

Clemson University

TigerPrints

All Theses

Theses

12-2021

Development and Promotion of Mass Timber Noise Barrier for Highways

Harsh Bothra
hbothra@clemson.edu

Follow this and additional works at: https://tigerprints.clemson.edu/all_theses



Part of the [Civil Engineering Commons](#), and the [Structural Engineering Commons](#)

Recommended Citation

Bothra, Harsh, "Development and Promotion of Mass Timber Noise Barrier for Highways" (2021). *All Theses*. 3681.

https://tigerprints.clemson.edu/all_theses/3681

This Thesis is brought to you for free and open access by the Theses at TigerPrints. It has been accepted for inclusion in All Theses by an authorized administrator of TigerPrints. For more information, please contact kokeefe@clemson.edu.

Clemson University

TigerPrints

All Theses

Theses

11-2021

Development And promotion Of Mass Timber Noise Barrier For Highways

Harsh Bothra

Follow this and additional works at: https://tigerprints.clemson.edu/all_theses



Part of the [Civil Engineering Commons](#), and the [Structural Engineering Commons](#)

DEVELOPMENT AND PROMOTION OF MASS TIMBER NOISE BARRIER
FOR HIGHWAYS

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Civil Engineering

by
Harsh Bothra
December 2021

Accepted by:
Dr. Weichiang Pang, Committee Chair
Dr. Laura Redmond, Committee Co-Chair
Dr. Patricia Layton

ABSTRACT

Highways are some of the biggest causes of noise pollution in the United States of America. To deal with the traffic noise coming from these highways, noise barriers have been erected across major highways. The goal is to reduce as much noise as possible through a sustainable solution. Unfortunately, the use of steel and concrete, commonly used materials, have undesired environmental impacts. A suggested sustainable alternative material would be mass timber. Mass timber products such as cross-laminated timber (CLT) and mass plywood panels (MPP) has attracted the attention of the construction industry in the U.S, as they are sustainable, light, cost-effective and have a net positive environmental impact as compared to traditional materials used in the industry. Additionally, they are expected to lose 20 dB(A) in transmission since they weigh more than 4 psf. In this study, the objective of the research was to evaluate and determine whether mass timber is a competitive alternative material for constructing noise barriers compared to concrete or steel. The design of prototype CLT noise barrier was carried out including seismic and wind loads representative of several regions across the U.S. Next, the environmental impact and cost was compared between a CLT and concrete noise barrier. Finally, a prototype using the proposed noise barrier design was erected to assess constructability and instrument it for long-term moisture monitoring to assess the performance of two different protective coatings. As a result of the study, CLT proved to be a viable alternative to concrete noise barrier while the moisture content in CLT varied from 28% during rainy condition to 10% under dry conditions.

DEDICATION

I am dedicating this work to my loving and supporting family, who have been my biggest support system through my education and career. You have been my reliable source of support and encouragement through the ups and downs of my life. To my loving parents, I would like to thank you for being good examples and teaching the values of hard work and the inspiration to achieve more.

ACKNOWLEDGMENTS

I want to acknowledge and give special thanks to my father for being my biggest inspiration and support through my civil engineering career and the very supportive teachers that have guided and taught me in the field. To my advisors Dr. Weichi Pang and Dr. Laura Redmond, I dearly appreciate the contributions made. I am also grateful for the efforts and time they took to encourage and advise me throughout my research. And I would like to express my gratitude to my committee member Dr. Patricia Layton, I am truly grateful for the support and encouragement throughout my research. Thank you, Caroline and Erwin, from Sansin Corporation, for being resourceful in providing the needed coating materials and technical support through the studies. Thank you, Khaleed, from SMT Research for being supportive of the sensors and other related technical support. I would also like to thank Adelaide Heigel for conducting the cost comparison on the noise barriers and contributing to the research study. I am also thankful to Bibek and Roth for all their help at different times during the study. I am also grateful to Akash Indani for helping me out in gathering the historical data from FHWA. Finally, I am grateful for the support from my friends and family throughout my time in grad school. I appreciate all the support, teamwork, and encouragement throughout our studies. I hope this extends beyond our studies. Above all, I thank God for making everything possible regardless of these hard times of the Covid-19 pandemic.

TABLE OF CONTENTS

	Page
TITLE PAGE.....	i
ABSTRACT.....	ii
DEDICATION.....	iii
ACKNOWLEDGMENTS.....	iv
TABLE OF CONTENTS.....	v
LIST OF TABLES.....	viii
LIST OF FIGURES.....	x
CHAPTER	
1. INTRODUCTION.....	1
1.1 NOISE BARRIERS.....	1
1.2 DEFINITION AND PROPERTIES OF MASS TIMBER.....	4
1.3 SCOPE OF RESEARCH.....	6

2. LITERATURE REVIEW.....	8
2.1 MASS TIMBER.....	8
2.2 CROSS LAMINATED TIMBER (CLT).....	10
2.3 MASS PLYWOOD PANEL (MPP).....	19
2.4 DESIGN OF NOISE BARRIER.....	23
2.5 MOISTURE EFFECTS IN CLT.....	30
3. DESIGN OF CLT NOISE BARRIER.....	34
3.1 DESIGN PROCEDURE AND GUIDELINES.....	34
3.2 STRUCTURAL MEMBER DESIGN.....	47
3.3 ENVIRONMENTAL IMPACT.....	51
3.4 COST ESTIMATES.....	51
3.5 3-D MODEL RENDERING.....	54
4. PROTOTYPE NOISE BARRIER.....	57
4.1 COATINGS USED TO IMPROVE CLT PERFORMANCE.....	57
4.2 SENSORS USED FOR LONG-TERM MOISTURE MONITORING.....	58
4.3 INSTALLATION PROCEDURE.....	62
4.4 RESULTS.....	71
4.5 SUMMARY.....	77
5. CONCLUSION AND RECOMMENDATION.....	78
5.1 CONCLUSION.....	78
5.2 RECOMMENDATION FOR FUTURE STUDY.....	82
REFERENCES.....	83
APPENDICES.....	87

A: DESIGN OF NOISE BARRIER.....	88
B: CONCRETE BREAKOUT STRENGTH.....	101
C: INSTALLATION GUIDE FOR SENSORS.....	104

LIST OF TABLES

Table	Page
Table 2.1: Benefits and applications of MPP.....	20
Table 3.1: No of crashes per million miles travelled (NHTSA).....	37
Table 3.2: Probability of crashes near noise barrier location.....	38
Table 3.3: CLT manufactures in USA.....	39
Table 3.4: Pressure exposure and elevation coefficient (AASHTO).....	42
Table 3.5: Gust effect factor (AASHTO).....	43
Table 3.6 Drag coefficient (AASHTO).....	43
Table 3.7: Site factor F_{PGA} at zero period on acceleration spectrum (AASHTO).....	44
Table 3.8: Site factor F_a at short period range of acceleration spectrum (AASHTO).....	45
Table 3.9: Site factor F_v at long period range of acceleration spectrum (AASHTO).....	45
Table 3.10 : Cost analysis summary.....	53
Table 4.1 : Max. and min. moisture content recorded in CLT panel.....	77

List of Tables (Continued)

Table	Page
Table 4.2 : Wind design summary.....	79
Table 4.3 : Seismic design summary.....	80

LIST OF FIGURES

Figure	Page
Figure 1.1: Application of noise barrier.....	2
Figure 1.2: Materials used in construction of noise narrier from 1963-2016.....	4
Figure 1.3: Typical layup of 3-ply CLT.....	5
Figure 1.4: Typical layup of MPP.....	6
Figure 2.1: Statistical analysis on cement production and emissions.....	18
Figure 2.2: Noise berms and noise wall.....	25
Figure 2.3: Noise walls on bridges vs. noise walls on retaining walls.....	26
Figure 2.4: Comparative decibel scale.....	27
Figure 3.1: Layout of noise barrier (GDOT).....	35
Figure 3.2: Linear miles and unit costs of noise barrier by height.....	36
Figure 3.3: Average annual daily traffic (AADT) near to noise barrier location.....	37
Figure 3.4: AASHTO wind map.....	41
Figure 3.5: Installation of the CLT panel.....	54
Figure 3.6: Rear view of noise barrier (A), shim angles (B), seating angles(C).....	55
Figure 3.7: Top view of noise barrier	56
Figure 3.8: Isometric view of noise barrier.....	56
Figure 4.1: Point moisture measurement sensor (PMM).....	60

List of Figures (Continued)

Figure	Page
Figure 4.2: Driving rain gauge.....	61
Figure 4.3: Research data acquisition and transfer process from A3 to cloud.....	62
Figure 4.4: Drilling out a concrete core from the pavement.....	63
Figure 4.5: Compression test of concrete core.....	64
Figure 4.6: Original steel post (A), steel post coated with primer (B), painted steel post(C).....	65
Figure 4.7: Original CLT panel (A), sanded CLT panel (B).....	66
Figure 4.8: First coat of TeakLife coating (A), First coat of WoodForce coating (B).....	66
Figure 4.9: Coated CLT panel.....	67
Figure 4.10: Installed noise barrier at BEL lab, Pendleton SC.....	68
Figure 4.11: Installing PMM's at the required depths in the CLT panel.....	69
Figure 4.12: Sensors installed on the noise barrier for long term monitoring (Front View).....	70
Figure 4.13: Sensors installed on the noise barrier for long term monitoring (Rear View).....	70
Figure 4.14: Sensors installed on CLT panel.....	71
Figure 4.15: Temperature data from sensors compared with NOAA station.....	73

List of Figures (Continued)

Figure	Page
Fig 4.16: Precipitation data from sensors compared with NOAA stations.....	74
Fig: 4.17: Moisture content in CLT panel at 1”	75
Fig: 4.18: Moisture content in CLT panel at 2”	76
Fig: 4.19: Moisture content in CLT panel at 3”	76

CHAPTER ONE

INTRODUCTION

1.1 NOISE BARRIERS

In the United States of America, traffic noise has become one of the worst noise pollution issues for both urban and residential areas (Forouhid, 2017). Some of the early noise mitigation measures included; planting vegetation, creating buffer zones, managing traffic and sometimes constructing noise insulated buildings. Today, the use of noise or sound barriers has become one of the most effective methods to mitigate railway, highway, and industrial noise (Forouhid, 2017).

The use of sound barriers on American highways dates back to the early 1970s when mass adoption of sound barriers in the U.S was facilitated by the noise regulations (Hammer, Swinburn, & Neitzel, 2014). Noise barriers proved to be more effective in reflecting the noise from highways as compared to other noise abatement measures. By 2006 the technology was considered a standard solution to highway noise pollution (Forouhid, 2017). The sound barriers are designed in consideration of all the principles of acoustical science. According to the fundamentals within acoustical science, sound travels as longitudinal waves, meaning these waves can be reflected, diffused, or absorbed depending on the material or matter that intercepts the path of the sound waves (Everest & Pohlmann, 2015). When these sound waves fall on a hard surface, they bounce off the surface or they are reflected. Diffusion of sound waves happens when the sound wave falls on an irregular surface, which will result in the sound waves breaking up and being sent to

many smaller paths (Everest & Pohlmann, 2015). Lastly, absorption of the sound waves happens when they fall on a soft, foam-like surface, which is likely to absorb most of the sound's kinetic energy. They are designed to help block all the unwanted sound power being emitted by heavy traffic vehicles coming from the highways (Forouhid, 2017). Since sound waves travel in a ray, they can be blocked by anything within the line of sight of the source. When designing the sound barriers, specific sound sources have to be modeled such as; tire noise, engine sound, and aerodynamic noise.

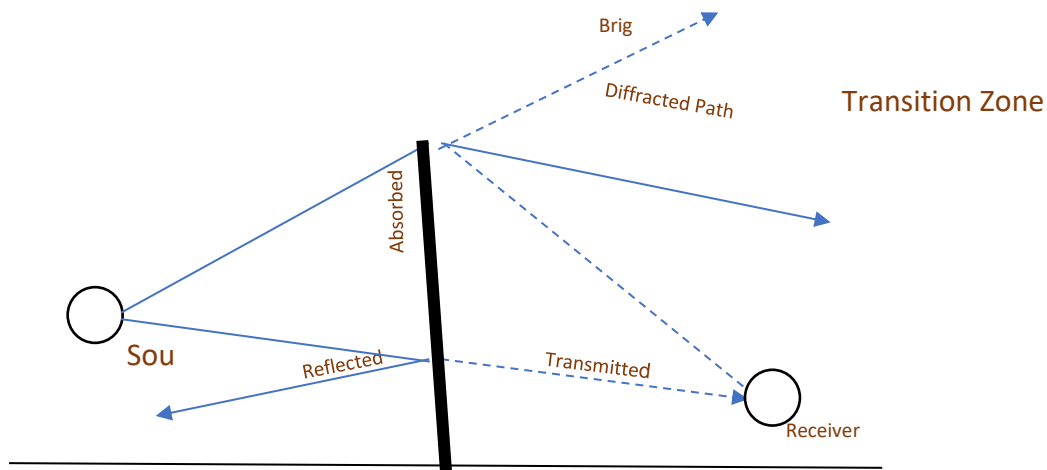


Fig 1.1: Application of Noise Barrier

Several materials are used for sound barriers. Some of these materials include steel, wood, concrete, composites as well as insulating wool. Each of these materials has different properties that may affect how sound is reflected or absorbed by the sound barriers. In general, materials that exhibit hardness are likely to absorb less sound as compared to soft materials. Materials such as steel, concrete, or masonry form hard surfaces that can reflect sound waves to the source, which neutralizes the sound waves

(Arenas et al., 2015). Porous surfaces formed from materials such as insulating wool and composites work by absorbing most of the sound waves (Forouhid, 2017). Materials play a huge role in the selection of suitable noise barriers. In addition to the materials properties, the aesthetics and cost are important to consider when designing a noise barrier.

Concrete and steel are considered to be the most traditional materials that have been used for highway noise barriers. To achieve maximum efficiency and ensure no noise goes over the noise barrier most of the walls must be raised higher than the surroundings. Noise barriers along highways may also have an aesthetic impact on areas around highways. Most of the noise barriers are limited to 25 feet, which is a height that could obscure most of the scenery and townscapes around highways. The overall effect is an unappealing surrounding for both motorists and people living near to highway noise barriers. In order to overcome some of the limitations of the traditional materials used on noise barriers, more absorptive materials are being adopted. The two wood products that show the potential for use in noise barriers are Cross-Laminated Timber (CLT) and Mass Plywood Panel (MPP).

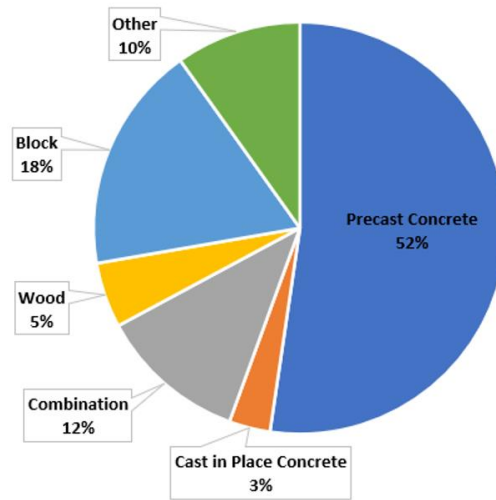


Fig 1.2: Materials Used in Construction of Noise Barrier from 1963-2016

1.2 DEFINITION AND PROPERTIES OF MASS TIMBER

Wood products are increasingly becoming popular as a building material. Wood products are known to be environmentally friendly compared to concrete and steel (Roberts, 2020). The use of wood products is also considered to be more esthetically appealing to most motorists (Roberts, 2020). In addition, wood is lighter as compared to concrete and steel, which has an economical advantage for transportation costs. According to Harte (2017), mass timber is a term that categorizes different wood products that vary in size and functions. Examples of mass timber include glue-laminated beams (Glulam), nail-laminated timber (NLT), laminated veneer lumber (LVL), dowel-laminated timber (DLT), mass plywood panel (MPP) and cross-laminated timber (CLT). Out of all the many forms of mass timber, the one that has had the most architectural possibilities and has a wide area of application in the construction industry is CLT (Barber, 2018).

Cross-laminated timber is made from lumber boards that have been glued to each other forming layers. Timber boards are stacked together to form different-sized timber slabs. The thickness of the CLT may vary depending on the manufacturing and transportation limitations. CLT members can match and sometimes exceed the performance of steel and concrete members (Roberts, 2020). They are widely used for ceilings, floors, and sometimes the entire building (Barber, 2018).



Fig 1.3: Typical Layup of CLT 3 Ply

Another form of mass timber that is gaining traction in the construction industry is the mass plywood panel (MPP). As compared to CLT, MPP offers design flexibility and an overall better structural support. The MPP panels are made up of thin veneer layers, whereas in CLT timber boards are used, which explains the design flexibility benefits of using the MPP (Baas, Riggio, & Barbosa, 2021). Both MPP and CLT are relatively new materials in the construction industry.



Fig 1.4: Typical Layup of MPP

1.3 SCOPE OF RESEARCH

The objective of the research is to evaluate and determine whether mass timber is a competitive alternative material for constructing noise barriers compared to concrete or steel. Mass timber has been found to exhibit key properties that meet all the requirements needed in a noise barrier. For instance, mass timber can be layered to desirable thickness such that they can easily reflect sound. Wood has actively been used as sound insulations in the construction industry (e.g. walls, floors). Structurally, mass timber exhibits high bending strength and has lower weight than a concrete or steel system. In this research, factors such as cost, environmental impact, manufacturing, installation, and maintenance will further be evaluated to compare CLT noise barriers to concrete/steel noise barriers.

A detailed cost comparison between CLT noise barriers and concrete noise barriers is conducted as a part of this research. A 1/2-mile theoretical project was selected in Florida and total costs with respect to material, transportation and installation were considered. Consultation with Mark Witt from Sea Rise Precast, Miami FL and various manufacturers of mass timber including Kattera, Smartlam, Structurlam, Freres Lumber and Sterling Solutions were used as the basis of the cost estimates.

Regarding the maintenance, one of the key steps is wood treatments and coating that are essential in increasing the lifespan of the CLT panels. In this work, various coating options and treatment solutions were discussed with members of the advisory board and a summary of these discussions is provided. In addition, the prototype noise barrier is instrumented with temperature and moisture sensors to assess the performance of two different coatings to protect the panels from UV and moisture.

The organization of this thesis is as follows, chapter two is a literature review of mass timber and moisture effects in CLT. Also included is a brief overview of the current design process for noise barriers. Chapter three begins with a short overview of the code-based design methodology followed by the design of a prototype noise barrier. In this chapter, the environmental impact study and the cost comparison to concrete noise barriers are also included. Chapter four focuses on the prototype noise barrier. First, the treatment and coating options discussed with the advisory board are presented, then details of the coating selected for testing on the prototype are given and the sensor setup for long term moisture monitoring is presented. After that, the steps involved in installing the prototype noise barrier and the moisture sensors are presented. Finally, results from the first three months of moisture monitoring are presented. Chapter five gives a summary of the findings from this work and the next steps towards maturing the design of CLT noise barriers

CHAPTER TWO

LITERATURE REVIEW

2.1 MASS TIMBER

The construction industry has undergone lots of changes in terms of construction technologies and building or construction materials. For years, concrete and steel have been perceived as the prime materials needed in the construction of strong structures and buildings (Karacabeyli, & Douglas, 2013). Today, there is more than just strength to consider when it comes to the use of construction materials. Factors such as the environmental impacts, costs, waste management, and aesthetical impact play a huge role in the selection of what construction materials need to be used. According to Albee (2019), the use of wood and its different forms and products has proved to substantially reduce environmental pollution and reduce greenhouse gas emissions within the building sector.

The use of wood in the building sector or the construction industry goes back to prehistoric times. Therefore, for centuries, human beings have relied on readily available wood to raise structures and build their homes. Unfortunately, the Great Chicago Fire was a disaster that made people perceive wood to be very unstable and unsafe in construction. The Great Chicago Fire happened in 1871, and the disaster led to the death of over 300 people (Roberts, 2020). The majority of the structures at that time were built of wood. The disaster had given the wood a bad reputation when compared to steel and concrete. After the disaster wood was used less and less until new forms of wood started getting back into

the spotlight (Roberts, 2020). The new form of wood that has started creating curiosity in the building sector is mass timber.

Mass timber refers to massive timber that is created by laminating or sticking up pieces and layers of softwood to create a single block of structural timber. The common softwoods that are preferred in the making of mass timber are pine, spruce, and fir. According to Quesada (2019), softwood is best suited in the making of mass timbers, but in some cases, deciduous wood from ash, beech, and birch are used, in which they are patched together to form larger and stronger pieces. In summary, mass timber is created by putting up wood together like Legos, which makes it possible for these types of wood to have a variety of applications in the construction industry. Since mass timber encompasses a wide range of products, the sizes and functions of these products can be used to determine the precise type of mass timbers (Karacabeyli, & Douglas, 2013). The common mass timber products used today are laminated veneer lumber (LVL), glue-laminated (glulam) beams, cross-laminated timber (CLT), and dowel-laminated timber (DLT) (Stoner, 2020). Cross-laminated timber has gained new architectural popularity because of how it is revolutionizing the industry through its mass applications.

2.2 CROSS LAMINATED TIMBER (CLT)

The history of the development of CLT goes back to the early 1990s. Austria is the first country to start the early development of CLT. The softwood forestry in Austria gave it the advantage to start experimenting on the use of a variety of mass timber in the building sector. The development of CLT was championed by Gerhard Schickhofer, a researcher who later was recognized for his forestry works and research which later saw him win a prestigious forestry prize in 2019. Schickhofer's work helped build a foundation for the development of the new material as well as popularizing CLT. The adoption of CLT in the construction of residential housing spread through Austria and Europe by the start of 2000. Unlike in the United States, European building standards tend to favor solid materials such as steel, concrete, and bricks. This made adoption and use of CLT in the construction industry lean towards residential construction, where CLT tends to provide sustainability.

