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# An approach to light-frame disaster relief housing

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SENIOR DESIGN PROJECT REPORT
prepared under my supervision by

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entitled

AN APPROACH TO LIGHT-FRAME DISASTER RELIEF HOUSING

be accepted in partial fulfillment of the requirements for the degree of

BACHELOR OF SCIENCE IN CIVIL ENGINEERING

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Advisor Date

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Department Chair Date

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by

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SENIOR DESIGN PROJECT REPORT

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AN APPROACH TO LIGHT-FRAME DISASTER RELIEF HOUSING

Hayley Dickson, Megan Cronan, Anne Walkingshaw and Katherine Busch

Department of Civil Engineering
Santa Clara University, Spring 2013

**ABSTRACT**

*An Approach to Light-Frame Disaster Relief Housing* investigated the use of bamboo structures to provide safe, affordable and easily constructible housing in developing countries that are prone to natural disasters. The team chose to use the Cagayan Valley Region in Northern Philippines that has a demonstrated need for relief housing due to its susceptibility to high seismic activity, monsoons, and floods. The proposed solution includes a complete structural and geotechnical foundation design of a house that can resist the demand loads determined for the region. The structural system is designed using bamboo and includes a lateral force resisting system, and gravity force resisting system, and roof and floor diaphragms. The structural system ties into the foundation, which was designed to withstand flood loads and provide a proper load path from the structural system to the ground.

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## INTRODUCTION

### *Natural Disaster and Vulnerability*

Every year earthquakes, monsoons, and cyclones affect millions of people worldwide and cause engineering failures in the built environment. Regardless of material used in construction or location of the disaster, timber, concrete, steel and all other materials are vulnerable if not designed or constructed properly. After the 1989 Loma Prieta earthquake in San Francisco, an estimated 16,000 housing units were uninhabitable and total of 63 fatalities occurred as a direct result of the quake (HOLZER 2013). Even in the United States where building codes are heavily enforced, major damage still occurs in large-scale events.

This leaves developing countries with building codes that are either non-existent or very limited highly vulnerable in the face of natural disaster. Structural collapse is an engineering failure that directly affects the life safety of a country's citizens

***Figure 1.*** *Collapse in San Francisco after 1989 Loma Prieta Earthquake (NATIONAL GEOGRAPHIC 1989)*

This need was once again realized when a 7.0 magnitude earthquake struck the Caribbean on January 12th, 2010 bringing immense devastation to the nation of Haiti, with an astounding final death toll of over 320,000 (BAKUN/PRESCOTT 2013). One of the most notable causes that contributed to the death of Haitian citizens as an aftermath of the quake was building failure. The magnitude of improper construction and insufficient structural design was brought into harsh light when it was estimated that nearly a quarter million homes were lost. The devastation of the Haiti earthquake emphasized an immediate need for sustainable, economical and structurally sound housing for not just Haiti but for other vulnerable parts of the developing world as well.

***Bamboo House Design 2011-2012***

*An Approach to Light-Frame Disaster Relief Housing* is a continuation of a senior design project started in the 2011-2012 academic year. The project aimed to design a structural system entirely out of bamboo for use as disaster relief housing in the Philippines. Building off of this original concept, the 2013 Bamboo House team focused on further developing and refining the system to realize the new design focus. This included incorporating traditional architectural styles in the region, designing a complete foundation plan based on site-specific soil data, and an evaluation of constructability by building a prototype section.

***The Philippines***

The Philippines ranked as the third most vulnerable country to natural disasters on the United Nations Disaster Risk Index in 2011. In addition, according to Maplecroft's 2012 rankings, the Philippines face the second greatest financial risk in the world due to the effects of natural disasters. This extremely high risk of natural disasters, and the financial and public-safety risk that comes with it, prompts both a regulatory need and an emergency response need for disaster relief housing in the Philippines.

