

Lawson, M., Asce, M., Ogden, R. G., & Bergin, R. (2012). *Application of Modular Construction in High-Rise Buildings*. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000057

Lawson, M., Ogden, R., & Goodier, C. (2014). *Design in Modular Construction*. https://doi.org/10.1201/B16607

Li, C. Z., Hong, J., Xue, F., Shen, G. Q., Xu, X., & Mok, M. K. (2016). Schedule risks in prefabrication housing production in Hong Kong: a social network analysis. *Journal of Cleaner Production*, *134*(Part B), 482–494. https://doi.org/10.1016/J.JCLEPRO.2016.02.123

Liu, Z., Gu, Z., Bai, Y., & Zhong, N. (2018). Intermodal transportation of modular structure units. *World Review of Intermodal Transportation Research*, *7*(2), 99–123. https://doi.org/10.1504/WRITR.2018.091245

Mao, C., Xie, F., Hou, L., Wu, P., Wang, J., & Wang, X. (2016). Cost analysis for sustainable off-site construction based on a multiple-case study in China. *Habitat International*, *57*, 215–222. https://doi.org/10.1016/J.HABITATINT.2016.08.002

MBI. (2019). *2019 Report: Permanent Modular Construction*. www.hallahanassociates.com

McGraw, Cassino, K. E., Bernstein, H. M., Gudgel, J., Gudgel Michele Russo, J. A., Laquidara-Carr, D., Director, L. A., Taylor Art Director, W., Manager Alison Lorenz, P., Savad Design Harry Segal, S., Director Alex Flannery, C., Editor Enver Fitch, D., & Green Associate Contributor Bruce Buckley Research Project Manager, L. (2011). *McGraw-Hill*

Construction Prefabrication and Modularization: Increasing Productivity in the Construction Industry SmartMarket Report Executive Editor. www.construction.com

O'Connor, J. T., Asce, M., O'brien, W. J., Choi, J. O., & Asce, S. M. (2014). Critical Success Factors and Enablers for Optimum and Maximum Industrial Modularization. *Journal of Construction Engineering and Management*, *140*(6), 04014012. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000842

O'Connor, J. T., O'Brien, W. J., & Choi, J. (2013). Industrial Modularization: How to Optimize? How to Maximize? In *Research Report 283-11, Construction Industry Institute*. https://www.construction-institute.org/resources/knowledgebase/knowledge-areas/modularization/topics/rt-283

Polat, G. (2008). Factors Affecting the Use of Precast Concrete Systems in the United States. *Journal of Construction Engineering and Management*, *134*(3), 169–178. https://doi.org/10.1061/(ASCE)0733-9364(2008)134:3(169)

Rippon, J. A. (2011). *THE BENEFITS AND LIMITATIONS OF PREFABRICATED HOME MANUFACTURING IN NORTH AMERICA*.

Smith, I., Asiz, A., Gupta, G., (2007). High Performance Modular Wood Construction Systems. *Final Report, Value to Wood Program, Project UNB5, Natural Resources Canada, Ottawa, Canada, 2007, p.80. Project No. UNB5*

Sun, Y., Wang, J., Wu, J., Shi, W., Ji, D., Wang, X., & Zhao, X. (2020). Constraints Hindering the Development of High-Rise Modular Buildings. *Applied Sciences 2020, Vol. 10, Page 7159*, *10*(20), 7159. https://doi.org/10.3390/APP10207159

Thompson, J. (2019). *Modular Construction: A Solution To Affordable Housing Challenges* (Vol. 17).

Valinejadshoubi, M., Bagchi, A., & Moselhi, O. (2022). Damage detection for prefabricated building modules during transportation. *Automation in Construction*, *142*, 104466. https://doi.org/10.1016/J.AUTCON.2022.104466

Wang, Z.-L., Shen, H.-C., & Zuo, J. (2019). Risks in Prefabricated Buildings in China: Importance-Performance Analysis Approach. *Sustainability 2019, Vol. 11, Page 3450*, *11*(12), 3450. https://doi.org/10.3390/SU11123450

Wuni, I. Y., Shen, G. Q. P., & Mahmud, A. T. (2019). Critical risk factors in the application of modular integrated construction: a systematic review. *Https://Doi.Org/10.1080/15623599.2019.1613212*, *22*(2), 133–147. https://doi.org/10.1080/15623599.2019.1613212

CURRICULUM VITAE

Seung Ho Song

University of Nevada, Las Vegas

Department of Civil and Environmental Engineering

Email: tkdrhrdls22@gmail.com

Education:

Bachelor of Engineering in Civil Engineering, May 2021

University of Nevada, Las Vegas, United States

Thesis Title:

Measuring Impacts and vibrations on a volumetric modular house during transportation

Thesis Committee:

Dr. Jin Ouk Choi (Advisor)

Dr. Moses Karakouzian (Advisory Committee Member)

Dr. Jee Woong Park (Advisory Committee Member)

Dr. Jaewon Lim (Graduate College Representative)