Looking at the material preference in North America, it is clear that in the United States, most residential construction use stick-frame construction, which is primarily wooden material (Brandt et al., 2021). Entry of the CLT into the American market took longer than expected, precisely fifteen years. CLT never stood a chance when compared to stick-frame construction since stock-frame construction is relatively cheaper and ubiquitous. Meaning that in North America, CLT had to target a different market in the construction industry other than in residential construction. Finally, in 2010, North American architects saw the possibility of using CLT in the construction of bigger structures and buildings. The properties of CLT were a perfect substitute to concrete and

steel, which were the main materials used in the construction of bigger buildings (Karacabeyli, & Douglas, 2013). By 2015, the International Building Code (IBC) had recognized the new architectural possibilities of CLT which led to its incorporation into the IBC.

CLT is a mass timber product that is opening up new architectural possibilities, a factor that has seen the product gain traction both in Europe and the United States (Karacabeyli, & Douglas, 2013). The panel-shaped product is made up of at least three layers of wooden lamella that have been glued together. Just like in the making of veneer plywood, each layer of wood used in CLT is made in a crosswise structure to achieve a high degree of dimensional stability (Shakya, 2020). The crosswise structure prevents dimensional change since each adjacent layer is designed to be at right angles. The properties of CLT allow it to be used as a wall and ceiling element in the construction industry. Another important detail that is put into consideration when gluing up lumber boards into CLT is; the grain of each adjacent layer needs to face against each other. Gluing three layers of lumber boards is the least, however, CLTs can be made thick and large by stacking up more layers (Stoner, 2020). Some of the largest and thickest CLT can measure up to 98-feet-wide by 18-feet-long.

Stacking up and gluing up large and thick slabs of wood creates one major advantage, which is the capability to exceed the performance of steel and concrete. The number of layers that must be glued together varies depending on the specific applications (Gagnon et al., 2013). Therefore, CLT has a variety of uses, some of the common ones being in the making of floors, ceilings, walls, and even construction of an entire building

(Quesada, 2019). The potential of mass timber to decarbonize the construction industry, coupled with its architectural qualities has got many people happy and looking forward to its mass adoption.

The application and adoption of CLT in the construction industry have surpassed what was initially expected. For centuries, most people have been skeptical when it comes to using wood products as the primary material in building. The better reason as to why wood has been seen as an inferior choice to concrete and steel is the weaknesses of wood, especially when in fire situations or disasters (Stoner, 2020). The perception of wood being a weaker material has slowly changed through the evolution of mass timber and the increasingly large use of CLT. One of the key reasons that make CLT a great choice as compared to any other wood product is because it performs better in fire. According to Brandt et al (2021), conventionally, stick-frame and plywood have been utilized in the construction of buildings in the United States. The biggest weakness of these structures is the fact that they are flammable. However, CLT is changing this narrative about wood products in the building sector. CLT is designed and developed by the layering of individual lumber boards, which makes them large, compressed, and solid, which makes the CLT difficult to ignite (Gagnon et al., 2013).

The layered structure of the CLT gives it the benefits of self-extinguishing capabilities. In the case of a fire, the outer layers that catch fire tend to char, forming an exterior shield that protects inner layers from the fire. These capabilities of the CLT allow it to maintain the structural integrity of a building even when they are exposed to intense fire for longer periods (Karacabeyli, & Douglas, 2013). The US Forest Service has

performed extensive tests that involve blasting the CLT into the fire, and from these blast tests, CLT has been confirmed to perform well in fire (Albee, 2019). CLT surpasses steel when it comes to handling fire because steel gets damaged once it passes the yielding temperature, which is not the case with CLT.

Another advantage that makes building with CLT more sustainable when compared to steel and concrete is the fact that constructions using mass timber are faster, produce less waste, and require less labor. In conventional construction, most of the materials that are used must be ordered in mass quantities, cut, and assembled on-site (Karacabeyli, & Douglas, 2013). Most of the processes of preparing the materials need a lot of extra labor. Looking at CLT, most of the labor and fabrication are done by the manufacturer or at the factory. The factories use Computer Numerical Control machines to measure and cut the CLT precisely, which reduces wastage of materials. Each dimension of a building is put into consideration whenever the CLT is being made (Stoner, 2020). Once the CLT is on-site, it takes very little time and less labor to assemble an entire building.

In terms of how different materials handle earthquakes, CLT has an edge when compared to concrete. Buildings made of concrete run the risk of cracking and having to be demolished during earthquakes (Gagnon et al., 2013). All these are benefits and reasons that best support the use of CLT in construction.

Manufacturing of CLT primarily involves the lamination of dimension lumber. The lumber lamination process uses structural adhesives to bond the dimension lumber or SCL through face joints, edge joints, and end joints. One thing that must be noted is that any CLT product that has been made without face bonds such as nail laminated CLT is not

recognized by the ANSI/APA PRG 320 standard (Karacabeyli, & Douglas, 2013). The ANSI/APA PRG 320 is a compliance code that is used to recognize CLT products that have been certified and their quality approved (Karacabeyli, & Douglas, 2013). ANSI/APA PRG 320 plays a key role in assuring the CLT product performance and quality. What makes ANSI/APA PRG 320 standards important is that they utilize and rely on European manufacturing and engineering processes of CLT as well as take into account the lumber resources and manufacturing preferences of North America. The ANSI/APA PRG 320 also takes into consideration the end-user expectations of the CLT products.

The CLT component requirements can be generally categorized into two, laminations and adhesives. Starting with the lam stock, there are specific softwood lumber species that are permitted for mass timber. In North America, the softwood lumber species used must be recognized by the Canadian Lumber Standards Accreditation Board (CLSAB) or the American Lumber Standards Committee (ALSC) (Karacabeyli, & Douglas, 2013). All the standard-grade lumber has one advantage in common- they are heat treated. Other specifications that must be put into consideration in the selection of lumber is ensuring the same lumber species is used within each layer. It is important to maintain the same lumber species to avoid differential physical and mechanical properties of wood/lumber.

Factors such as the net lamination thickness play a huge role in the development process of the CLT. There are specific dimensions that are specified, for instance, the least and most thickness, when developing the CLT layers (Karacabeyli, & Douglas, 2013). The least thickness should be 16 mm or 5/8 inch, whereas the maximum thickness of the CLT

layer not exceeding 51 mm or 2 inches. In terms of the net lamination, width is determined by the lamination thickness of the parallel layers. All the dimensions of the lumber of the CLT layers matter since they determine some of the properties of the overall CLT product.

Another key component used in the development of CLT is adhesives. All the adhesives used for CLT must meet specific standard qualities, which in this case are the AITC 405 requirements. The AITC 405 requirement is used to determine certain properties of adhesives by assessing factors such as extreme glue bond durability and heat durability. Tests such as heat durability or performance are used in determining whether the adhesives being used exhibit heat delamination. According to Sheine, Donofrio, and Gershfeld (2019), heat delamination is a CLT characteristic that can affect CLT when exposed to fire since it increases the CLT's char rate. Putting such factors into account, several adhesives qualify the standard requirements in the development of CLT.

Below is a list of good examples of the recommended adhesives that can be used in CLT production:

- Polyurethane (PUR).
- Emulsion polymer isocyanate (EPI); and
- Phenol-resorcinol formaldehyde (PRF).

Above listed adhesives used in CLT shall meet the requirements of AITC 405 or CSA O112.10. These three adhesives are some of the common adhesives in the construction industry. In North America, PRF stands as one of the well-known adhesives and it is widely adopted for structural use such as in the manufacturing of glulam. On the

other hand, EPI adhesives are commonly used for wood lamination and wood I-joint. Lastly, PUR adhesives are widely used in Europe for CLT production.

CLT has many areas of application in building and construction. Some of the early and common applications are ceilings and wall elements. In the oil and gas industry, CLT is becoming hand since they can be used in the construction of temporary paths, and off paved roads (rig mats). The use and applications of the CLT products vary in the construction industry. In residential, industrial, and commercial constructions, CLT has proved to be good being used as non-load bearing and static load-bearing elements (Karacabeyli, & Douglas, 2013). Rig mats that have been made from the CLT have a wide range of applications some of which include the construction of interior and exterior walls, ceiling and roof elements, balcony slabs, and staircases (Dolan et al., 2019). The advantage of using CLT products is that they are lightweight, and this is an advantage that architects can utilize by using CLT as extensions onto an existing building. Other special applications include being used as installation elements and as wooden towers for wind turbines.

CLT can be combined and mixed with other construction materials such as concrete and steel. The advantages of being able to combine and use CLT alongside other conventional construction materials makes it a good material for the construction of large structures and multi-story buildings. One of the tallest buildings constructed from CLT is located in Brumunddal, Norway. The building has 18 stories and a maximum height of 80 meters.

The possibilities of using CLT in construction are limitless. Putting into consideration that CLT can be produced in different dimensions, which can match up the

structural strength of steel and concrete. According to Dolan et al (2019), depending on project or building requirements, the number of layers in a single panel can range from three to seven. The total thickness for the commercially available panels is about 50 cm (Karacabeyli, & Douglas, 2013). manufacturers can produce CLT panels with widths up to 6 meters and lengths of up to 20 meters.

Most of the structures that have been built using CLT are strong and durable enough to last for centuries. For CLT to last centuries, special attention has to be paid when it comes to how they are designed and how well they are protected against moisture and weather (Dolan et al., 2019). The CLT applications continue to grow, and this has seen significant growth of the CLT market across the globe. As the acceptance of CLT as an alternative to labor-intense materials increases, the production capacity of CLT is expected to increase to 4.5 million cubic meters by 2022, from just 2.5 million cubic meters in 2019 (Roberts, 2020).

The construction industry has been pointed out as one of the industries that contribute to global carbon emissions. Building and construction materials roughly contribute 11 percent of the greenhouse gas emitted globally. The carbon impact from buildings is estimated to increase over the years due to construction and materials used. However, for a sustainable future, there is a need to come up with solutions to reduce carbon emissions, and this is where mass timber will excel (Puettmann, Sinha, & Ganguly, 2019). The argument is that the manufacturing of cement and concrete contributes to about 8 percent of the global greenhouse gas emissions. In addition to that, 5 percent of the global GHG is emitted by the global iron and steel industry (Roberts, 2020). Rapid urbanization

in both developed and developing countries as well as the increase in population only means that the consumption of construction materials such as cement and steel will increase over the years, having a significant impact on the environment.

Countries such as China and India are leading in the production of cement, which shows how population and rapid urbanization can lead to an increase in demand for cement and other building materials. According to figure 1.2, between 2011 and 2013, China had increased its production of cement, which surpassed the amount of cement produced by the US in the entire 20th century (Timperley, 2018). Substituting the cement and steel using CLT will have a significant reduction of the GHGs. First, using CLT will cut down the use of excess fossil fuel which is used in the making of steel as well as concrete structures.

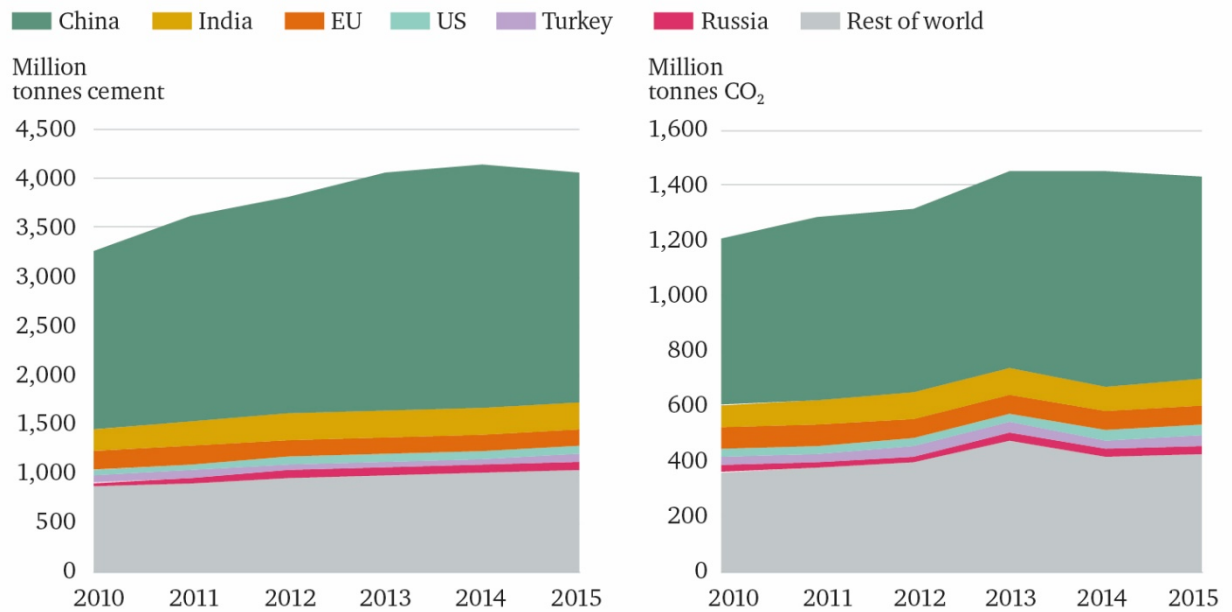


Fig 2.1: Statistical analysis on cement production and emissions

The use of CLT as an alternative to concrete and steel does not eliminate carbon emissions since CLT production lifecycle accounts for some of the greenhouse gas

emissions. Starting with forestry; processes such as logging, once a tree is cut down some of the soil carbon is released (Karacabeyli, & Douglas, 2013). In addition to the released soil carbon, wastes from trees eventually rot releasing more carbon. The process of logging requires the used machinery to cut and process timber as well as heavy vehicles to transport the wood. The machinery emits a lot of carbon into the atmosphere (Karacabeyli, & Douglas, 2013). However, comparing the amount of carbon released in the lifecycle of mass timber, it is nothing compared to carbon emissions from the production of cement and steel, which makes the use of CLT in the construction industry to be a more sustainable approach (Timperley, 2018).

2.3 MASS PLYWOOD PANEL (MPP)

Mass Plywood Panel (MPP) is a wood product that is made when mass timber panels are assembled with lamellas. Unlike CLT, the MPP is made from thin sheets of wood or plywood layered together in alternative patterns (Sheine, Donofrio & Gershfeld, 2019). The thin sheets of wood are joined together in layers using resin. MPP is made to have the same strength as any other wood products used in construction, but with the advantage of added dimensional stability. Another benefit of working with MPP is that they can be made into different shapes due to their flexible capabilities. They can also be cut precisely by the manufacturer using Computer Numeric Control technologies, depending on the customer specifications (Freres Lumber Co., n.d.).

MPP has the advantage of being produced in different dimensions as well as being able to be cut down according to customer specifications. Having these advantages allows

MPP to be used in different applications. In a building, MPP can be used as a roof, floor, and wall panel. These panels can measure up to 12 inches thick. Thicker MPP measuring up to 24 inches are commonly used as columns and beams (Miyamoto, Sinha & Morrell, 2020). Large and bigger buildings up to 18 stories can as well be made using MPP since it is strong just like concrete and steel as well as fire-resistant.

Benefits of using MPP in construction	MPP Applications
They require small labor force	Floors
Fire resiliency	Roofs
Economical to transport	Elevator shafts
Environmentally sustainable	Walls and shearwalls
Fast construction	Beams and columns
Aesthetically appealing	
Better flexibility in design	
Less waste (harvest to construction)	

Table 2.1: Benefits and applications of MPP

MPP is a veneer-based product, and the veneer is selected from a variety of trees. Most of the trees are acquired from Frere’s timberlands. Veneers are very thin slices of wood that have been cut from the trunks of trees. The dimensions of the veneer are normally less than 3 millimeters thick (Freres Lumber Co., n.d.). The veneer can be produced from either hardwood or softwood. Douglas fir and pine are the common tree species used in the making of softwood veneer. Other tree species used in the making of veneer are birch, cedar, ash, butternut, and maple (Sheine, Donofrio, & Gershfeld, 2019).

Since MPP is dominantly produced by Freres Lumber Co. they are the ones that make most of the decisions in the tree species used in the making of its veneer. Freres Lumber Co. is a premier wood product manufacturing plant that has dedicated the past 100 years to bringing innovation in the woodwork industry (Freres Lumber Co., n.d.). The company is a family business that has an exceptional experience. The company has core values that revolve around the love for innovation and deep respect for wood.

The types of glue used in bonding MPP are formaldehyde-based resins. This is the glue or resin that bonds the individual veneer pieces into thicker MPP panels. There has been huge concern about the use of formaldehyde-based products due to Volatile Organic Compounds (VOC). However, studies have come to prove that the amount of formaldehyde exposure humans get from these resins used has an insignificant impact on the human body (Freres Lumber Co., n.d.). The human body does not accumulate but rather metabolizes it which avoids build-ups.

In today's construction industry, wood products are becoming a big game-changer. It is easy to say that mass plywood panels are becoming a direct competition to cross-laminated timber. Innovation and competition among mass timber products have enabled engineers and architects to have more options or other options in the building sector (Freres Lumber Co., n.d.). One key advantage that MPP has over the CLT is that it uses less energy to produce due to the sustainability followed by Freres Lumber Co. According to Brandt et al (2004), Freres Lumber Co. which is the company that has patents for Frere's MPP has a long history of being a wood products manufacturer with principles that are mindful of

the company's environmental impact. All the wood that is used in the making of MPP comes from Freres Timber's 17,000 acres which are sustainably managed forests.

Most of the trees that are used in MPP are usually small because they are normally suppressed by bigger trees, and this makes them unsuitable for dimensional lumber. The small trees are easier to acquire even during the thinning process of a forest. Technically, the production of MPP takes or uses 20-30 percent less wood when compared to the production of CLT (Freres Lumber Co., n.d.). It takes less wood for MPP to reach and exceed the structural properties needed.

At this point, it is clear that mass timber has the upper hand when it comes to its environmental impact when compared to conventional materials like concrete and steel. It takes less energy to harvest and manufacture wood products than it takes in the production of steel and concrete. All the wood used in the production of MPP is acquired from managed forests, which are one of the solutions to regulating the amount of carbon that is released into the atmosphere (Freres Lumber Co., n.d.). Trees absorb some of the carbon dioxides that have been emitted from the steel and cement products and instead store them as carbon. This means that once the tree has been harvested, the carbon that is stored in the tree remains within the tree's lifetime without having to be released to the environment. Since more trees can always be planted, it is a good approach to reducing the amount of carbon that is emitted into the atmosphere.

Using MPP for homes has another crucial benefit to the environment. Mass timber has better thermal performance when compared to concrete and steel. These great thermal performance benefits allow homes to retain heat, which cuts down the amount of energy

that goes into keeping our homes warm. Lowering the amount of energy used in our homes has a bigger impact on creating a sustainable environment (Miyamoto, Sinha & Morrell, 2020). Lastly, MPP is a veneer-based product, which means that its production utilizes much smaller logs which leaves less waste as well as needs less energy to dry.

2.4 Design of Noise Barrier

The use of noise barriers in the United States started in 1963. The noise barriers are designed to accomplish one task, which is to reduce the amount of highway traffic noise pollution. These noise barriers have been used in addressing federal, state, and local highway traffic noise. It's been over 5 decades since the first noise barrier was built, and much has changed more especially with the technologies and methodologies that are used in barrier designs (Fleming et al., 2004). One of the factors that have contributed to the substantial advancement in barrier design is the increased concern by motorists and communities. The barriers that are used today are less expensive and are arguably more environmentally friendly as compared to the first generation of barrier designs.

Largely noise barrier systems are divided into two basic types, which are the ground-mounted and structure-mounted noise barriers (Fleming et al., 2004). The ground-mounted noise barrier system is a barrier type that is installed by constructing them into or on top of the ground. The three common types of noise barriers under this category are; Noise berms, noise walls, and a combination of both (noise walls and noise berm).

Noise berms are noise barriers that have been made using the most naturally occurring materials such as stone, rock, rubble, or soil. Noise berms are made by raising

the earthen materials such that they slope gradually making the sides of the highway a bit raised (Klingner, McNerney, & Busch-Vishniac, 2003). The design approach used in creating the noise berms makes them occupy more space when compared to noise walls. On the other hand, noise walls are noise barriers that must be fabricated off-site, after which they can be transported to the site and assembled (Fleming et al., 2004). The only elements of the noise walls that must be fabricated on-site are the cast-in-place concrete walls if there are any. The noise walls are primarily classified by the type of material used in fabricating the noise barrier. The common types of noise wall systems are; brick and masonry, post-and-panel, direct burial panels, cast-in-place concrete noise walls and precast concrete noise walls. Figure 2.2 compares the noise berms with the noise walls.