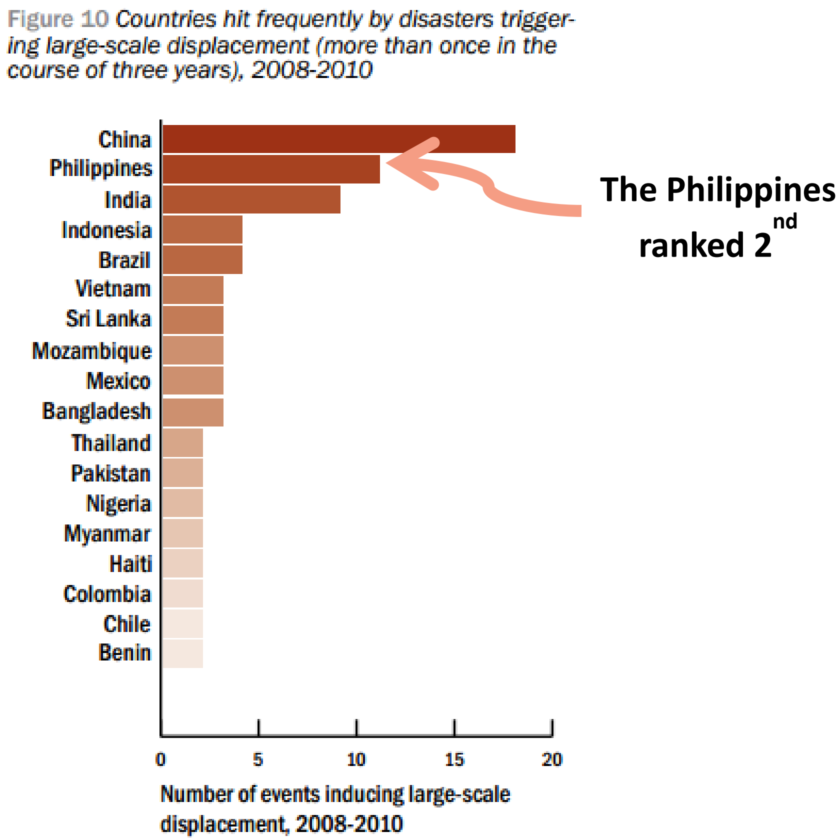



***Figure 2***. *Natural disaster rankings*

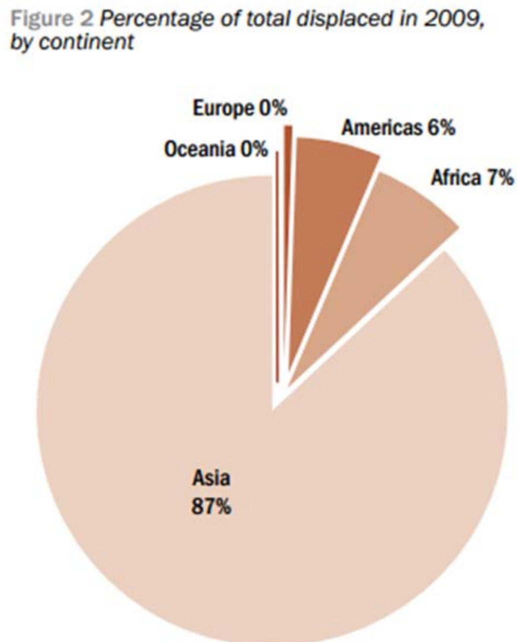



***Figure 3.*** *Percentage displaced by continent*

**Current housing situation in the Philippines**

In the Philippines, there are 102 households per 100 occupied housing units and there is an average household size of 4.9 people per household (NSO, 2010). The average population growth rate in the Philippines is 2.04 percent annually and the number of households increased by 21.4 percent in a seven-year period between 2000 and 2007 (NSO, 2010). Therefore, there is currently a housing shortage in the Philippines and this shortage will continue to increase unless the rate of construction of new homes also increases. This creates an immediate need to build new homes in the Philippines.

**A specific focus on the Cagayan Valley region**


***Figure 4.*** *Cagayan Valley - The Northern Philippine region*

The Cagayan Valley Region consists of the provinces of Batanes, Cagayan, Isabela, Nueva Vizcaya and Quirino and stretches over 6.6 million acres in the northwest area of the Philippines. Most of the area lies in a large valley and supports an agricultural economy. Although not a primary crop, the production of bamboo is prevalent in the Cagayan Valley (NERBAC 2013). The average annual household income is equivalent to $3000 US dollars which is less than half of the average income of households located in urban areas of Northern Philippines. Currently, homes in the region are not built to withstand high loads and are susceptible to damage caused by earthquakes and high winds.

| | **Cagayan Valley Region** | **National Capital Region** | **National Average** |
|---|---|---|---|
| **Average Annual Family Income** | PHP 181,000 ($4,300) | PHP 356,000 ($8,500) | PHP 206,000 ($4,900) |
| **Unemployment Rate** | 3.3% | 9.5% | 7.1% |
| **Average Size of a Residential House** | $81m^2$ ($870ft^2$) | $1120m^2$ ($12,000ft^2$) | $190m^2$ ($2,000ft^2$) |
| **Population Density** | 114 people/$km^2$ | 19,137 people/$km^2$ | 308 people/$km^2$ |
| **Average Household Size** | 4.4 people | 4.3 people | 4.6 people |
| **Functional Literacy Rate** | 86.1% | 94.0% | 86.4% |

***Table I.*** *A comparison of census data statistics of the Cagayan Valley Region, National Capital Region and the Philippines national averages (NSO, 2013)*

In 2003, the Republic of the Philippines's National Statistics Office (NSO) predicted that the population of the Cagayan Valley Region would double in thirty-one years if the current population growth trends continued (NSO, 2003). In the Cagayan Valley Region, nine in ten families own their home (NSO, 2003). Since most families who receive the new design own their home, they should be personally vested in the success of the project. Additionally, 84.4 percent of the population over the age of ten is literate and capable of following instructions (NSO, 2013). NSO defines functionally literate as having basic reading, writing and computational skills. Building manuals will be written with clear language and translated into the dialects of the region further insuring the success of the project.

### Non-profit housing efforts in the Philippines

Low-income housing in the Philippines is currently being built by three non-profit organizations: Habitat for Humanity, Build Change and Gawad Kalinga. All three organizations operate in the Metro Manila Region, and only Habitat for Humanity builds homes in the Cagayan Valley. Houses are primarily built using concrete and masonry due to the ease of construction. However, under extreme loading, these structures experience shear and brittle failure, which causes catastrophic damage to the homes. The project utilizes bamboo as an alternative to current construction practices and provides a safe, affordable and more durable housing option.

**Table 2.** Most common construction materials used for occupied residential housing units in the Philippines (NSO, 2010)

| Element | Construction Material | Percent of Total Units |
|---|---|---|
| Outer Walls | Concrete/Brick/Stone | 36.8% |
| | Half Concrete/Brick/Stone and Half Timber | 20.8% |
| | Bamboo/Sawali/Cogon/Nipa | 19.8% |
| | Other | 22.6% |
| Roof | Galvanized Iron/Aluminum | 75.0% |
| | Other | 25.0% |

**BAMBOO: A LIGHT FRAME APPROACH**

Many current disaster relief housing efforts in developing countries focus on designs that use heavily imported materials like steel and concrete. In addition to being imported, this heavy-frame construction is often expensive and results in dangerous failure modes that threaten life-safety. Concrete masonry fails in brittle shear which, when not detailed properly, causes a devastating level of failure. Steel is a ductile material, however when connections between concrete and steel are not detailed properly failure can result in heavy damage.