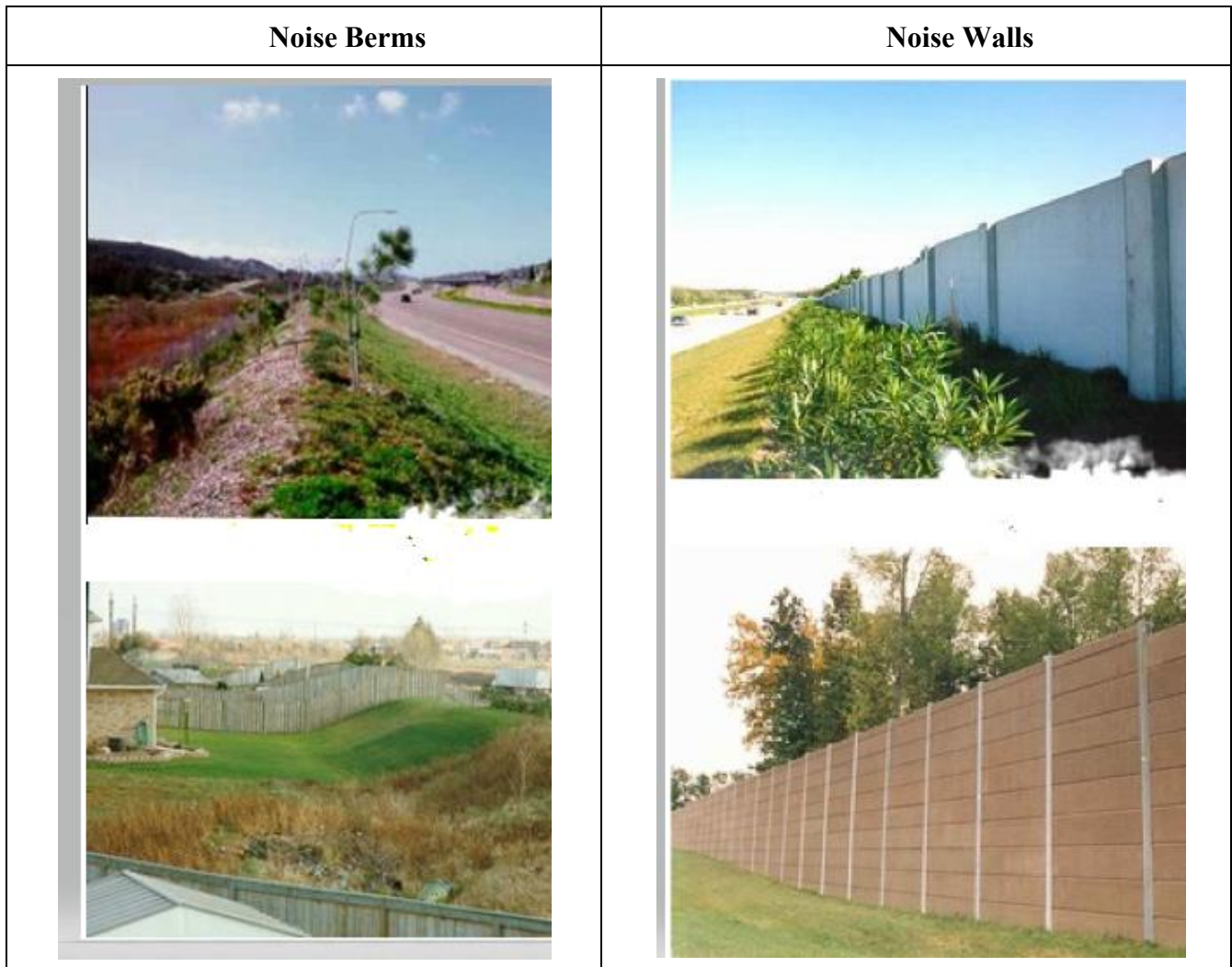


Fig 2.2: Noise Berms and Noise Walls.

The second category of noise barrier is structure-mounted noise walls. These noise barrier types are different from the ground-mounted noise walls since they are used on structures, such as bridges. The two common noise walls that fall under the structure-mounted noise walls are; the noise walls on retaining walls and noise walls on bridges (Fleming et al., 2004). Noise walls on bridges are a type in which the noise barrier, which is normally a wall, is attached to bridges, whereas noise walls on retaining walls are a type

of structure-mounted noise walls that are installed to retain fill sections on highways. Figure 2.3 illustrates the difference between the noise wall on bridges and noise walls on retaining walls.





Noise wall on bridges	Noise wall on retaining walls
 <p>Figure 58. Noise wall on a bridge photo #1717</p>	 <p>Figure 62. Noise wall on a retaining wall photo #2947</p>
 <p>Figure 59. Noise wall on a bridge photo #5090</p>	 <p>Figure 63. Noise wall on a retaining wall photo #531</p>

Fig 2.3: Noise wall on bridges and Noise wall on retaining walls.

Many considerations play a part in noise barrier designs. These considerations are grouped as; acoustical considerations, drainage and utility considerations, structural consideration, safety considerations, installation considerations, cost considerations, and maintenance considerations (Klingner, McNerney, & Busch-Vishniac, 2003). The acoustical considerations cover all the fundamentals of highway traffic noise. To come up with a barrier design, it is important to understand the characteristics of sound. According to Fleming et al (2004), highway noise is primarily generated from the vehicle engines, exhaust pipes, and the tires of the vehicle as they interact with the road or pavement. The sound from all these sources can be measured using a logarithmic scale, which in return can be used to determine whether the sound is harmful to humans. The logarithmic scale used for measuring sound pressure is known as the decibel (dB) scale (Knauer et al., 2006). To better understand the different logarithmic scales for different noise sources, figure 2.4 shows how different noise sources compare.

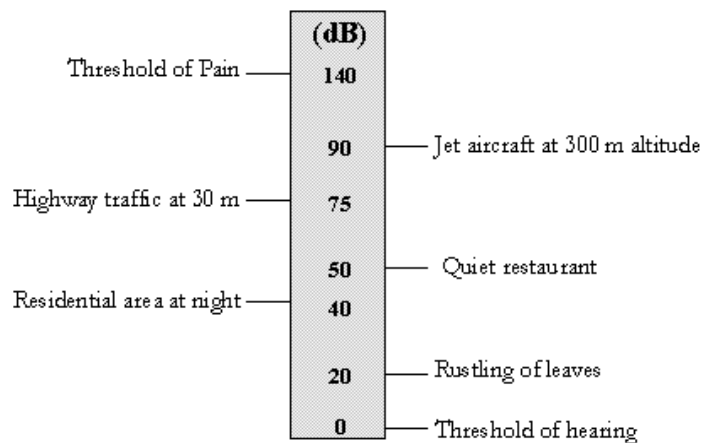


Fig 2.4: Comparative decibel scale.

Depending on the levels of sound pressure or the amplitude of the sound (loudness), barrier designs have to be made such that the noise levels are kept to a minimum. The noise barrier can work to reduce the noise pollution from the highway by using four key approaches. The first is by absorbing the noise, or by reflecting the noise, or transmitting it, or forcing the noise to take a much longer path (diffracted path) (Knauer et al., 2006).

Another key consideration in barrier designs is the drainage and utility considerations. It is important when designing and setting up the noise barrier to ensure that they meet all the drainage requirements. Developing these noise barriers on highways has a significant interference to the normal drainage patterns (Knauer et al., 2006). Some of the approaches to take when addressing the drainage issues associated with noise barrier installation include:

- Accommodating drainage flow within the barrier overlap sections.
- Accommodating water flow using drainage holes and passages running through the barrier, along with or beneath the barrier.

Other considerations are structural and safety considerations. In terms of structural considerations, the primary goal is to identify any structural issues that have to be addressed in the process of coming up with the most appropriate noise barrier design. Structural considerations start with the expansion and contraction of the material used in the making of the barriers. Depending on the moisture variation and temperature conditions, the materials are likely to expand and contract (Fleming et al., 2004). Not putting these factors into consideration can easily lead to structural, aesthetic, and acoustical problems. In terms of structural considerations, other factors that count are the noise barrier loadings. Different

loads have structural impacts on the barriers (Klingner, McNerney, & Busch-Vishniac, 2003). Some of the loads that have to be a part of the consideration are; the dead load, wind loads, impact loads, and snow loads.

Coming up with the right noise barrier design takes a lot of evaluation and key steps. The barrier design procedure is systematic, and it involves elements of engineering, acoustical, and community involvement. The barrier design process starts with acoustical evaluation. Acoustical evaluations are done when new highways are being constructed or when a need for expansion arises (Knauer et al., 2006). The acoustical evaluation aims to determine whether there is a need for noise abatement. Acoustical evaluation is done in four key steps:

- Selection of noise-sensitive receivers.
- Measuring or modeling to determine the existing noise levels.
- Determining future noise impacts.
- Assessing the feasibility of noise abatement.

Once the acoustical evaluation is done, the data and information obtained are used in developing barrier designs. Therefore, the second step would be developing the barrier design. The information obtained from the acoustical evaluation is key when determining whether the need for a noise barrier is feasible and reasonable (Knauer et al., 2006). Developing the barrier designs follows six steps. The first step is using the acoustical evaluation inputs to come up with a plan, profile, and the cross-sections of different barrier acoustical locations, heights, scenarios, and lengths (Fleming et al., 2004). The acoustical evaluation input is key in determining the estimated costs as well. The second step is

documenting every detail of the desired noise barriers and forwarding these details to be used in designing the barriers.

Once the person responsible for the designing of the noise barriers has completed the design process, the next step is to review and assess the designs. Any changes or necessary modifications can be suggested at this stage just in case. The fourth step is to have the design refined accordingly. The fifth step involves developing accompanying specifications (Knauer et al., 2006). And the final step is coming up with the final design which clearly outlines the final Plans, Specifications, and Estimates package.

2.5 MOISTURE EFFECTS IN CLT

The use of CLT in construction and building comes with numerous advantages. However, just like in any other construction material, wood structural systems show certain durability concerns. The primary durability concerns of CLT are moisture effects. CLT panels used in construction can easily be exposed to moisture through roof leaks, vapor condensation, or wicking from wet foundations (dos Santos Bobadilha, 2020). Once CLT has been exposed to moisture, most of the water is distributed throughout the panel. Unfortunately, water absorption by the panels will start showing certain problems over a long time or during short-term wetting. The problems include dimensional changes, microbial growth, and moisture damage. Moisture management is needed at every stage of the CLT panel lifecycle (dos Santos Bobadilha, 2020). Moisture management is essential in prolonging the lifetime of the CLT panels used on buildings and structures.

Over the years, much attention has been paid to the moisture or weather protection of timber. Through numerous studies, today there are many publications full of recommendations on the measures to take in ensuring CLT is protected from the effects of moisture. Wood can easily be affected if not protected from weather elements (Olsson, 2020). For instance, exposure of wood to moisture or water at a favorable temperature would result in the wood growing molds. The molds are microbes that can grow on wood if the conditions are right, which for wood would be a relative humidity of above 75 percent or 15 percent moisture combined with favorable temperatures. Once mold starts to grow on wood, it can be hard to detect it with our naked eyes, which is why a microscope has to be used in the detection of molds on wood.

More studies need to be put into understanding the effects of moisture in CLT. One of the areas in which more study would be essential is in understanding the weathering performance of CLT. Olsson (2020), notes that in most parts of the country, the weathering performance of CLT remains unknown. The situation calls for more research and the implementation of codes that could be used for weathering and moisture management in CLT. According to Olsson (2020), weathering refers to the type of surface degradation on wood that results from exposure to environmental factors. Exposing unprotected wood to environmental elements such as water and the sun will result in the degradation of the wood's surface. Other risks that are faced by unprotected wood are; stains, decay, mildew, and warp.

The hygroscopic nature of wood allows its physical properties and durability to be determined by the moisture content of the wood. In simple terms, wood is likely to swell

with the increase of moisture content and shrink with the decrease in moisture content (Öberg & Wiege, 2018). In the long run, the fluctuation of moisture content led to wood expanding and contracting. If wood is exposed to excessive moisture for an extended period of time, it may not get back to its original size. Other elements of wood that are affected through weathering are the wood's toughness and its tensile strength. Weathering can also affect the strength of bonded wood if the moisture content in the wood goes above Fiber Saturation Point (FSP) of wood. It can introduce stresses as well as compromise the mechanical connections of the CLT.

Being able to absorb moisture makes wood to be at risk of experiencing mold growth. To eliminate chances of mold growth, it is important to clear and wash out the mold damages (Wang, Wang, & Ge, 2020).

Heat is another factor that can contribute to the thermal degradation of CLT. Temperature affects wood differently, which is by increasing the intensity of oxidative and photochemical reactions. Under the effect of high temperature of about 160⁰ C, the wood acquires darker shade resulting in thermal degradation (dos Santos Bobadilha, 2020). Also, thermal or temperature fluctuations above 160⁰ C can lead to the formation of fine cracks onto the wood and noticeable degradation of the mechanical properties of the wood.

In conditions or places where temperature and humidity are elevated, wood is most likely to undergo changes in its properties including the growth of fungi on its surface (Öberg, & Wiege, 2018). To help protect the wood from the temperature and weathering effects, it is important to protect the wood. There are a few effective methods that have been used to protect or preserve the wood. Some of these methods include the use of paints,

stains, varnish, and other water-repellent coatings (Öberg, & Wiege, 2018). Well-coated or protected CLT retains its structural strength and is more durable as compared to untreated wood.

CHAPTER THREE

DESIGN OF NOISE BARRIER

3.1 DESIGN PROCEDURE AND GUIDELINES

This section presents the fundamentals of noise barrier design in the light of current noise barrier design codes, the national design specification (NDS 2018), the American association of state highway and transportation officials (AASHTO), the CLT Handbook, and the MPP Handbook. In addition, this chapter will also present a cost comparison between a CLT noise barrier and a concrete noise barrier. In addition, the environmental impacts due to the construction of concrete noise barriers compared to the CLT noise barrier are assessed. In this section, the immediate and long-term environmental impacts of using CLT vs concrete noise barriers are presented. Finally, the proposed CLT noise barrier design is showcased with a 3D model using solid works.

The first step in designing an effective noise barrier is to identify the location to obtain appropriate loads (seismic, wind, and snow). Going through several Department of Transportations' (DOT's) websites, it was determined that Georgia DOT is planning to build a noise barrier in Hoschton City which is located in Jackson County Georgia. So this location was selected for the prototype noise barrier design. In addition, the design we compared with the required member sizes for a high seismic region and a high wind region.

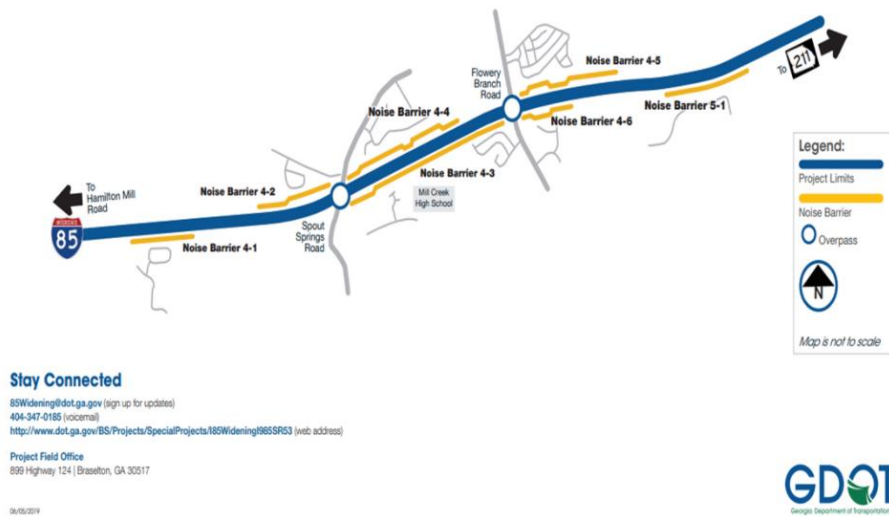


Fig 3.1: Layout of Noise Barrier (GDOT)

The next step after identifying the location was to determine the height and span length for the noise barrier. The height of the noise barrier depends on the terrain conditions and the required reduction in the noise level in the region. To determine the appropriate height for the selected location, data was collected on typical noise barrier heights from the Federal Highway Administration Noise Barrier Database (U.S Department of Transportation Federal Highway Administration, n.d.). The approach led to the formulation of an Excel sheet in which the data of noise barriers built from 1963 to 2016 was logged and the graphs were plotted according to the different categories. The average height of the noise barrier turned out to be 15 ft. Based on the factors mentioned before the height of the barrier to be designed to be 16ft. The figure below is a summary of the noise barrier heights and the unit costs found from the Federal Highway Administration Noise Barrier Database.

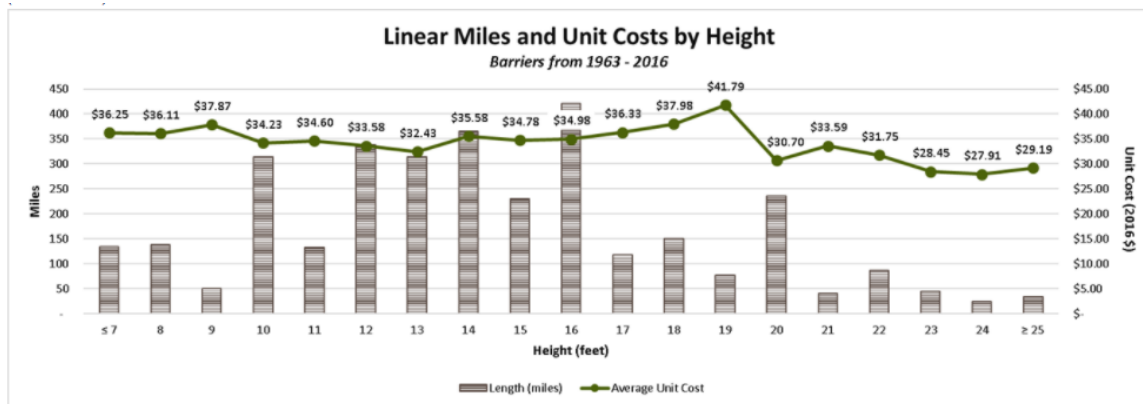


Fig 3.2: Linear miles and unit costs of noise barrier by height

There are several factors which effect the selection of the span length of the noise barrier: transportation, installation challenges, replacement considerations in the case of an accident or damage and out of plane loading. Concrete is a heavy material weighing around five times the weight of CLT, which means that longer spans are possible to transported and installed for CLT noise barriers. However, longer spans mean more material to be replaced if a panel was damaged in an accident.

A key factor that helped in facilitating the decision about the span length of the noise barrier was accident probability. The statics from the National Highway Traffic Safety Administration (NHTSA, n.d.) which is a subsidiary of the United States Department of Transportation (USDOT) is mentioned below:

Year	Vehicle Miles Travelled (Millions)	Police Reported Vehicle Traffic Crashes	Crash Per Million Miles Travelled
2018	3,240,327	6,734,000	2.08
2017	3,212,347	6,453,000	2
2016	3,174,408	6,821,000	2.15
2015	3,095,373	6,296,000	2.03

Table 3.1: No of crashes per million miles travelled (NHTSA, n.d.)

From the GDOT’s website, we were able to locate the Georgian traffic count station which is very close to the proposed location to build a noise barrier. Average Annual Daily Traffic (AADT) is the total volume of vehicle traffic of a highway for a year divided by 365 days. Following is the AADT for the station

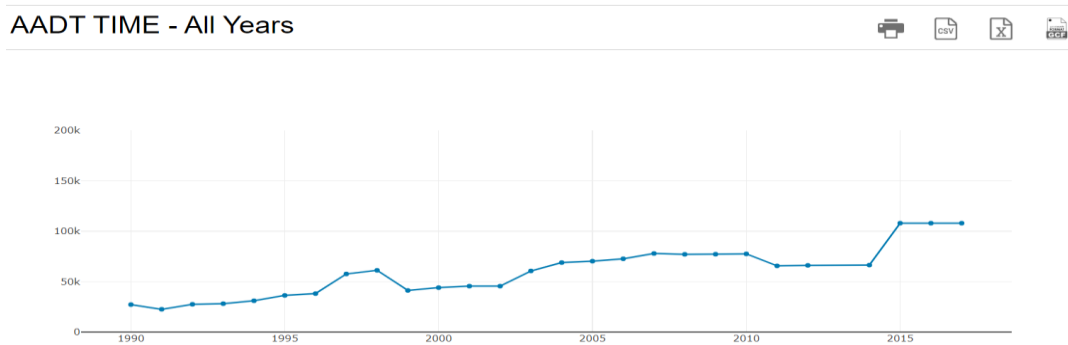


Fig 3.3: Average Annual Daily Traffic (AADT) near to noise barrier location (NHTSA, n.d.)

AADT for the years 2015 through 2017 seems to be constant about 108K, Therefore the probability of crash in the years 2015 to 2017 will be:

Year	AADT	Cash per million miles travelled	Expected Crash
2017	108K	2	Every 5 days
2016	108K	2.15	Every 5 days
2015	108K	2.03	Every 5 Days

Table 3.2: Probability of crashes near noise barrier location

Based on the above factors the noise barrier was designed for 20 ft. span. This will be twice the span length used for concrete noise barrier, which results in a smaller number of foundations and quicker installation for CLT compared to concrete noise barriers.

Once the candidate noise barrier height and span were established, designs for CLT and MPP noise barrier of these dimensions were produced following code requirements.

There are different manufactures of CLT located across the country. For this project Kattera, Structurlam, and Smartlam were considered. Since each manufacturer uses different species of wood, the layups are a little bit different, and the strength varies from one manufacturer to another. To compare the properties of CLT from the three manufacturers, we used an Excel sheet. From the comparison, we were able to come up with suggestions of CLT Panel Layup from each manufacturer.

Manufacturer	Katerra	Smartlam
Manufacturing Unit	Washington	Montana, Alabama
Species	Spruce-Pine Fir, Douglas fir Larch	Spruce-Pine Fir & Hem Fir Douglas Fir & Larch Southern Yellow Pine
Bonding adhesive	Component polyurethane (formaldehyde-free)	PURBOND polyurethane

Table 3.3: CLT manufactures in USA

However, for MPP, Freres lumber was found to be the only manufacturer of MPP in the United States.

Different loads are expected to act on the noise barrier. These loads are critical factors in designing the noise barriers and therefore need to be taken into consideration. The four loads that are put into consideration are.

Dead Load : The dead load is the summation of the weight of the materials used in designing the noise barrier. In this case, the dead load was the summation of the weight of the CLT panel and steel post. To precisely calculate the weight of the CLT panel, the weight per cubic foot of the CLT panel is multiplied with the length, width, and thickness of the panel. The exact weight of the CLT panel depends on the density of the species and layup, for the calculation the weight of the panel was assumed to be 35 pounds per cubic foot (Evans, 2013).

$$SW_{\text{Panel}} = \text{Density}(\text{pcf}) * \text{Length}(\text{ft.}) * \text{Width}(\text{ft.}) * \text{Thickness}(\text{in})$$

$$SW_{\text{Panel}} = 35 \text{ pcf} * 20' * 16' * 4.125''$$

$$SW_{\text{Panel}} = 3850 \text{ pounds}$$

The sections for the steel post were selected based upon the loading and geographical location of the noise barrier. The steel post considered for the design (W10X33) weighs 33 pounds per linear foot (AISC Steel Manual). Therefore, to calculate the self-weight of the steel post for the design purpose multiply the weight with the length of the post.

$$SW_{\text{Post}} = \text{Weight(plf)} * \text{Length(ft.)}$$

$$SW_{\text{Post}} = 33 \text{ plf} * 16.5'$$

$$SW_{\text{Post}} = 545 \text{ pounds.}$$

Wind load: Noise barriers should be designed for wind loads. The goal should be designing noise barriers that are capable of withstanding wind loads or different magnitudes without compromising their efficiency. Determining the wind loads and how they will impact the noise barriers takes a lot of considerations and factors. The first factor will be the wind speed. The wind speeds are distributed based on the geographical location where the noise barrier will be raised. Therefore, it is important to use contour maps, which helps in specifying the wind speeds per location or region. Wind speed measurements have been used conventionally in noise barrier designs, however, today using wind pressure is preferred. Wind Speed (V): The design 3 second gust wind speed, used in determination of design wind loads shall be determined from the figure below.

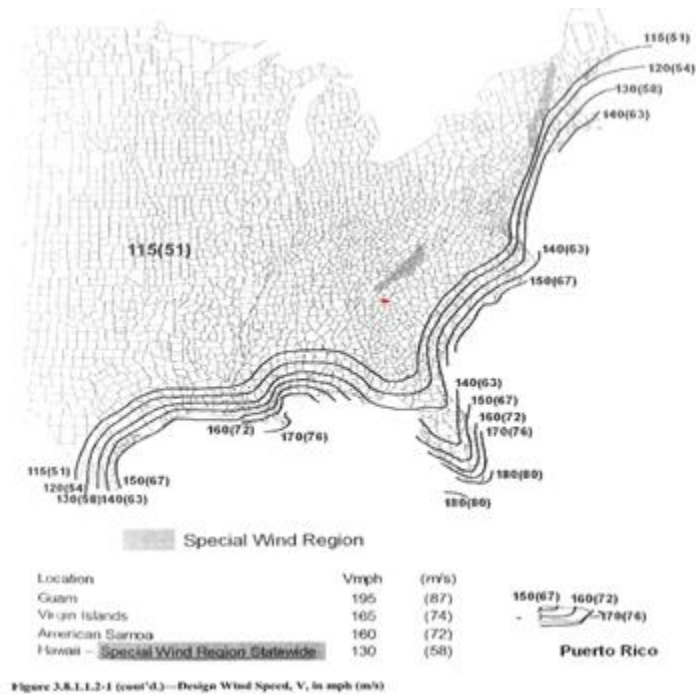


Fig 3.4: AASHTO Wind Map

$V = 115 \text{ MPH}$ (For the location highlighted on the wind map)

Besides the wind pressure, the next factor that was taken into account in determining the wind loads is the wind exposure category. The wind exposure category was found to be dependent on the ground roughness categories. To determine the wind exposure categories, it is important to understand that wind pressure may vary depending on whether the wind direction is being affected by the nearby infrastructure, which can be buildings and/or trees. The assumption that is made is that wind direction will be acting perpendicular to the noise barriers. The wind exposure category is specified in the AASHTO C3.8.1.1.3. Wind Exposure Category B applies for the prototype design location since there are multiple structures with mean height of 33 ft. or less. Next, the value for

pressure exposure and elevation coefficient (K_z) must be obtained, For structures having height less than 33 ft., no reduction in the value of K_z is applied.

Structure Height, Z (ft)	Wind Exposure Category B	Wind Exposure Category C	Wind Exposure Category D
≤ 33	0.71	1.00	1.15
40	0.75	1.05	1.20
50	0.81	1.10	1.25
60	0.85	1.14	1.29
70	0.89	1.18	1.32
80	0.92	1.21	1.35
90	0.95	1.24	1.38
100	0.98	1.27	1.41
120	1.03	1.32	1.45
140	1.07	1.36	1.49
160	1.11	1.40	1.52
180	1.15	1.43	1.55
200	1.18	1.46	1.58
250	1.24	1.52	1.63
300	1.30	1.57	1.68

Table 3.4: Pressure Exposure and Elevation Coefficient (Section 3 : Loads and Load Factors, AASHTO, 2020)

From the above table pressure exposure and elevation coefficient $K_z = 0.71$.

The gust effect factor (G) is a function of the size and dynamic characteristics of the structure including the sound barrier, natural frequency and damping. The average values for sound barriers are specified in the AASHTO Table 3.8.1.2.1-1.

Structure Type	Gust Effect Factor, G
Sound Barriers	0.85
All other structures	1.00

Table 3.5: Gust Effect Factor (Section 3 : Loads and Load Factors, AASHTO, 2020)

From the above table gust effect factor for sound barrier $G = 0.85$

Another important element that is key in calculating the possible wind loads that are expected to act on the noise barrier is the drag coefficient. The drag coefficient for different structures, (noise barriers, bridges, and box-girder substructures), are specified in the C_D table 3.8.1.2.1-2 in AASHTO.

Component		Drag Coefficient, C_D	
		Windward	Leeward
I-Girder and Box-Girder Bridge Superstructures		1.3	N/A
Trusses, Columns, and Arches	Sharp-Edged Member	2.0	1.0
	Round Member	1.0	0.5
Bridge Substructure		1.6	N/A
Sound Barriers		1.2	N/A

Table 3.6 Drag Coefficient (Section 3 : Loads and Load Factors, AASHTO, 2020)

Form the above table Drag Coefficient for Sound Barriers $C_d = 1.2$

Seismic Loads: Seismic events can easily lead to noise barriers collapsing or sustaining damage. The AASHTO LRFD requirements specify the design approaches and considerations for seismic loads. In case of a large earthquake, the noise barrier should be able to sustain damage without necessarily collapsing, and the damages should be easy to detect and make the necessary repairs.

The location of the noise barrier plays a role in the seismic load consideration. The design process therefore will require the use of maps with contour lines showing the seismic zones. AASHTO LRFD figures 3.10.2.1-21 presents the series of seismic zone maps. Once the seismic zones where the noise barriers will be located have been evaluated, the next set of calculations will involve the short-period (S_s), long-period

spectral coefficients (S_1), and the peak ground acceleration (PGA). Following are the respective values according to the AASHTO Maps applicable for our location:

Peak Ground Acceleration $PGA=0.09$ (AASHTO Fig 3.10.2.1-1)

Spectral Acceleration Coeff. period of 0.2 Seconds $S_s = 0.18$ (AASHTO Fig 3.10.2.1-2)

Spectral Acceleration Coeff. period of 1 Seconds $S_1 = 0.06$ (AASHTO Fig 3.10.2.1-2)

The values of site factors are dependent on the soil class, since geotechnical information was not available for the prototype design location, soil class D was assumed.

Following are the values of site factors for PGA, S_s and S_1 .

Site Class	Peak Ground Acceleration Coefficient (PGA) ¹				
	$PGA < 0.10$	$PGA = 0.20$	$PGA = 0.30$	$PGA = 0.40$	$PGA > 0.50$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	0.9
F ²	*	*	*	*	*

Table 3.7: Site Factor F_{PGA} at zero period on acceleration spectrum (Section 3 : Loads and Load Factors, AASHTO, 2020)

From the above table $F_{PGA} = 1.6$

Site Class	Spectral Acceleration Coefficient at Period 0.2 sec (S_S) ¹				
	$S_S < 0.25$	$S_S = 0.50$	$S_S = 0.75$	$S_S = 1.00$	$S_S > 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	0.9
F ²	*	*	*	*	*

Table 3.8: Site Factor F_a at short period range of acceleration spectrum (Section 3 : Loads and Load Factors, AASHTO, 2020).

From the above table $F_a = 1.6$

Site Class	Spectral Acceleration Coefficient at Period 1.0 sec (S_1) ¹				
	$S_1 < 0.1$	$S_1 = 0.2$	$S_1 = 0.3$	$S_1 = 0.4$	$S_1 > 0.5$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.7	1.6	1.5	1.4	1.3
D	2.4	2.0	1.8	1.6	1.5
E	3.5	3.2	2.8	2.4	2.4
F ²	*	*	*	*	*

Table 3.9: Site Factor F_v at long period range of acceleration spectrum (Section 3 : Loads and Load Factors, AASHTO, 2020)

From the above table $F_v = 2.4$

According to seismic zone maps, seismic zone 1 is considered to be the location with the least seismic events, therefore calculating the seismic loads is not a necessity and the noise barriers can be designed without seismic loads being put into consideration. The AASHTO LRFD Article 3.10.9 specifies the default values for the seismic design forces per zone. According to seismic zone assessment, zone 4 represents areas with a higher probability of experiencing seismic forces or loads. If the noise barrier is to be located in such zones, it would be important to put seismic loads into consideration.

Vehicular Collision Forces: During a car crash, there is usually an exchange of energy from the vehicle to the object it hits and back to the vehicle depending on the kind of variables that have been involved in the change of state of motion of the vehicle. The force of vehicular collision is the product of the vehicle's mass and the vehicle's acceleration (R.W.L, et al., 2020). As the vehicle hits an obstacle, a bridge for instance, the car exerts force equivalent to the product of its mass and acceleration to the bridge and the bridge, if completely static and at rest, exerts an equal but opposite force on the car. This force is usually what makes a vehicle to bounce back after collision, an effect best described by Newton's third law of motion (PatrickCornille, 1999), The vehicular force of collision also takes into account the material of the sound barrier to be used. When a vehicle has a collision on a surface, the exertion of the action force is dependent on whether the object is completely still and immovable or whether the object is elastic or can break. When the vehicle makes a collision and the object collided with doesn't move at all or break, the

reaction force transferred to the vehicle by the object can be devastating to the people or contents inside the vehicle.

Sound barriers typically consist of two components: a sound barrier and a traffic railing (LuigiMaffei, et al., 2013). For design, vehicular force of collision will be applied to the sound barrier such unless that sound barrier will be behind a crush worthy road railing at a distance of more than four feet (4ft). For the sake of the prototype design, it was assumed that sound barrier is behind a crashworthy traffic railing with a sound setback more than 4 ft., hence vehicular collision forces need not be considered (AASHTO 15.8.4-Vehicular Collision forces, Case 4)

3.2 STRUCTURAL MEMBER DESIGN

Design of CLT Panel

The CLT panel used in the design was V3 layup. CLT panels having a V3 layup means No 2. southern pine lumber in all the longitudinal layers and No. 3 southern pine lumber is used for all the transverse layers. The V3 CLT panel was checked against bending, shear, bearing and deflection. The structural properties of the panel were referenced from APA PRG 320 standard and NDS 2018. Bending, shear, bearing and deflection of the panel are calculated from the following equations from table 10.3.1 NDS 2018 respectively:

$$F_b'S_{\text{eff}} = F_b S_{\text{eff}} * C_m * C_t * C_L * K_{Fb} * \phi_b * \lambda \quad (3.1)$$

$$F_s'I_{\text{beff}} = F_s * C_m * C_t * K_{Fs} * \phi_s \quad (3.2)$$

$$F_{c\perp}' = F_{c\perp} * C_m * C_t * C_b * K_{Fc\perp} * \phi_{c\perp} \quad (3.3)$$

$$EI_{\text{app}} = EI_{\text{eff}}' / (1 + ((EI_{\text{eff}}' * k_s) / (GA_{\text{eff}}' * L_{\text{panel}}^2))) \quad (3.4)$$

$$\Delta = (5 * W_{\text{panel}} * L_{\text{panel}}^4) / (384 * EI_{\text{app}}) \quad (3.5)$$

In the above equations, $F_b'S_{\text{eff}}$ = adjusted effective flatwise bending moment of CLT, $F_b S_{\text{eff}}$ = effective reference flatwise bending moment of CLT, C_m = wet service factor, C_t = temperature factor, C_L = beam stability factor, K_{Fb} = Format conversion factor for bending, ϕ_b = Resistance factor for bending, λ = time effect factor, $F_s'I_{\text{beff}}$ = adjusted effective rolling shear of CLT, $F_s I_{\text{beff}}$ = reference effective rolling shear of CLT, K_{Fs} = Format conversion factor for rolling shear, ϕ_s = Resistance factor for rolling shear, $F_{c\perp}'$ = adjusted compressive stress of CLT, $F_{c\perp}$ = reference compressive stress of CLT, C_b = bearing area factor, $K_{Fc\perp}$ = Format conversion factor for compression, $\phi_{c\perp}$ = Resistance factor for compression, EI_{app} = apparent bending stiffness of CLT, EI_{eff} = effective bending stiffness of CLT, k_s = shear deformation adjustment factor, GA_{eff} = effective shear stiffness of CLT, L_{panel} = length of the CLT panel, Δ = deflection, W_{panel} = udl acting on panel. The design parameter and analysis of a V3 layup CLT panel is shown in Appendix A.

Design of Steel Post

Steel post design and analysis was performed according to the guidelines of AISC edition 15th, Different steel sections for the post were analyzed, W steel section was designed as a post as it was easy to install and aesthetically pleasing. Steel post was checked for bending and shear using the following equations

$$\phi M_n = \phi_b * C_b * (M_p - (M_p - 0.7 * F_y * S_x) * ((L_b - L_p) / (L_r - L_p))) \quad (3.6) \text{ (Eq F2-3 AISC, 15}^{\text{th}} \text{ edition)}$$

$$\phi V_n = \phi_v * C_v * F_y * A_w \quad (3.7) \text{ (Eq G2-1 AISC, 15}^{\text{th}} \text{ edition)}$$

In the equations 3.6 and 3.7 , ϕM_n = factored nominal flexural strength, ϕ_b = resistance factor for flexure, C_b = moment gradient factor, M_p = plastic moment capacity, F_y = yield strength of steel, S_x = section modulus in x direction, L_b = actual unbraced length, L_p = unbraced length at plastic limit state, L_r = unbraced length at rupture limit state, ϕV_n = factor shear strength, ϕ_v = resistance factor for shear, C_v = web shear coefficient, A_w = area of web. The design parameter and analysis of a W section steel post is shown in Appendix A.

Design of Connections

Different connections were designed throughout the design process of the noise barrier. The connections include the lap joint connection in mass timber panel, shim angles, seating angles and anchor bolt. Simpson strong tie fasteners with a withdrawal capacity of 500 lbf were checked for the withdrawal loads using the formula from table 11.3 NDS, 2018 edition mentioned below:

$$W' = \phi_w * K_{FW} * \lambda * C_m^2 * C_t * C_{eg} * C_{tn} * W \quad (3.8)$$

In the equation 3.8, W' = adjusted withdrawal capacity, ϕ_w = resistance factor for withdrawal, C_m = wet service factor, K_{FW} = Format conversion factor for withdrawal, C_t = temperature factor, C_{eg} = end grain factor, C_{tn} = toe nail factor, λ = time effect factor, W = reference withdrawal capacity. The design of lap connection for the mass timber panel is shown in appendix A.

The seating angle and shim angle both were checked against flexure and shear using the following equations

$$\phi V_n = \phi_v * 0.6 * F_y * b * t_{angle} * C_{v2} \quad (3.9) \text{(Eq. G3-1 AISC, 15th Edition)}$$

$$\phi M_n = \phi_b * F_y * S_x \quad (3.10) \text{(Eq. F9-16 AISC, 15th Edition)}$$

In the equation 3.9 and 3.10, ϕV_n = factored shear capacity, ϕ_v = shear resistance factor, F_y = yield strength of steel, b = width of steel angle, t_{angle} = thickness of steel angle, C_{v2} = shear buckling coefficient, ϕM_n = factored flexural strength, S_x = section modulus. The design of seating angle and shim angle is shown in Appendix A.

Anchor bolts were checked for shear strength using the following equation

$$\phi R_n = \phi_v * F_{nv} * A_b \quad (3.11) \text{(Eq. J3-1 AISC, 15th Edition)}$$

In the equation 3.11, ϕR_n = design shear strength, F_{nv} = nominal shear stress, A_b = nominal area of bolt. The design of anchor bolts is shown in Appendix A.

3.3 ENVIRONMENTAL IMPACT

Using CLT panels for noise barriers has a positive environmental impact as compared to the use of concrete. To better understand the varying impact, a carbon dioxide emission calculation was performed. Timber panels used in construction do not emit carbon dioxide but rather they store the carbon dioxide for the rest of their lifecycle. Unfortunately, the construction of concrete noise barrier panels emits carbon dioxide. A timber noise barrier panel with the dimensions of 20'x16'x4.125" is capable of storing up to 4500lbs of carbon dioxide, whereas a concrete noise barrier panel of the same dimension can result in an emission of up to 1630lbs of carbon dioxide into the atmosphere. Therefore, the use of Mass Timber noise barrier panels is a good option as compared to concrete noise barrier panels. Carbon Emission study on 20' X 16' X 4.125" Timber panel and Concrete panel was carried out, 1630 lbs., of CO₂ will be emitted during the construction process of Concrete panel whereas 4500 lbs. of CO₂ will be stored if we use Timber Panel therefore Adoption of mass timber noise panels will result in a reduction of up to 6130lbs of CO₂, The use of timber noise barrier panels has proved to have a positive environmental impact when compared to their concrete counterparts.

3.4 COST ESTIMATES

Cost is a key factor when it comes to justifying the type of noise barriers that can be used to reduce noise level on our highways. Cost analysis between the use of timber noise barriers and concrete noise barriers was performed. The numbers and information

used for the cost analysis were acquired through a case study that was carried out in Florida using data from the local precast manufactures and installer.

The factors that were looked at in terms of cost were the materials, transportation, and installation. Upon comparing the costs from different manufactures of CLT in the U.S we found that the CLT panels (20'X8') cost around \$10/sf and an additional \$2/sf was assumed for the treatment of the panels. The steel post cost was provided by the local supplier and may vary in different regions in U.S, we assumed \$5.25/sf for the steel post. The material used in making CLT noise barriers, which includes posts and treatment costs \$17.25 per square foot. For precast concrete, the cost was provided by Mark Witt form Sea Precast Plant, FL. The cost including the posts was \$11.50 per square foot. Therefore, in terms of materials, precast concrete is considered to be less costly, but this is just a small part of the equation. The other part of the equation is the transportation and the installation costs. As there are fewer CLT manufacturing plants in the U.S compared to precast concrete plants, the transportation distance for CLT was assumed to be 250 miles compared to 100 miles for precast concrete. It was estimated that CLT costs \$8.50 per square foot for the transportation and installation cost, whereas precast concrete costs \$13.50 per square foot. The cost analysis revealed CLT for noise barriers would be slightly less expensive when compared against the concrete noise barriers for this case study.

	CLT	Precast Concrete
Panel Dimensions	20' X 8'	10' X 8'
Distance	250 Miles from project site	100 Miles from project site
Material Cost	\$ 17.25/SF including posts and treatment	\$ 11.5/SF including posts
Total Material Cost	\$ 644,554	\$ 485,760
Transportation & Installation cost	\$ 8.5/SF	\$13.5/SF
Project Cost	\$1,003,594	\$1,056,000

Table 3.10: Cost Analysis Summary

3.5 3-D Model Rendering

Having a model during the design process improves the understanding of the project therefore 3-D model of the noise barrier was developed using Solid works. All the structural members and the connections were drawn to understand the design process.

Following are the photos from the 3D model:

In the figure below the CLT panels are sliding from the top into the steel post, Then two CLT panels are connected using a lap joint connection. 4" long Simpson Strong tie fasteners having withdrawal capacity of 500 lbf are installed at the lap joint connection.



Fig 3.5: Installation of the CLT Panel

Panels are allowed to sit on the seating angles so that they do come in contact with the ground surface. Shim angles are installed in the steel post according to the thickness of the panel so that the panel does not move.

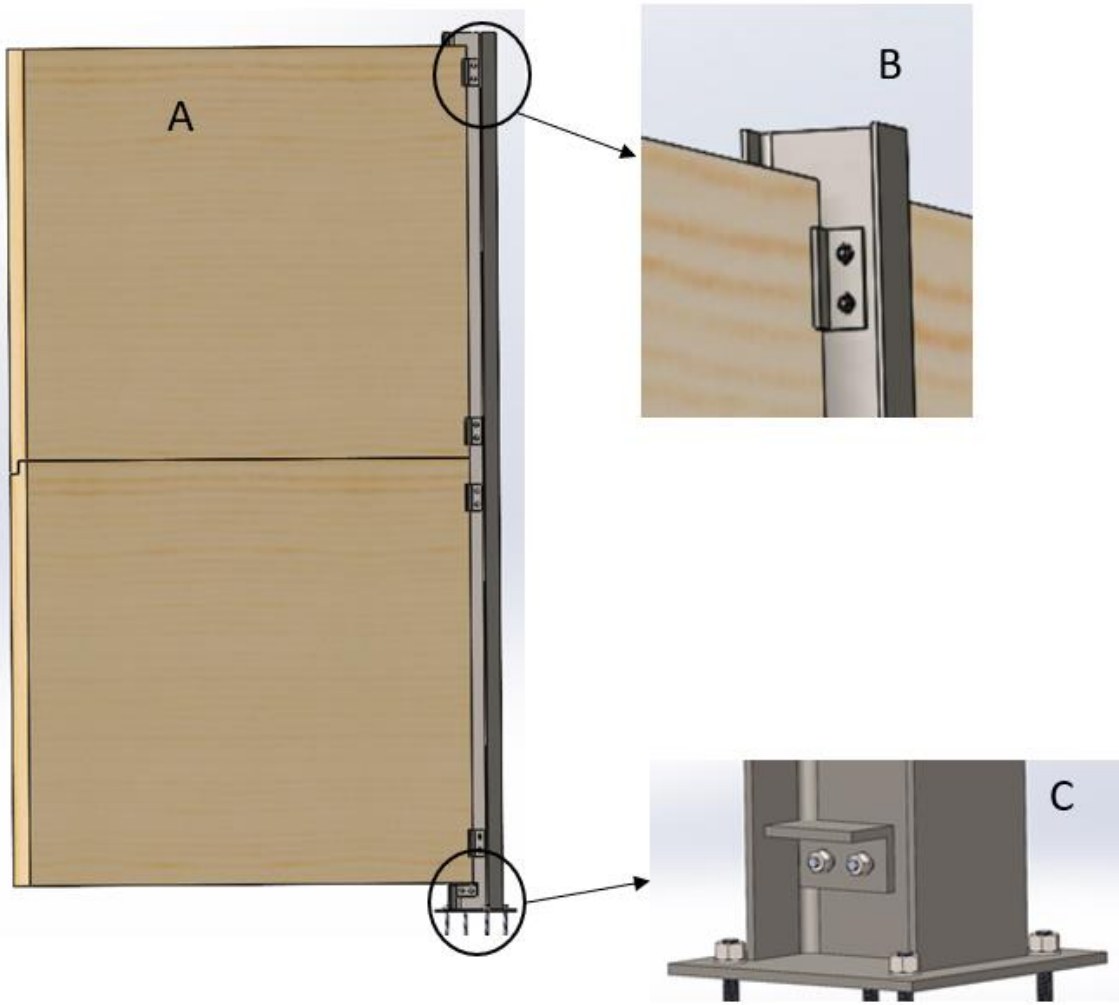


Fig 3.6: Rear view of noise barrier (A), Shim Angles (B), Seating Angles(C)

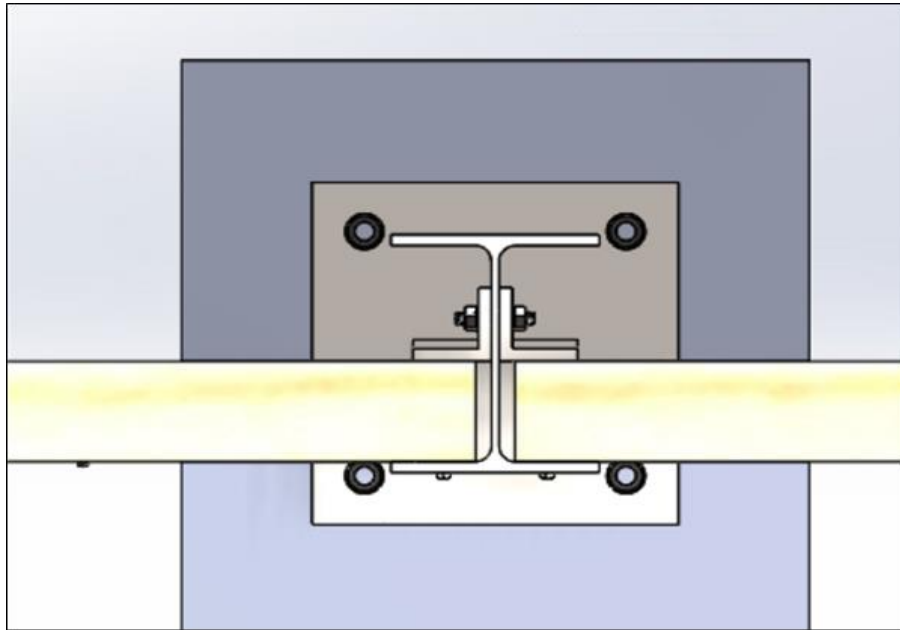


Fig 3.7: Top View of Noise Barrier

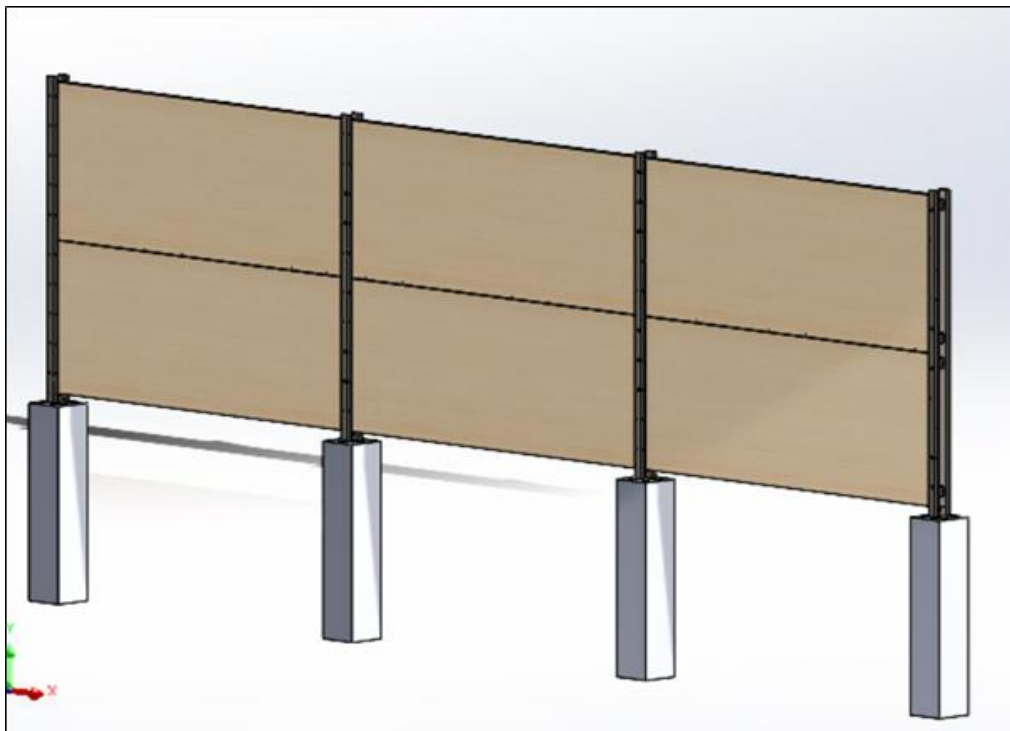


Fig 3.8: Isometric View of Noise Barrier

CHAPTER FOUR

PROTOTYPE NOISE BARRIER

4.1 COATINGS USED TO IMPROVE CLT PERFORMANCE

Treatment was initially considered as an option for moisture resistance of CLT noise barriers. However, in discussion with the Advisory Board, it would not be possible to work with pressure treated wood in the manufacturing plants and treatment facilities are not large enough to treat full noise barrier panels. Having a member from Sansin who has expertise in wood treatment in the advisory board, assisted in shortlisting a few possible coating options which could be applied on the CLT panel after it is produced and will protect against moisture and damages due to UV.

Sansin is a global leader in developing environmentally friendly wood finishes. Since its foundation in 1986, Sansin has dedicated its innovative research and development programs towards creating the best performing and aesthetically appealing water-borne wood finishes globally. The biggest achievement so far is the fact that the company is a global leader in developing environmentally friendly wood coatings and preservatives that serve as an excellent alternative to traditional wood coatings and preservatives. The company strives to meet the demand for its wood coating solutions through its many dealerships spread across the United States, Russia, Canada, and Western Europe. Two coatings WoodLife and Teakwood were selected for the prototype noise barrier panel and monitor the wood.

Sansin WoodForce is a wood treatment solution that is used to coat the exterior of wood, in return protecting wood from blackening, rotting, and discoloration through its water repellent properties. Unlike other coatings, WoodForce can be mixed and blended to create standard, custom, and vintage effects. WoodForce comes with other features such as being environmentally friendly, breathable, and easy to maintain. The application of WoodForce spans across new and old, weathered or restored vertical wood surfaces, which makes the coat good at wood cladding, logs, timbers, and wood roofing.

Sansin Teak Life UV, is a deep penetrating but yet waterborne solution that creates a monolithic bond with teak. Three key benefits result from using the Teak Life UV. First, it is a water-repellant, which reduces the water and moisture absorption capabilities of the CLT panel. The second benefit is its capability of reducing destructive ultraviolet light, thus improving the lifespan of the wood panel if their use and applications involves exposure to sunlight. Lastly, the Teak Life UV provides dimensional stability and protects against discoloration.

4.2 SENSORS USED FOR LONG-TERM MOISTURE MONITORING

SMT Research sensors were used to instrument the prototype noise barrier. To take reading about moisture, temperature, and rainfall data, sensors were installed in the panel and data is collected remotely. Data collected by these sensors/instruments is important in determining the properties of CLT under varied weather conditions. The sensors and instruments used were.

- Point Moisture Measurement (PMM).
- Rain Gauge.
- A3 data unit.
- Silicone.

Point Moisture Measurement (PMM)

The level of moisture a material absorbs can have an impact on its structural and physical properties. In the construction or building industry, it is important to take readings about moisture content on timber to determine the fiber saturation point (FSP). Knowing the FSP value, we can predict whether or not a MC change would affect shrinking or swelling of wood. Apart from dimensional change, higher MC in wood can also result in growth of fungi on wood surface which may result in deterioration of wood. The Point Moisture Measurement (PMM) is a reliable sensor that is designed to take readings on moisture content through direct contact measurements. PMM is versatile and this makes it applicable to different construction materials such as wood, concrete, and gypsum.

To make sure consistent data readings are taken, the PMM was used on different locations of the wood panel that was being tested. Once the PMM is screwed into the panel, a specific voltage is passed through the wood. The moisture content is measured by calculating the electrical resistance of the panel. The electrical resistance varies depending on the moisture content levels.



Fig 4.1: Point Moisture Measurement (PMM)

PMM works as a system, where a reading from the PMM sensor, which has an integrated temperature sensor as well, is transmitted to the SMT's wireless data loggers. Once the readings have been captured by the data loggers, they are transmitted to the Building Intelligence Gateway (BIG). BIG is a powerful computer that has been designed to gather sensor data. In the construction industry, BIG is mostly integrated with building control systems. When taking readings about moisture content in wood, the readings from the sensors are translated by BIG, where factors such as wood species and temperature compensation can be accounted for.

Rain Gauges

A rain gauge is a useful instrument that is capable of accurately measuring the amount of rain falling on a surface. In this project, the rain gauge used for data collection was the driving rain gauge. Wood as a material can withstand exposure to rainfall up to a certain level.



Fig 4.2: Driving Rain Gauge

A3 Data Unit

The A3 data unit is a wireless data acquisition unit designed to interface with a wide range of building sensors. The A3 data unit is multichannel which gives it the advantage of capturing data from a variety of sensors. The A3 data unit is capable of supporting up to 8 external sensors and can maintain a continuous stream of data since its sleek design allows it to be installed within occupied spaces, such as homes and in building units. The

versatility of the A3 data unit makes it reliable for monitoring both new construction and retrofit work.

The A3 data unit gathers or captures data from different sensors, after which it transmits the data wirelessly to the BiG, which is the interface on which the data is displayed and stored. The A3 data units can come bundled with relative humidity and temperature sensors as an option. Figure 4.3 below illustrates the data acquisition and transfer process between the A3 data unit and the BiG.

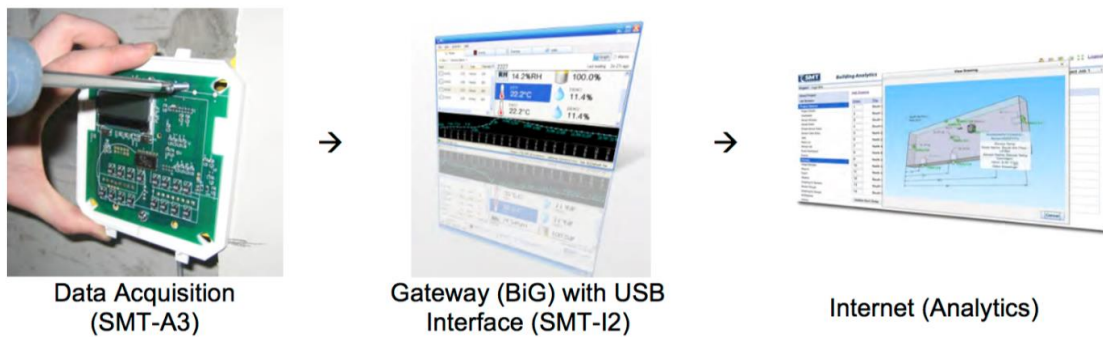


Fig 4.3: Research data acquisition and transfer process from A3 to cloud

4.3 INSTALLATION PROCEDURE

The prototype noise barrier was installed in one of the parking spaces at BEL lab in Pendleton, SC. Since the concrete strength of the pavement was unknown, compression strength was characterized to assure sufficient capacity for the anchor bolts. In order to do this 2” concrete cylinders were extracted from the existing pavement to perform a compression test on the cores.



Fig 4.4: Drilling out a concrete core from the pavement

After drilling the cores were completely cleaned and a flat surface was obtained at both the ends. The average compression strength of the concrete was 2800 psi. Concrete breakout strength of single anchor in tension was calculated by referring to appendix D.5.2.2 in ACI 318-11 and it turned out to be sufficient for the loads of noise barrier. The calculations are shown in Appendix B.



Fig 4.5: Compression test of concrete core

As per the CAD drawings, holes for anchor bolts were marked on the site. $\frac{7}{8}$ " holes were drilled on the site using a concrete hammer drill and $\frac{3}{4}$ " anchor bolts were epoxied 4" into the pavement. Using the forklift, the steel post of section W10X33 was bolted on the anchor bolts. To prevent the steel post from corrosion, the steel post was coated with primer and later on it was painted.

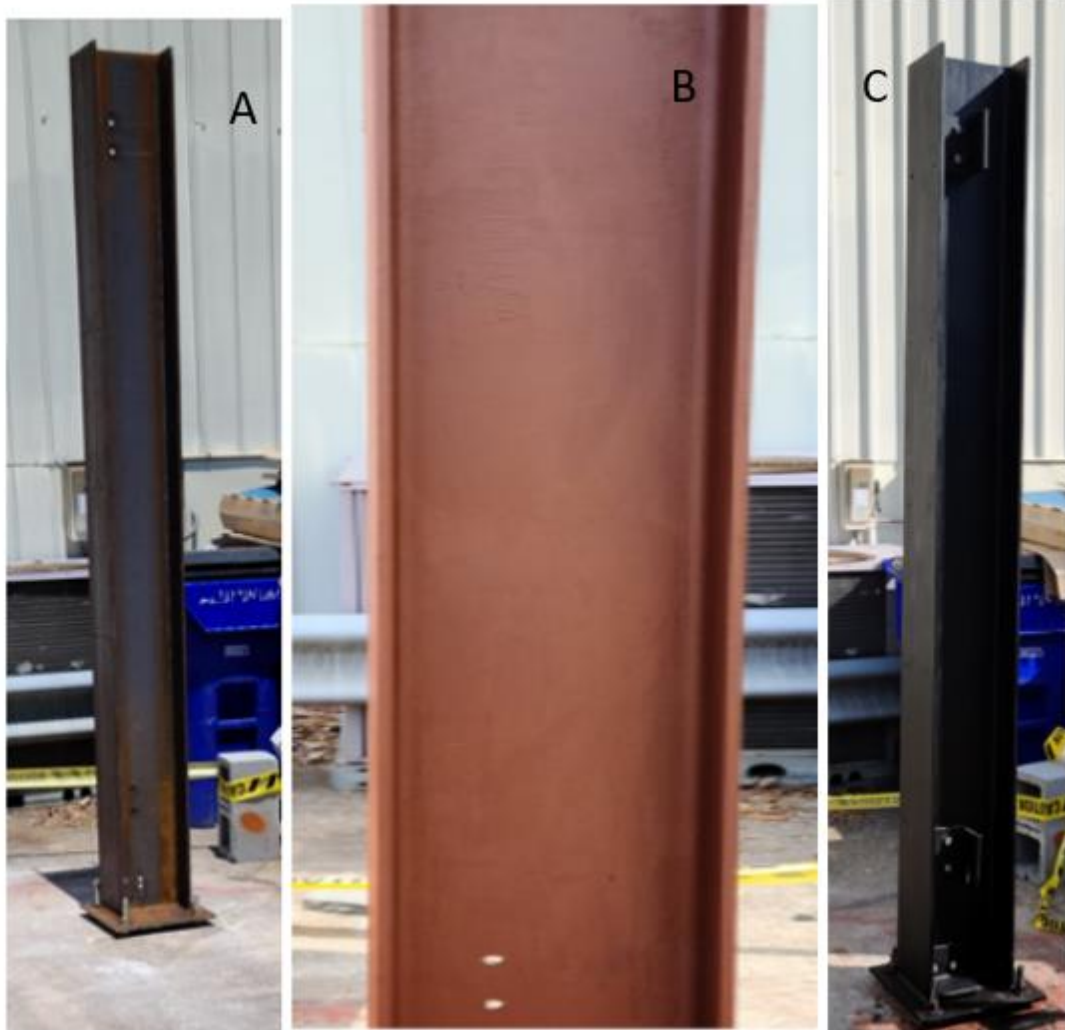


Fig 4.6: Original steel post (A), Steel post coated with primer (B), Painted steel post (C)

The CLT panel was stored outside exposed to the environment for a long period of time therefore before we use it for the noise barrier, a visual inspection was conducted and the panel was checked for dimensional stability, then necessary repairs were carried out. Before the application of the coatings the panel was sanded with 60/80 grit paper using the random orbital sander.



Fig 4.7: Original CLT panel (A), Sanded CLT Panel (B)

After the sanding was completed, the panel was thoroughly cleaned and vacuumed. The first coat of TeakLife coating was sprayed using the garden sprayer on the panel and the paint brush was used back and forth to apply it evenly on to the half portion of panel, the coat was left to dry for 24 hours following which the first of WoodForce was applied on the other half of the panel following the same procedure as previous and the coat was left to dry for another 24 hrs.



Fig 4.8: First coat of TeakLife coating (A), First coat of WoodForce coating (B)

The second coat of TeakLife and WoodForce was applied with the same procedure and was left to dry for another 24hrs. The panel was rotated and kept upside down and the same procedure was followed.



Fig 4.9: Coated CLT Panel

Before sliding the CLT panel into the post the shim and seating angles were placed in position on the steel post. With the help of a forklift the coated CLT panel was slid from the top into the post, after the installation the bolts of shim and seating angles were completely tightened.



Fig 4.10: Installed noise barrier at BEL Lab, Pendleton SC

Each Point Moisture Measurement (PMM) sensor had two screws. The length of the screws was based upon the depth in the panel where we want to get the moisture reading. So, the PMM's were installed at 1", 2" and 3" depth from the surface. Total 18 PMM's were installed out of which 6 were installed at 1" depth other 6 were installed at 2"

depth and renaming 6 were installed at 3” depth so that we can read the moisture in each ply of CLT panel.



Fig 4.11: Installing PMM's at the required depths in the CLT panel

The temperature sensor was installed at 1” and 2” depth in the panel. Total two driving rain gauges were installed, one on either side of the panel so that the bucket may collect the rainwater from both the directions of the panel. The installation procedure for PMM's, temperature sensor and driving rain gauge is briefly described in Appendix C



Fig 4.12: Sensors installed on noise barrier for long term monitoring (Front View)



Fig 4.13: Sensors installed on noise barrier for long term monitoring (Rear View)

4.4 RESULTS

The 8' X 8' CLT panel was coated with two different coatings from Sansin, each coating covering an area of 32 sq.ft. A total 18 Point Moisture Measurement (PMM) sensors were installed, out of which 9 PMM's were installed on each coating. For studying the variation of moisture in the panel, sensors were installed at different depths and locations. In order to study the Moisture variation in each ply of CLT panel we installed sensors at 1", 2" and 3" in the panel.

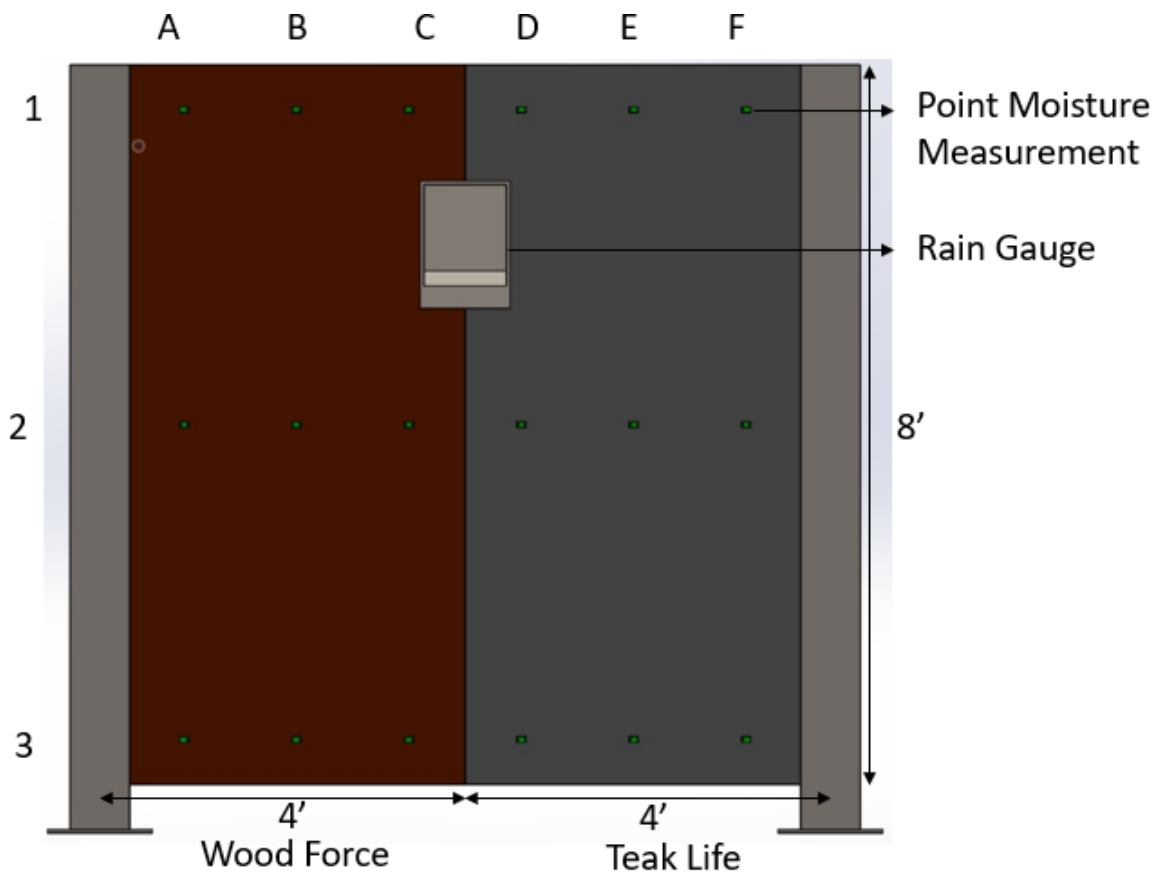


Fig 4.14: Sensors Installed on CLT panel

The A and F rows of sensors are installed at 1” into the panel while the B & E rows of sensors are installed at 2” into the panel and C & D rows of sensors are installed at 3” into the panel. The panel is equipped with two temperature sensors, one at 1" and the other at 2", in order to read the temp data from the temperature sensor are used in the correction factor for the moisture readings. Rain gauges were installed on the surface of the panel, Rain gauges record the amount of rainfall falling on the wall surface. The temperature and rain data from the sensors was compared to the data from the National Oceanic and Atmospheric Administration (NOAA) station. The closest NOAA station was around 5 miles away from the test location. The graph below displays the temperature data from the sensors installed at 1” and 2” into the panel, temperature sensor installed in the data logger and compares it to the temperature data from the NOAA station. As can be seen from the figure the temperature in the wood is around 25° Celsius hotter than the air temperature as wood deck gets heated up. Also, the temperature recorded by the sensor installed in data logger is comparatively hotter than air temperature since it is confined in aluminum box

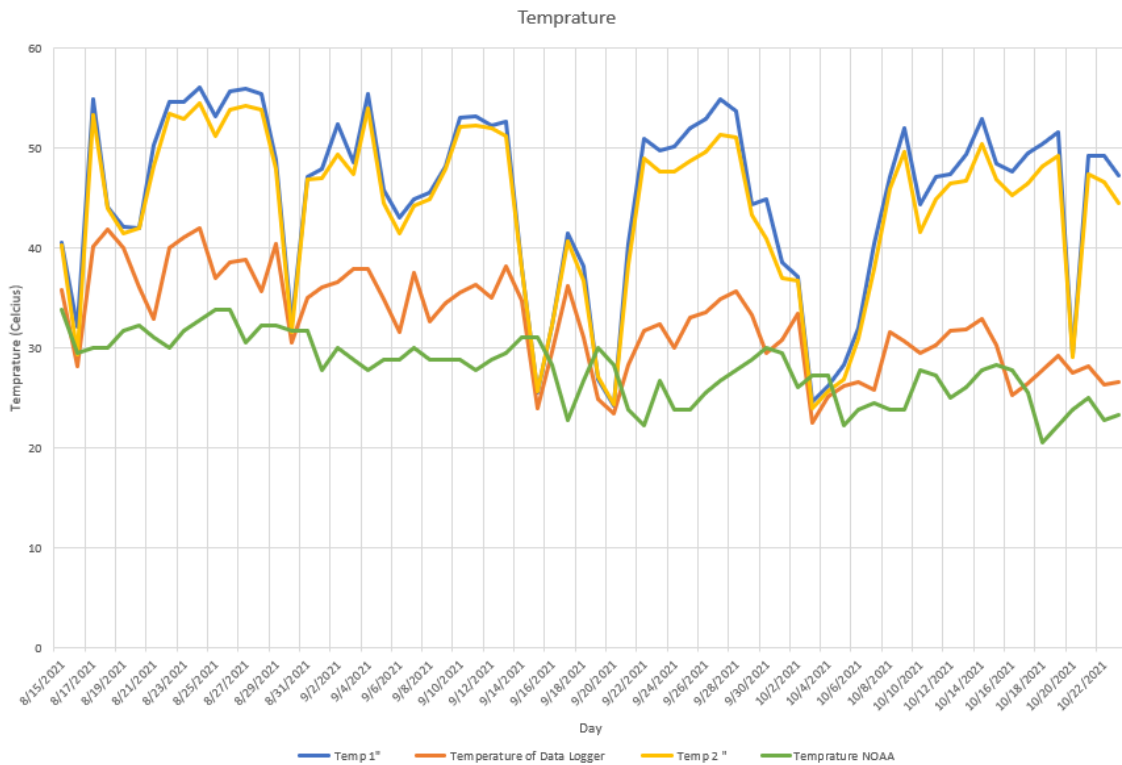


Fig 4.15 : Temperature Data from sensors compared with NOAA station

The graph below represents the data recorded from the rain gauges installed at front and back of the CLT panel compared with the precipitation data received from NOAA station.

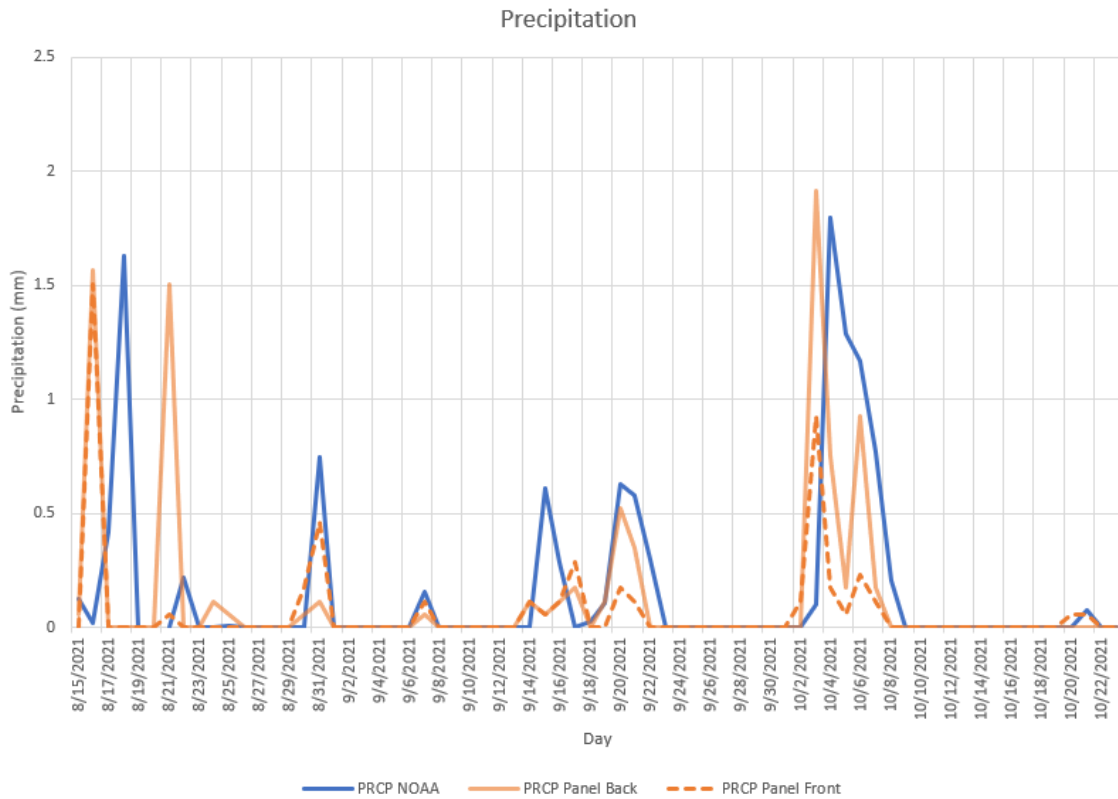


Fig 4.16 : Precipitation Data from sensors compared with NOAA stations

As we can see the rain recorded by the rain gauges installed at the surface of the panel varies, this is dependent on the direction of the wind and rain hitting the surface, to have accurate results we installed the gauges on the front and back of the panel .

The data from the sensors was recorded by A3 installed at the back of the panel and then transmitted to the cloud. The data from the cloud can be accessed from anywhere using BIG software. Adjustments for temperature and relative humidity were made while calculating moisture content for each location. The data from the sensors monitored from middle of the August 2021 to mid-October 2021 is shown below. Following are the graphs

which show the moisture recorded by the sensors installed at 1”, 2” and 3” respectively. The graph in yellow and blue represents the PMM sensors installed in the panel at certain depth. The sensors in yellow are installed on the panel coated with WoodForce and sensors in blue are installed on the panel coated with TeakLife. The graph in green depicts the amount and duration of rainfall. The graph in red depicts the RH in wood.

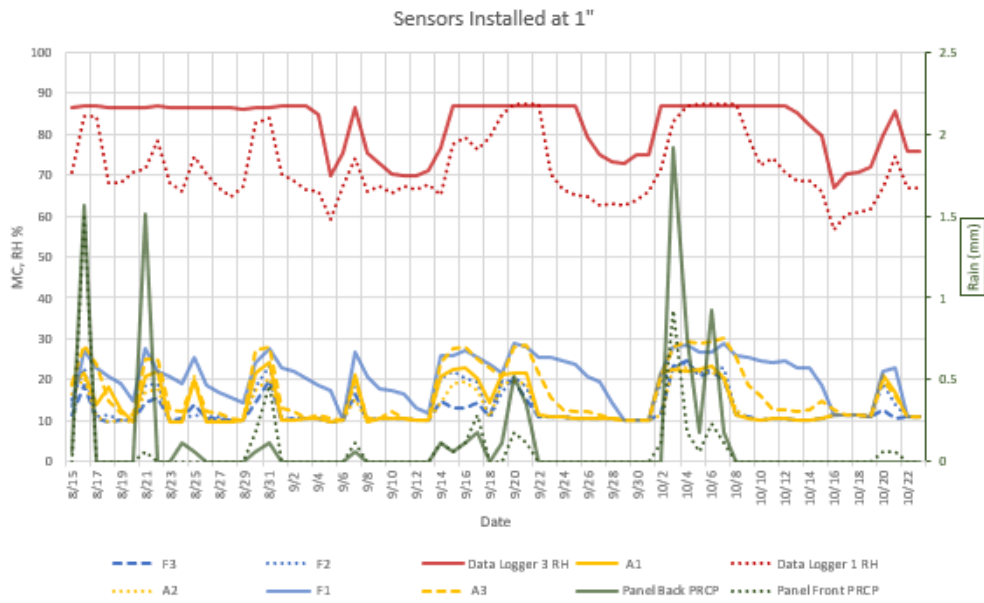


Fig: 4.17 : Moisture Content in CLT panel at 1”

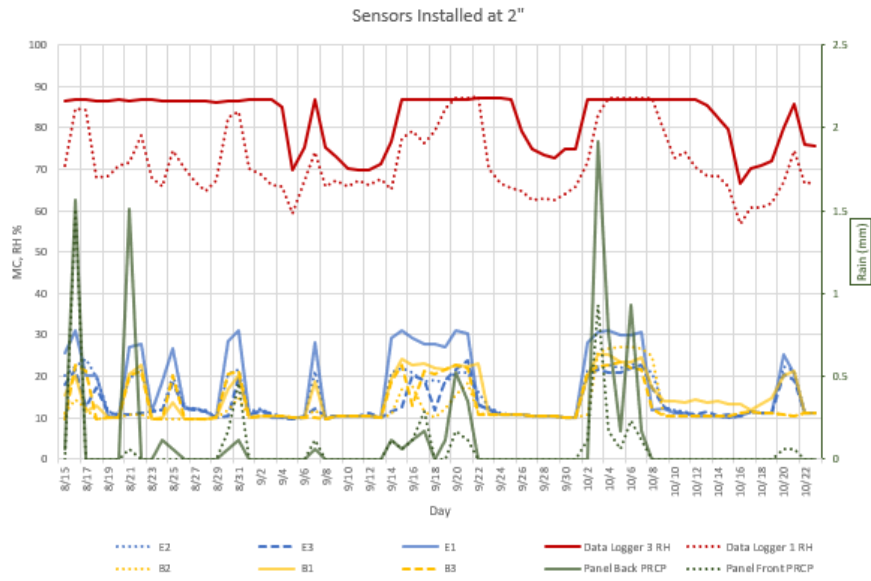


Fig: 4.18 : Moisture Content in CLT panel at 2”

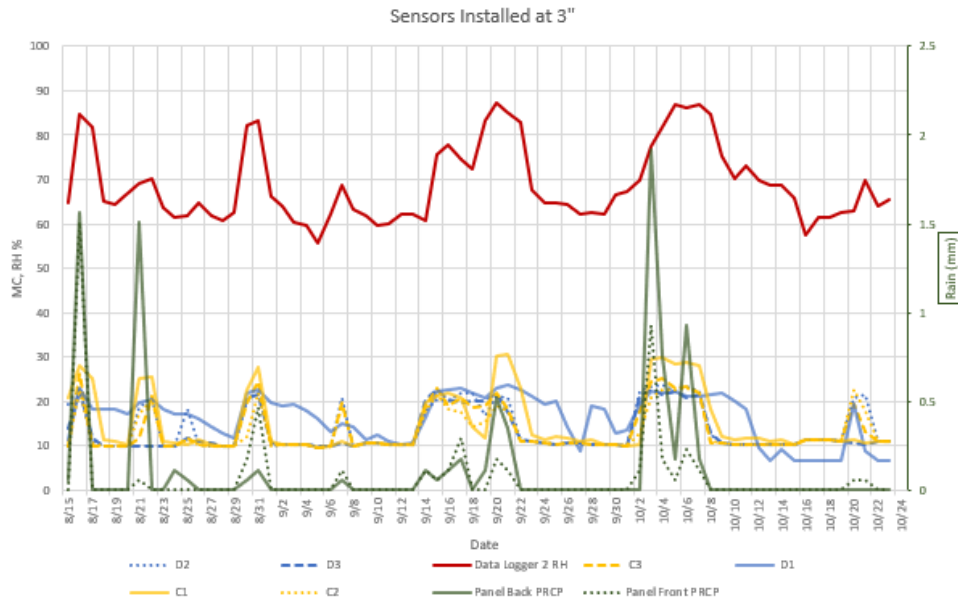


Fig: 4.19 : Moisture Content in CLT panel at 3”

From the above graphs we can see that the moisture content (MC) in the wood varies in the event of rain and moisture is dependent on relative humidity (RH) and

temperature. Corrections due to temperature and relative humidity during calculation of the MC. Following are the max and min, moisture content for each sensor over the period from August to October 2021:

Location	Max. Moisture Content %	Min. Moisture Content%
A	28%	10%
B	24%	10%
C	28%	10%
D	24%	10%
E	27%	10%
F	28%	10%

Table 4.1: Max. and Min. Moisture Content recorded in CLT panel

4.5 SUMMARY

Visual inspection was carried out on the panel, and we did not observe any dimensional change, microbial growth or any damage caused by moisture. The panel did not demonstrate any signs of thermal degradation due to UV. During the monitoring period we observed that the MC varies from 28% during the event of rain to 10% in dry state. After the event of rain, moisture content of the wood tends to decrease, temperature and relative humidity determine the time required for wood to dry, as per the data recorded from sensors, usually it takes about 24 hours to drop the MC from 28% to 10%. Similar results were obtained from both the coatings used to Treat CLT panel.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

The primary objective of this research was to evaluate the capabilities of mass timber when used as highway noise barriers and to design noise barriers using a wide range of considerations and assess its competitiveness with concrete noise barriers.

In the research, the design of the noise barrier had to be assessed against high winds and seismic regions. The analysis results showed that 3-ply CLT panels were structurally strong enough to withstand winds of up to 180 MPH, but for the steel post, we can expect to use a larger section than W10X33 in the region of wind speed of 180 MPH.

Parameters	Wind Speed = 115 MPH	Wind Speed = 140 MPH	Wind Speed = 180 MPH
Wind Pressure	0.025 ksf	0.036 ksf	0.06 ksf
Mpanel (Demand)	9.8 kip*ft	14.54 kip*ft	24.03 kip*ft
Mpost (Demand)	66.57 kip*ft	96.83 kip*ft	160 kip*ft
CLT Panel	V3 3 Ply	V3 3 Ply	V3 3 Ply
FbSeff(capacity)	30.05 kip*ft	30.05 kip*ft	30.05 kip*ft
Steel Post	W 10X33	W 10X33	W 10X54
ϕM_{npost} (Capacity)	107.03 kip*ft	107.03 kip*ft	205.7 kip*ft
Capacity-Demand ratio Panel	3	2.06	1.25
Capacity-Demand ratio Post	1.6	1.1	1.28

Table 4.2 : Wind Design Summary

Besides the wind speeds, there were analyses and considerations that had to be studied to make a full report about the usage of mass timber in designing noise barriers. The rest of these considerations included seismic analysis, cost, and environmental

impacts. Seismic analysis was carried out on the steel post, and it was proved that W10 X33 steel post should be sufficient for the very high seismic region with an S_s value of 2.25g.

Parameters	Low	Moderate	High	Very High
S_s (Spectral response acceleration at period of 0.2s)	0,5	1	1.5	2.25
PGA	0.2	0.4	0.6	0.9
S_1 (Spectral response acceleration at a period of 1s)	0.3	0.6	0.9	1.35
Moment (Demand)	18.1 kip*ft	28.3 kip*ft	38.6 kip*ft	57.9 kip*ft
Shear (Demand)	1.58 kip	2.47 kip	3.37 kip	5 kip
Steel Post	W 10X33	W 10X33	W 10X33	W 10X33
ϕM_{npost} (Capacity)	107.04 kip*ft	107.04 kip*ft	107.04 kip*ft	107.04 kip*ft

$\phi V_{npost}(\text{Capacity})$	128.47 kip	128.47 kip	128.47 kip	128.47 kip
Moment Capacity-Demand Ratio	5.91	3.8	2.77	1.84
Shear Capacity-Demand Ratio	81.31	52	38.12	25.7

Table 4.3 : Seismic Design Summary

A cost study for a project in Florida was conducted for a representative CLT noise barrier compared to a concrete noise barrier using data from member of the Advisory Board. It was determined for the ½ mile case study length, a cost reduction of around 5.2% was achieved. Precast concrete is relatively cheaper in terms of the total material costs for a noise barrier of the same dimensions. Few assumptions were made while performing the cost analysis, detailed study can be performed on the cost of foundation and installation which may result in cheaper CLT noise barrier. In the carbon impact analysis, replacing the concrete barrier with a CLT barrier would save around 6130 lbs. of carbon emission for each 20' of noise barrier.

Installation of prototype noise barrier in the BEL lab located in Pendleton SC was quite smooth. The only equipment used for installation was forklift for couple of hours. Following the installation of steel posts with a forklift, angles were bolted into place and then CLT panel was lowered from the top and positioned in place.

One more aspect of using mass timber for noise barriers that had to be addressed is durability as it relates to long-term moisture exposure. If the MC in wood rises over 30%, microbial organisms can attack the wood, causing decay if not properly treated. This research prepared the prototype with two different coatings from the Sansin corporation. To measure the moisture and temperature data on the prototype noise barrier, 18 moisture sensors and two temperature sensors were installed on the panel. The data is being monitored since mid-August 2021 and will be continually monitored beyond completion of this thesis. For the period of data observed, the MC in the CLT goes up to 28% in the event of rain and drops down to 10% in about 24 hours in normal weather. Using durable and high-quality coating such as Sansin's coating is a viable solution that addresses the effect of moisture retention in CLT panels.

5.2 RECOMMENDATION FOR FUTURE STUDY

Recommendation for future works is listed below:

- A) This study was limited to study the moisture content in coated CLT panel. A future study will involve installing similar noise barrier using uncoated CLT panel to provide benchmark data of moisture content in CLT panel.
- B) In this study, the moisture content could only be monitored for a few months, It is recommended that a future study be conducted to monitor the moisture content data in CLT panel throughout the entire year covering all the seasons.

- C) Two different types of coating option provided by Sansin were used to treat the CLT panel in this study. It is recommended to investigate more treatment or coating options for CLT.
- D) In addition, a pilot study/construction including, in-situ sound insulation characterization and long-term moisture monitoring can be developed.

REFERENCES

- Arenas, C., Leiva, C., Vilches, L. F., Cifuentes, H., & Rodríguez-Galán, M. (2015). Technical specifications for highway noise barriers made of coal bottom ash-based sound absorbing concrete. *Construction and Building Materials*, *95*, 585-591.
- Baas, E. J., Riggio, M., & Barbosa, A. R. (2021). Structural health monitoring data collected during construction of a mass-timber building with a data platform for analysis. *Data in Brief*, *35*, 106845.
- Barber, D. (2018). Fire safety of mass timber buildings with CLT in USA. *Wood and Fiber Science*, *50*(Special), 83-95.
- Everest, F. A., & Pohlmann, K. C. (2015). *Master handbook of acoustics*. McGraw-Hill Education.
- Forouhid, A. E. (2017). Noise emissions from highway with the use of measuring and modeling. *Vibroengineering PROCEDIA*, *15*, 94-99.
- Hammer, M. S., Swinburn, T. K., & Neitzel, R. L. (2014). Environmental noise pollution in the United States: developing an effective public health response. *Environmental health perspectives*, *122*(2), 115-119.
- Harte, A. M. (2017). Mass timber—the emergence of a modern construction material. *Journal of Structural Integrity and Maintenance*, *2*(3), 121-132.
- Roberts, D. (2020). The hottest new thing in sustainable building is, uh, wood. Retrieved from <https://www.vox.com/energy-and-environment/2020/1/15/21058051/climate-change-building-materials-mass-timber-cross-laminated-clt>
- Albee, R. R. (2019). Global Overview of the Cross-Laminated Timber Industry. Retrieved from <https://ir.library.oregonstate.edu/downloads/c534fv506>

- Brandt, K., Latta, G., Camenzind, D., Dolan, J., Bender, D., Wilson, A., & Wolcott, M. (2021). Projected cross-laminated timber demand and lumber supply analysis. *BioResources*, *16*(1), 862.
- Dolan, J. D., Wilson, A., Brandt, K., Bender, D. A., & Wolcott, M. P. (2019). Structural design process for estimating cross-laminated timber use factors for buildings. *BioResources*, *14*(3), 7247-7265.
- dos Santos Bobadilha, G. (2020). *Evaluation of Coatings Used for Prolonging the Durability of Cross-laminated Timber Against Weathering and Wood Decay Fungi*. Mississippi State University.
- Fleming, G. G., Knauer, H. S., Lee, C. S. Y., & Pedersen, S. (2004). FHWA Highway Noise Barrier Design Handbook.
- Freres Lumber Co., n.d. *MPP Design and Construction Guide*. [online] Frereslumber.com. Retrieved from: <https://frereslumber.com/wp-content/uploads/2019/09/MPP-Design-and-Construction-Guide.pdf>
- Gagnon, S., Bilek, E. T., Podesto, L., & Crespell, P. (2013). CLT Introduction to cross-laminated timber. In: *CLT handbook: cross-laminated timber/edited by Erol Karacabeyli, Brad Douglas.--US ed. 2013; pp. 1-45.*, 1-57.
- Klingner, R. E., McNerney, M. T., & Busch-Vishniac, I. J. (2003). *Design guide for highway noise barriers* (No. 1471-1474). Austin, TX, USA: Center for Transportation Research, Bureau of Engineering Research, University of Texas at Austin.
- Karacabeyli, E., & Douglas, B. (2013). CLT handbook. *US Edition, FPInnovations and Binational Softwood Lumber Council, Point-Claire, Quebec*.

- Knauer, H. S., Pedersen, S., Reherman, C. N., Rochat, J. L., Thalheimer, E. S., Lau, M. C., ... & Corbisier, C. (2006). *FHWA highway construction noise handbook* (No. DOT-VNTSC-FHWA-06-02; FHWA-HEP-06-015). United States. Federal Highway Administration.
- Miyamoto, B. T., Sinha, A., & Morrell, I. (2020). Connection performance of mass plywood panels. *Forest Products Journal*, 70(1), 88-99.
- Öberg, J., & Wiege, E. (2018). Moisture risks with CLT-panels subjected to outdoor climate during construction: focus on mould and wetting processes.
- Olsson, L. (2020). Moisture safety in CLT construction without weather protection—Case studies, literature review and interviews. In *E3S Web of Conferences* (Vol. 172, p. 10001). EDP Sciences.
- Puettmann, M., Sinha, A., & Ganguly, I. (2019). Life cycle energy and environmental impacts of cross laminated timber made with coastal Douglas-fir. *Journal of Green Building*, 14(4), 17-33.
- Quesada, H. (2019). Is the Cross-laminated timber (CLT) market an option for the hardwood industry? Retrieved from <https://sim.sbio.vt.edu/?p=2423>
- Roberts, D. (2020). The hottest new thing in sustainable building is, uh, wood. Retrieved from <https://www.vox.com/energy-and-environment/2020/1/15/21058051/climate-change-building-materials-mass-timber-cross-laminated-clt>
- Shakya, B. (2020). *Performance-Based Seismic Design of Multi-Story Light-Frame Wood Buildings Using Adaptive Displacement-Based Design Procedure* (Doctoral dissertation, Clemson University).

- Sheine, J., Donofrio, M., & Gershfeld, M. (2019). Mass Timber Modular Construction: Developments in Oregon. *Modular and Offsite Construction (MOC) Summit Proceedings*, 219-226.
- Stoner, M. W. (2020). *Performance of Cross-laminated Timber as a Residential Building Material Subject to Tornado Events* (Doctoral dissertation, Clemson University).
- Timperley, J. (2018). Q&A: Why cement emissions matter for climate change. *Carbon Brief*, 13.
- Wang, L., Wang, J., & Ge, H. (2020). Wetting and drying performance of cross-laminated timber related to on-site moisture protections: Field measurements and hygrothermal simulations. In *E3S Web of Conferences* (Vol. 172, p. 10003). EDP Sciences.
- Bryce, T. & MacMillan, K., (2005). Encouraging conceptual change: the use of bridging analogies in the teaching of action–reaction forces and the ‘at rest’ condition in physics. *International Journal of Science Education*, 27(6), pp. 737-763.
- LuigiMaffei, MassimilianoMasullo, FrancescoAletta & Gabriele, M., (2013). The influence of visual characteristics of barriers on railway noise perception. *Science of the Total Environment*, Volume 445–446,, pp. 41-47.
- PatrickCornille, (1999). Review of the application of Newton's third law in physics. *Progress in Energy and Combustion Science*, 25(2), pp. 161-210.
- R.W.L, H.Wu, Q.T.Yang & D.F.Wang, (2020). Vehicular impact resistance of seismic designed RC bridge piers. *Engineering Structures*, Volume 2

APPENDICES

Appendix A

Design Calculations

Design of Sound Barrier	
Location: Hoschton, GA	
Geometric Properties	
$L := 20 \text{ ft}$	
$H := 16 \text{ ft}$	
Panel Properties	
V3 3Ply CLT Panel	
$SW_{panel} := 35 \text{ pcf}$	Self weight of Panel
$L_{panel} := 20 \text{ ft}$	Length of Panel
$H_{panel} := 8 \text{ ft}$	Height of Panel
$t := 4.125 \text{ in}$	Thickness of Panel
Steel Post Properties	
W 10 X 33, Cantilevered Post with fixed at one end	
$SW_{post} := 33 \text{ plf}$	Self weight of steel post
$L_{post} := 16.5 \text{ ft}$	Length of Post
Design Loads	
Dead Load	
$DL_{post} := SW_{post} \cdot L_{post} = 0.545 \text{ kip}$	
$DL_{panel} := SW_{panel} \cdot t \cdot L_{panel} \cdot H_{panel} = 1.925 \text{ kip}$	
$DL := (DL_{post} + DL_{panel}) = 2.47 \text{ kip}$	Service dead load per post
$W_{u,dl} := 1.25 \cdot DL = 3.087 \text{ kip}$	Factored Dead Load
Wind Load	
$V := 115 \text{ mph}$	3 second gust speed Fig 3.8.1.1.2-1 AASHTO
Exposure Category B	
Ground Surface Roughness Category B	
$G := 0.85$	Gust Factor Table 3.8.1.2.1-1
$C_d := 1.2$	Drag Coefficient Table 3.8.1.2.1-2
$K_z B := 0.71$	Pressure and Elevation Coefficient Table C 3.8.1.2.1-1
$P_z := 2.56 \cdot 10^{-6} \cdot \left(\frac{V}{\text{mph}}\right)^2 \cdot G \cdot C_d \cdot K_z B \cdot \text{ksf}$	
$P_z = 24.519 \text{ psf}$	Wind Pressure
$W_{wind} := P_z \cdot H \cdot L = 7.846 \text{ kip}$	Force due to wind acting on post

$\frac{W_{wind}}{H} = 0.49 \text{ klf}$	Udl acting on post
$V_{post} := W_{wind} = 7.846 \text{ kip}$	Shear acting on post
$M_{post} := \frac{W_{wind}}{H} \cdot \left(\frac{H^2}{2}\right) = 62.767 \text{ kip} \cdot \text{ft}$	Max Wind moment acting on Intermediate post for Udl Loading
$W_{panel} := P_z \cdot H_{panel} = 0.196 \text{ klf}$	Wind force on one panel
$V_{panel} := \frac{W_{panel} \cdot L}{2} = 1.961 \text{ kip}$	Shear Acting on Panel
$M_{panel} := \frac{W_{panel} \cdot L^2}{8} = 9.807 \text{ kip} \cdot \text{ft}$	Max wind moment of one panel
Seismic Design	
$PGA := 0.09$	Peak Ground Acceleration Fig 3.10.2.1-1 AASHTO
$S_S := 0.18$	Horizontal Response Spectral Acceleration Coefficient at period of 0.2 seconds Fig 3.10.2.1-2 AASHTO
$S_1 := 0.06$	Horizontal Response Spectral Acceleration Coefficient at period of 1.0 seconds Fig 3.10.2.1-3 AASHTO
Soil Class D	
$F_{pga} := 1.6$	Site Factor at zero period on acceleration spectrum Table 3.10.3.2-1 AASHTO
$F_a := 1.6$	Site Factor at short period on acceleration spectrum Table 3.10.3.2-2 AASHTO
$F_v := 2.4$	Site Factor at long period on acceleration spectrum Table 3.10.3.2-3 AASHTO
Calculated Quantities	
$A_s := PGA \cdot F_{pga} = 0.144$	
$S_{DS} := S_S \cdot F_a = 0.288$	
$S_{D1} := S_1 \cdot F_v = 0.144$	
$T_S := \frac{S_{D1}}{S_{DS}} = 0.5$	$T_o := 0.2 \cdot T_S = 0.1$
$DL := SW_{panel} \cdot t \cdot H + SW_{post} = 225.5 \text{ plf}$	Dead Load Including Weight of Post

$$m := \frac{DL}{plf} \cdot .03108 \cdot slug = 7.009 slug$$

Mass per ft

$$E := 4176000 ksf$$

Modulus of Elasticity

$$I_x := 171 in^4$$

Moment of Inertia of steel post W
10 X 33

Modal Periods for a uniformly loaded cantilever

$$T_1 := \left(\left(\frac{3.516}{\frac{H^2}{ft^2}} \cdot \left(\frac{\frac{E}{ksf} \cdot \frac{I_x}{ft^4}}{m \cdot 10^{-3}} \right)^{0.5} \right)^{-1} \right) \cdot 2 \cdot \pi \cdot sec = 0.206 s$$

$$T_2 := \left(\left(\frac{22.03}{\frac{H^2}{ft^2}} \cdot \left(\frac{\frac{E}{ksf} \cdot \frac{I_x}{ft^4}}{m \cdot 10^{-3}} \right)^{0.5} \right)^{-1} \right) \cdot 2 \cdot \pi \cdot s = 0.033 s$$

$$T_3 := \left(\left(\frac{61.7}{\frac{H^2}{ft^2}} \cdot \left(\frac{\frac{E}{ksf} \cdot \frac{I_x}{ft^4}}{m \cdot 10^{-3}} \right)^{0.5} \right)^{-1} \right) \cdot 2 \cdot \pi \cdot s = 0.012 s$$

$$T_4 := \left(\left(\frac{120.9}{\frac{H^2}{ft^2}} \cdot \left(\frac{\frac{E}{ksf} \cdot \frac{I_x}{ft^4}}{m \cdot 10^{-3}} \right)^{0.5} \right)^{-1} \right) \cdot 2 \cdot \pi \cdot s = 0.006 s$$

Elastic Seismic Response Coeff (C_{sm})

Elastic Seismic Response Coefficient (C_{sm})

Using LRFD Article 3.10.4.2

- For periods less than or equal T₀:
For mode m, the elastic seismic response coefficient = C_{sm} = A_s + (S_{DS} - A_s) (T_m / T₀)
- For periods greater than T₀ and less than or equal T_s : C_{sm} = S_{DS}
- For periods greater than T_s : C_{sm} = S_{D1} / T_m

Using the above table

$$C_{sm1} := S_{DS} = 0.288$$

$$C_{sm2} := A_s + (S_{DS} - A_s) \cdot \left(\frac{T_2}{T_0 \cdot s} \right) = 0.191$$

$$C_{sm3} := A_s + (S_{DS} - A_s) \cdot \left(\frac{T_3}{T_0 \cdot s} \right) = 0.161$$

$$C_{sm4} := A_s + (S_{DS} - A_s) \cdot \left(\frac{T_4}{T_0 \cdot s} \right) = 0.153$$

Modal and Total Responses

To Calculate Base shear For Cantilever

$$c1 := 0.613 \quad \text{For Mode 1}$$

$$c2 := 0.188 \quad \text{For Mode 2}$$

$$c3 := .065 \quad \text{For Mode 3}$$

$$c4 := .033 \quad \text{For Mode 4}$$

$$V_1 := c1 \cdot H \cdot C_{sm1} \cdot \frac{32.2}{s^2} \cdot m = 0.637 \text{ kip}$$

$$V_2 := c2 \cdot H \cdot C_{sm2} \cdot \frac{32.2}{s^2} \cdot m = 0.13 \text{ kip}$$

$$V_3 := c3 \cdot H \cdot C_{sm3} \cdot \frac{32.2}{s^2} \cdot m = 0.038 \text{ kip}$$

$$V_4 := c4 \cdot H \cdot C_{sm4} \cdot \frac{32.2}{s^2} \cdot m = 0.018 \text{ kip}$$

To Calculate Base Moment For Cantilever

$$c1 := 0.726 \quad \text{For Mode 1}$$

$$c2 := 0.209 \quad \text{For Mode 2}$$

$$c3 := .127 \quad \text{For Mode 3}$$

$$c4 := .090 \quad \text{For Mode 4}$$

$$M_1 := c1 \cdot V_1 \cdot H = 7.405 \text{ kip} \cdot \text{ft}$$

$$M_2 := c2 \cdot V_2 \cdot H = 0.435 \text{ kip} \cdot \text{ft}$$

$$M_3 := c3 \cdot V_3 \cdot H = 0.077 \text{ kip} \cdot \text{ft}$$

$$M_4 := c4 \cdot V_4 \cdot H = 0.026 \text{ kip} \cdot \text{ft}$$

Total Base shear and base moment are determined by calculating the square root of sum squares (SRSS) for modal base shear and modal base moments, respectively

$$V_{\text{seismic_post}} := \left(V_1^2 + V_2^2 + V_3^2 + V_4^2 \right)^{0.5} = 0.652 \text{ kip}$$

$$M_{\text{seismic_post}} := \left(M_1^2 + M_2^2 + M_3^2 + M_4^2 \right)^{0.5} = 7.418 \text{ kip} \cdot \text{ft}$$

Vehicular Collision Force

$$W_{TLA} := 4 \text{ kip} \quad \text{Collision force for TL4 criteria}$$

$$x := 14 \text{ ft} \quad \text{Point of application of collision force}$$

$$l := 3.5 \text{ ft} \quad \text{Collision force distribution length}$$

$$W_{\text{collision}} := \frac{W_{TLA}}{l} = 1.143 \text{ klf}$$

Case 1: Load acting on midspan

$$V_{\text{collision_panel}} := \frac{W_{\text{collision}} \cdot l}{2 \cdot L} \cdot \left(2 \cdot \left(\frac{L}{2} - \frac{l}{2} \right) + l \right) = 2 \text{ kip}$$

$$M_{\text{collision_panel}} := V_{\text{collision_panel}} \cdot \left(\left(\frac{L}{2} - \frac{l}{2} \right) + \frac{V_{\text{collision_panel}}}{W_{\text{collision}}} \right) = 20 \text{ kip} \cdot \text{ft}$$

Case 2: Load acting on post

$$V_{collision_post} := W_{TLA} = 4 \text{ kip}$$

$$M_{collision_post} := W_{TLA} \cdot x = 56 \text{ kip} \cdot \text{ft}$$

Summary of Unfactored Forces

Wall Panel:

Shear:

Wind Load: $V_{panel} = 1.961 \text{ kip}$

Moment:

Wind Load: $M_{panel} = 9.807 \text{ kip} \cdot \text{ft}$

Vehicular Collision: $M_{collision_panel} = 20 \text{ kip} \cdot \text{ft}$

Steel Posts

Shear:

Wind Load: $V_{post} = 7.846 \text{ kip}$

Seismic Load: $V_{seismic_post} = 0.652 \text{ kip}$

Vehicular Collision: $V_{collision_post} = 4 \text{ kip}$

Moment:

Wind Load: $M_{post} = 62.767 \text{ kip} \cdot \text{ft}$

Seismic Load: $M_{seismic_post} = 7.418 \text{ kip} \cdot \text{ft}$

Vehicular Collision: $M_{collision_post} = 56 \text{ kip} \cdot \text{ft}$

Capacity of CLT panel

V3: No 2 Southern Pine in all Longitudinal layers or No 3 Southern Pine in transverse layer

$C_m := 1$	When MC < 16% otherwise contact manufacture for adjustment value Article 10.1.5 NDS
$C_t := 1$	Assuming T < 100F, for diff Temp Refer Table 2.3.3 NDS
$C_L := 1$	No lateral support required, d <= b, Article 3.3.3 NDS
$K_{Fb} := 2.54$	Table 10.3.1 NDS
$\phi_b := 0.85$	Table 10.3.1 NDS
$\lambda := 1$	Time Effect Factor, N 3.3 NDS
$C_b := 1$	Bearing Area Factor 3.10.4 NDS
$K_{FCper} := 1.67$	NDS Table 10.3.1
$\phi_c := 0.9$	NDS Table 10.3.1

Check for Bending

$$F_b S_{eff} := 1740 \frac{\text{lb} \cdot \text{ft}}{\text{ft}} \quad \text{For V3, Bending Strength per width, PRG 320}$$

For 8 ft (Height of one panel)

$$F_b S_{eff} := F_b S_{eff} \cdot H_{panel} = (1.392 \cdot 10^4) \text{ lb} \cdot \text{ft}$$

$$F_b S_{eff}' := F_b S_{eff} \cdot C_m \cdot C_t \cdot C_L \cdot K_{Fb} \cdot \phi_b \cdot \lambda = 30.053 \text{ kip} \cdot \text{ft}$$

Check for Shear

$$K_{Fs} := 2 \quad \phi_s := 0.75$$

$$F_s := 1750 \frac{\text{lb} \cdot \text{ft}}{\text{ft}} \quad \text{For V3, Shear Strength per width, PRG 320}$$

For 8 ft (Height of one panel)

$$F_s := F_s \cdot H_{panel} = (1.4 \cdot 10^4) \text{ lb} \cdot \text{ft}$$

$$F_s' := F_s \cdot C_m \cdot C_t \cdot K_{Fs} \cdot \phi_s = 21 \text{ kip}$$

Check Compressive Stress at Bearing Points

$$V_{bearing} := SW_{panel} \cdot t \cdot H \cdot \frac{L}{2} = 1.925 \text{ kip}$$

$$b := 3 \text{ in} \quad w := 4.125 \text{ in}$$

$$f_{cper} := \frac{V_{bearing}}{b \cdot w} = 155.556 \text{ psi}$$

$$F_{cper} := 725 \text{ psi}$$

$$F'_{cper} := F_{cper} \cdot C_m \cdot C_t \cdot C_b \cdot K_{FCper} \cdot \phi_c = (1.09 \cdot 10^3) \text{ psi}$$

$$F_{cper}' > f_{cper} = 1 \quad \frac{F'_{cper}}{f_{cper}} = 7.005 \quad \text{Therefore OK}$$

Check for Min Bearing Area

$$f_{cper_min} := \frac{F'_{cper}}{2} = 544.838 \text{ psi}$$

$$A_{min} := \frac{V_{bearing}}{f_{cper_min}} = 3.533 \text{ in}^2 \quad \text{Min Bearing Area}$$

Check for Deflection

3 PLY V3 Layup

$$EI_{eff} := 95 \cdot 10^6 \text{ lbf} \cdot \frac{\text{in}^2}{\text{ft}} \quad \text{Value per ft of width, From PRG 320}$$

$$GA_{eff} := 0.49 \cdot 10^6 \frac{\text{lbf}}{\text{ft}} \quad \text{Value per ft of width, From PRG 320}$$

$$k_s := 4.8 \quad \text{Shear Deformation factor Table 10.4.1.1 NDS}$$

$$EI_{eff} := EI_{eff} \cdot H_{panel} = (7.6 \cdot 10^8) \text{ lbf} \cdot \text{in}^2$$

$$GA_{eff} := GA_{eff} \cdot H_{panel} = (3.92 \cdot 10^6) \text{ lbf}$$

$$EI_{app} := \frac{EI_{eff}}{1 + \frac{k_s \cdot EI_{eff}}{GA_{eff} \cdot L_{panel}^2}} = (7.479 \cdot 10^8) \text{ lbf} \cdot \text{in}^2$$

$$EI'_{app} := EI_{app} \cdot C_m \cdot C_t = (7.479 \cdot 10^8) \text{ lbf} \cdot \text{in}^2$$

$$\Delta := \frac{5 W_{panel} \cdot L_{panel}^4}{EI'_{app} \cdot 384} = 0.944 \text{ in}$$

$$\Delta_{limit} := \frac{L}{360} = 0.667 \text{ in} \quad \Delta_{limit} := \frac{L}{240} = 1 \text{ in}$$

Half Lap Joint Connection

Using ASSY ECOFAST Partially Threaded 0.3125in*4 in

$$d := 0.3125 \text{ in} \quad L_{\text{screw}} := 4 \text{ in} \quad L_{\text{thread}} := 2.375 \text{ in}$$

$$V_u := P_z \cdot L_{\text{panel}} \cdot H_{\text{panel}} = 3.923 \text{ kip} \quad \text{Wind Load}$$

$$V_{u1} := SW_{\text{panel}} \cdot t \cdot H_{\text{panel}} \cdot L_{\text{panel}} = 1.925 \text{ kip} \quad \text{Load due to self weight}$$

$$W := 279 \frac{\text{lb}}{\text{in}} \cdot L_{\text{thread}} = 662.625 \text{ lbf} \quad \text{Capacity per bolt from MTC Design Guide Table RDV.1.1 ASSY}$$

$$Z := 194 \text{ lbf} \quad \text{Reference lateral design values for CLT lap joints loaded in shear Table PP.2.2}$$

Using LRFD Calculation

$$C_m := 1 \quad \text{Table 11.3.3 NDS}$$

$$C_t := 1 \quad \text{Table 11.3.4 NDS}$$

$$C_g := 1 \quad \text{Table 11.3.6A,B,C,D NDS}$$

$$C_{\Delta} := 1 \quad \text{Section 12.5.1 NDS}$$

$$C_{eg} := 1 \quad \text{Section 1.5.2 NDS}$$

$$C_{di} := 1 \quad \text{Section 12.5.3 NDS}$$

$$C_{tn} := 1 \quad \text{Section 12.5.4 NDS}$$

$$\phi_z := 0.65 \quad \text{Connection Resistance Reduction Factor}$$

$$K_{FZ} := 3.32 \quad \text{Format Conversion Factor NDS 11.3.1}$$

$$\lambda := 1 \quad \text{Time Effect factor}$$

$$W' := \phi_z \cdot K_{FZ} \cdot \lambda \cdot C_m^2 \cdot C_t \cdot C_{eg} \cdot C_{tn} \cdot W = (1.43 \cdot 10^3) \text{ lbf}$$

$$Z' := \phi_z \cdot K_{FZ} \cdot \lambda \cdot C_m \cdot C_t \cdot C_g \cdot C_{eg} \cdot C_{tn} \cdot C_{di} \cdot C_{\Delta} \cdot Z = 418.652 \text{ lbf}$$

$$\alpha := 90 \text{ deg}$$

Angle between the wood surface and the direction of applied load

$$\sin(\alpha) := 1 \quad \cos(\alpha) := 0$$

$$Z'_{\alpha} := \frac{W' \cdot Z'}{W' \cdot \cos(\alpha)^2 + Z' \cdot \sin(\alpha)^2} = (1.43 \cdot 10^3) \text{ lbf} \quad \text{Section 12.4 NDS Combined lateral and withdrawal loads}$$

No of Nail required (N)

$$N_{\text{wind}} := \frac{0.9 V_{u1} + V_u}{Z'_{\alpha}} = 3.955 \quad \text{Using Load Combination 0.9DL+W}$$

Provide 6 Nails

Steel Post Design

$$E := 29000 \text{ ksi}$$

$$F_y := 50 \text{ ksi}$$

$$V_{post} = 7.846 \text{ kip}$$

Shear Demand on Post

$$M_{post} = 62.767 \text{ ft} \cdot \text{kip}$$

Moment Demand on Post

For W 10X33, From AISC Steel Manual

$$d := 9.73 \text{ in} \quad t_w := 0.29 \text{ in} \quad I := 171 \text{ in}^4 \quad Z := 38.8 \text{ in}^3 \quad r_y := 1.94 \text{ in} \quad b_f := 7.96 \text{ in}$$

$$T := 7.5 \text{ in} \quad S_x := 35 \text{ in}^3 \quad t_f := 0.435 \text{ in} \quad k_1 := 0.75 \text{ in}$$

$$\lambda_{flange} := 9.15 \quad \lambda_{web} := 27.1 \quad A_w := (d - 2 \cdot t_f) \cdot t_w = 2.569 \text{ in}^2$$

Check for Compactness

$$\lambda_{flange_limit} := 0.38 \cdot \sqrt{\frac{E}{F_y}} = 9.152 \quad \lambda_{web_limit} := 3.76 \cdot \sqrt{\frac{E}{F_y}} = 90.553$$

$$\lambda_{flange} < \lambda_{flange_limit} = 1$$

$$\lambda_{web} < \lambda_{web_limit} = 1$$

Therefore Section is Compact

Check for LTB

Section F2 AISC

$$L_b := 16 \text{ ft}$$

$$L_p := 6.85 \text{ ft}$$

From Table 3-2 AISC

$$L_r := 21.8 \text{ ft}$$

$$L_p < L_b < L_r = 1$$

Moment Strength

$$\phi_b := 0.9$$

$$C_b := 1$$

Conservative

$$M_p := \phi_b \cdot F_y \cdot Z = 145.5 \text{ kip} \cdot \text{ft}$$

$$\phi M_n := \phi_b \cdot C_b \cdot \left(M_p - (M_p - 0.7 F_y \cdot S_x) \cdot \left(\frac{L_b - L_p}{L_r - L_p} \right) \right) = 107.035 \text{ kip} \cdot \text{ft} \quad \text{eqn F2-3 AISC}$$

$$\phi M_n > M_{post} = 1$$

$$\phi M_n < M_p = 1$$

Therefore OK

Shear Strength

$$\lambda_{web_limit} := 2.24 \cdot \sqrt{\frac{E}{F_y}} = 53.946$$

Chapter G AISC

$$\lambda_{web} < \lambda_{web_limit} = 1$$

$$\phi_v := 1 \quad C_v := 1$$

$$\phi V_n := \phi_v \cdot C_v \cdot F_y \cdot A_w = 128.47 \text{ kip}$$

$$\phi V_n > V_u = 1$$

Therefore OK in Shear

Deflection

$$W := \frac{V_{post}}{L_{post}} = 0.476 \text{ klf} \quad \text{Assuming UDL is acting on post}$$

$$\Delta := \frac{W \cdot L_{post}^4}{8 \cdot E \cdot I} = 1.535 \text{ in} \quad \frac{L_{post}}{180} = 1.1 \text{ in}$$

Base Plate Design

Post: W 10X33

$$B := 12 \text{ in}$$

Assume Base Plate Width

$$N := 12 \text{ in}$$

Assume Base Plate Length

$$\lambda := 1$$

Conservative Approach

$$m := \frac{N - 0.95 d}{2} = 1.378 \text{ in}$$

$$n := \frac{B - 0.8 b_f}{2} = 2.816 \text{ in}$$

$$n' \lambda := \frac{1 \cdot \sqrt{d \cdot b_f}}{4} \cdot \lambda = 2.2 \text{ in}$$

$$l := \max(m, n, n' \lambda) = 2.816 \text{ in}$$

$$t_{pl_req} := 1.5 l \cdot \sqrt{\frac{V_{post}}{B \cdot N \cdot F_y}} = 0.139 \text{ in}$$

Plate Dimensions 14*14*0.5 in

Bolt Design

$$DL := SW_{panel} \cdot \frac{L_{panel}}{2} \cdot \frac{H_{panel}}{2} \cdot t = 0.481 \text{ kip} \quad \text{Dead load for each bolt}$$

$$W := P_z \cdot \frac{L_{panel}}{2} \cdot \frac{H_{panel}}{2} = 980.741 \text{ lbf} \quad \text{Wind load for each bolt}$$

$W_u := (0.9 DL + 1 W) 2 = 2.828 \text{ kip}$	Since we are using one bolt for two sides of panel
$F_{nv} := 54 \text{ ksi}$	Table J3.2 AISC
$\phi := 0.75$	
$d := 0.5 \text{ in}$	Dia of Stud
$A_b := \frac{\pi \cdot d^2}{4} = 0.196 \text{ in}^2$	
$\phi R_n := \phi \cdot F_{nv} \cdot A_b = 7.952 \text{ kip}$	Eqn J3-1 AISC
$\phi R_n > W_u = 1$	
Angle Design 3"X3"X0.5"	
$b := 3 \text{ in}$ $F_y := 36 \text{ ksi}$ $t_{angle} := 0.5 \text{ in}$ $E := 29000 \text{ ksi}$ $\phi_b := 0.8$ $\phi_v := 0.75$	
$S_x := 1.06 \text{ in}^3$	
$k_v := 5.34$	From G2.1-2 AISC
$\frac{b}{t_{angle}} \leq 1.1 \cdot \sqrt{\frac{k_v \cdot E}{F_y}} = 1$	From eqn G2-9 AISC
$C_{v2} := 1$	
$\phi V_n := \phi_v \cdot 0.6 \cdot F_y \cdot b \cdot t_{angle} \cdot C_{v2} = 24.3 \text{ kip}$	
$\phi M_n := \phi_b \cdot F_y \cdot S_x = 2.544 \text{ kip} \cdot \text{ft}$	
Shim Angle Design	
$DL := SW_{panel} \cdot \frac{L}{2} \cdot \frac{H_{panel}}{2} \cdot t = 0.481 \text{ kip}$	
$W := P_z \cdot \frac{L}{2} \cdot \frac{H_{panel}}{2} = 0.981 \text{ kip}$	
$V_u := DL = 0.481 \text{ kip}$	
$\phi V_n > V_u = 1$	
$M_u := W \cdot 1.8 \text{ in} = 0.147 \text{ kip} \cdot \text{ft}$	UDL Acts on 2.4 in
$\phi M_n > M_u = 1$	

Seating Angle Design

$$DL := SW_{\text{panel}} \cdot \frac{L}{2} \cdot H \cdot t = 1.925 \text{ kip}$$

$$W := P_z \cdot \frac{L}{2} \cdot H = 3.923 \text{ kip}$$

$$V_u := DL = 1.925 \text{ kip}$$

$$\phi V_n > V_u = 1$$

$$M_u := W \cdot 1.8 \text{ in} = 0.588 \text{ kip} \cdot \text{ft}$$

UDL Acts on 2.4 in

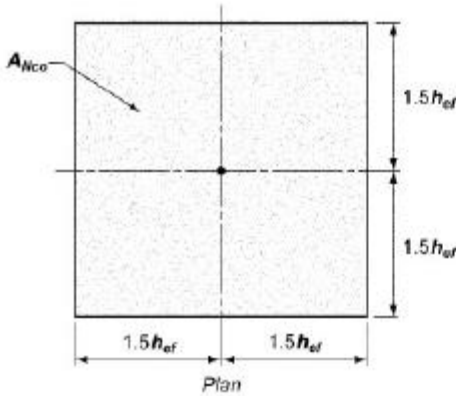
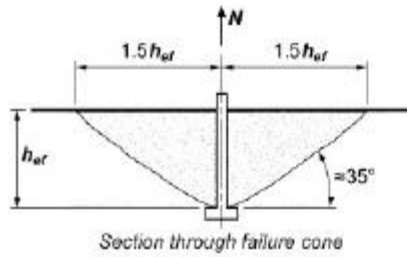
$$\phi M_n > M_u = 1$$

Appendix B

Concrete Breakout Strength

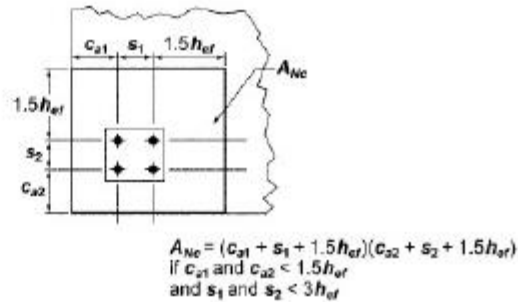
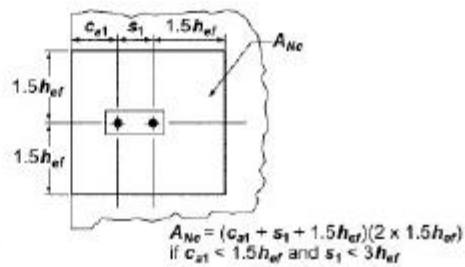
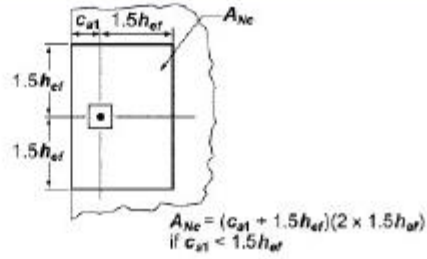
CONCRETE BREAKOUT STRENGTH IN TENSION	
DEMAND	
$SW_1 := 35 \text{ pcf}$	Self weight of CLT
$SW_2 := 33 \text{ plf}$	Self weight of steel post
$H := 8 \text{ ft}$	Height of Steel Post
$L := 8 \text{ ft}$	Span of CLT Panel
$t := 4.125 \text{ in}$	Thickness of CLT Panel
$DL_1 := SW_1 \cdot \left(\frac{L}{2}\right) \cdot t = 48.125 \text{ plf}$	CLT DL for tributary width
$DL := (DL_1 + SW_2) \cdot H = 0.649 \text{ kip}$	DL acting as UDL on post
Wind Load	
$V := 115 \text{ mph}$	3 second gust speed Fig 3.8.1.1.2-1 AASHTO
Exposure Category B	
Ground Surface Roughness Category B	
$G := 0.85$	Gust Factor Table 3.8.1.2.1-1
$C_d := 1.2$	Drag Coefficient Table 3.8.1.2.1-2
$K_z B := 0.71$	Pressure and Elevation Coefficient Table C 3.8.1.2.1-1
$P_z := 2.56 \cdot 10^{-6} \cdot \left(\frac{V}{\text{mph}}\right)^2 \cdot G \cdot C_d \cdot K_z B \cdot \text{ksf} = 0.025 \text{ ksf}$	
$W_{wind} := P_z \cdot \left(\frac{L}{2}\right) = 0.098 \text{ klf}$	Wind Load Acting on Panel on tributary width
$W_{post} := W_{wind} = 0.098 \text{ klf}$	
$M_{post} := \frac{W_{post} \cdot H^2}{2} = 3.138 \text{ kip} \cdot \text{ft}$	Moment acting on the fixed base of cantilever post

The critical edge distance for headed studs, headed bolts, expansion anchors, and undercut anchors is $1.5h_{ef}$.



$$A_{Nco} = (2 \times 1.5h_{ef}) \times (2 \times 1.5h_{ef}) = 9h_{ef}^2$$

(a)



(b)

Fig. RD.5.2.1—(a) Calculation of A_{Nco} , and (b) calculation of A_{Nc} for single anchors and groups of anchors.

Given

$$\phi := 0.70$$

$$h_{ef} := 4 \text{ in}$$

$$s := 10 \text{ in}$$

$$k_c := 17$$

$$\lambda := 1$$

$$f'_c := 2800 \text{ psi}$$

$$\psi_{ec,n} := 1$$

$$\psi_{ed,n} := 1$$

$$\psi_{c,n} := 1$$

$$c_{amin} := 1.5 h_{ef}$$

$$c_{amin} < c_{ac} = 1$$

$$c_{ac} := 2 h_{ef}$$

Assumed 4 in Embedment Length
spacing between anchors
post installed anchor
Normal Weight Concrete
Compressive strength of concrete
No eccentric loading
No edge Effect
Cracked concrete (shrinkage cracks)

$$\psi_{cp,n} := \frac{c_{amin}}{c_{ac}} = 0.75 \quad \text{Post weld type anchor}$$

$$A_{nc} := (1.5 \cdot h_{ef} + s + 1.5 \cdot h_{ef}) \cdot (1.5 \cdot h_{ef} + s + 1.5 \cdot h_{ef}) = 484 \text{ in}^2$$

$$A_{nco} := (1.5 \cdot h_{ef} + 1.5 \cdot h_{ef}) \cdot (1.5 \cdot h_{ef} + 1.5 \cdot h_{ef}) = 144 \text{ in}^2$$

Concrete Breakout strength for single anchor in tension

$$N_b := k_c \cdot \lambda \cdot \left(\frac{h_{ef}}{\text{in}} \right)^{1.5} \cdot \left(\frac{f_c}{\text{psi}} \right)^{0.5} \text{ kip} = (7.196 \cdot 10^3) \text{ kip} \quad \text{ACI 318-11 D.5.2.2}$$

$$N_{cb} := \frac{A_{nc}}{A_{nco}} \cdot \psi_{ed,n} \cdot \psi_{c,n} \cdot \psi_{cp,n} \cdot N_b = (1.814 \cdot 10^4) \text{ kip} \quad \text{ACI 318-11 D.5.2.1}$$

Since $N_{cb} > N_b = 1$

Therefore, Concrete Breakout strength of a single anchor in tension in cracked concrete

$$\phi N_b := \phi \cdot k_c \cdot \lambda \cdot \left(\frac{h_{ef}}{\text{in}} \right)^{1.5} \cdot \left(\frac{f_c}{\text{psi}} \right)^{0.5} \text{ lbf} = 5.038 \text{ kip} \quad \text{ACI 318-11 D.5.2.2}$$

Demand Strength

$$N_{b_demand} := \frac{M_{post}}{s} = 3.766 \text{ kip}$$

$$N_{b_capacity} := \phi N_b$$

$$\frac{N_{b_capacity}}{N_{b_demand}} = 1.338$$

Therefore OK

Appendix C

Installation guide for sensors

Sensors and Components



PMM

- The insulated probe of the desired length is attached to the PMM as shown in the picture



Installation of PMM

- When installing the PMM into the desired location
 - Mark the location with a sharpie using PMM holes
 - Use a 3/16" drill bit to predrill for the extensions
 - Drill length should be the length of the insulated extension jacket and bottom bolt
 - The exposed measurement portion of the extension should be tapped into place



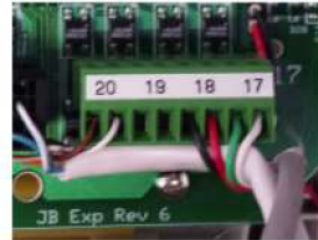
Installation of PMM

- For very long PMM extensions that are very difficult to tap into place half of PMM extension length can be pre-drilled using a 1/4" drill bit with the remaining portion of the extension being drilled with the 3/16" bit.
- It is recommended to use unique drill bits with drill stops for each required PMM length.
- Once PMM is installed ensure that the cable is secured to the CLT panel either using a staple or an eyelet zip-tie and screw. This ensures that there is sufficient strain relief in the cable as well as prevents the PMM from being pulled out.



Connecting PMM's to A3

- Since we are only getting moisture data from PMM, connect Red and Black wire from the PMM to the A3.
- Each A3 will have 8 terminals which means you can connect 8 PMM's to each A3
- Remember the terminal number for each PMM, it will help you recognize while setting up the sensors in BiG software.



Installation of A3

- Post Connection of the PMM's to the A3, Install the A3 on to the panel by drilling screws into it.
- Make sure that you pass the PMM cable through the holes provided and face it downwards so that no water enters A3
- Close the lid and tighten the screws
- 3 AA batteries are required to operate the A3

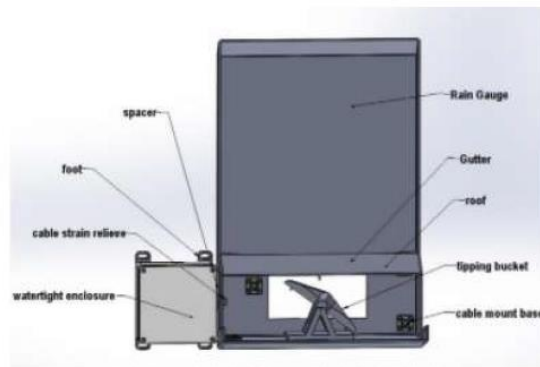


Turn Up A3

- To connect to the network, press menu and go to network and select it: when the device says “Joining to Network 25” it is connected.
- To force measure the readings at any point select menu and then go to measure.



Driving Rain Gauge



Labelled diagram of a Driving Rain Gauge

Installation of Driving Rain Gauge

- Avoid locations where trees or plantings could potentially drop leaves, debris, etc., causing the drain system to be blocked.
- 2. Use signage or other acceptable methods when the Driving Rain Gauge is used near grade, balconies, or windows so that objects are not deposited into the gauge, causing readings to be



Rain Gauge with cover closed and open. When open, 3 fastening locations are available



Close-up of opened cover and right side thumb-screw.

Programming Driving Rain Gauge

- Cut the supplied RJ11 wire as required and connect and twist the yellow and green wires together, as shown. Polarity is not essential.
- Connect the yellow-green pair and red wire according to the following table, also shown in the figure. For an A3 unit, the red wire is connected to port 1, and the yellow-green pair is connected to port 3.

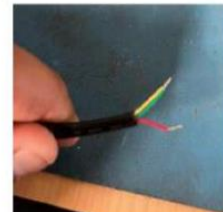


Figure: Twist the green and yellow wires before connecting to the A2/A3 unit.



- The Menu button on the A2 is not present. The menu button on the A3 unit is not functional. To take a reading, press the Select button once to wake up the screen and another time to select measure. The unit will automatically join the network when connected.

Maintenance of Driving Rain Gauge

- Cleaning and verification are required only at the time of installation and annually after that. If the gauge is installed in an area with known airborne debris, it is suggested to monitor it and determine an appropriate maintenance schedule.