This project approaches disaster relief housing from a light-frame design philosophy. Most homes in the United States are built using timber, a light-frame material. These structures typically perform very well in seismic events due to redundancy in the system and proper detailing to develop the high material strength. This type of construction is generally effective both economically and structurally in the U.S., however rough sawn lumber is not readily available in most developing countries. For this reason, the team chose a light-frame approach that uses bamboo as the main structural component. The impressive strength properties and availability of material in regions in heavy need of disaster relief housing make it an ideal candidate for construction. *An Approach to Light-Frame Natural Disaster Relief Housing* aims to harness the good material properties of bamboo to design a system that is effective for the Cagayan Valley in the Northern Philippines. Table X below shows the material properties of Guadua bamboo versus the commonly used rough sawn lumber, Douglas Fir-Larch No. 1. Material properties that are important in determining overall strength of a system and its components like modulus of elasticity, flexural strength, and compressive strength are all higher for Guadua bamboo. This makes it a viable candidate for replacing timber and potentially even performing better given proper detailing and design.

| Material Property | Guadua Bamboo | Douglas Fir-Larch No. 1 | Increase Ratio |
|---|---|---|---|
| **Modulus of Elasticity** | 2200 ksi | 1800 ksi | 1.2 |
| **Flexural Strength** | 6700 psi | 1200 psi | 5.6 |
| **Compressive Strength** | 5000 psi | 1550 psi | 2.6 |
| **Tensile Strength** | 1000 psi | 800 psi | 2.75 |

*Table X. Comparison of Guadua Bamboo (PECK/WALLACE 2012) and Douglas Fir-Larch No. 1 (NDS 2005)*

Although modern construction has begun incorporating bamboo, in the Philippines and other developing countries bamboo often carries the stigma of being "the poor man's lumber." The aim of *An Approach to Light-Frame Natural Disaster Relief Housing* is to begin to shift the association between bamboo and low-income housing and redefine it as "the sustainable man's lumber." In order to accomplish this, there were four main principles employed in the guiding design philosophy.

1. *Accessible* - The overall system design must be understood by people with limited to no technical background. This was aimed to be accomplished by avoiding complicated connection details and an easy integration of gravity and lateral systems into the finished structure.
2. *Cost Effective* – This is a design for a rural community in the Philippines with limited access to economic resources. Avoiding expensive materials and using material that could be locally sourced were chosen to potentially reduce the overall cost.

3. *Durable* – The structure must be designed to resist loads associated with high seismic activity, wind and floods. An effective structural will resist the site-specific loads and avoid collapse or complete failure.
4. *Long-term* – Rather than a temporary disaster relief solution, the aim of *An Approach to Light-Frame Natural Disaster Relief Housing* is to provide a structure with the life-span of a traditional single family home. The approach aims to design a home that can be easily built in a relatively short amount of time, but has the durability of a more permanent structure.

### ***Selection of Bamboo Species to be used for design***

The testing and construction prototype for this project was completed using the bamboo species guadua angustifolia. Guadua was chosen for the lab and prototype work because it is the most common structural bamboo and it is grown in central and south America so it is the easiest and cheapest to source in California. Guadua angustifolia is a Central and South American species but is comparable to the Asian species bambusa vulgaris. Bambusa vulgaris is one of four species of bamboo that is naturally grown and prevalent in the Cagayan Valley Region (NERBAC 2013).

**Table III.** A comparison of material properties between two species of bamboo: Bambusa Vulgaris and Guadua Angustifolia

| Material Property | Bambusa Vulgaris | Guadua Angustifolia |
|---|---|---|
| **Modulus of Elasticity** | 1300 ksi[1] | 2200 ksi[2] |
| **Compressive Strength** | 8.6 ksi[3] | 5 ksi[4] |
| **Tensile Strength** | 20 ksi[1] | 10 ksi[5] |
| **Shear Strength** | 1.0 ksi[2] | 0.4 ksi[4] |

[1]Average of values from (Ghavami, 2008) & (Sharma, 2010)
[2](Sharma, 2010)
[3]Average of values from (Ghavami, 2008) & (Gyansah, et al., 2010)
[4](Trujillo, 2009)
[5]Average of values from (Sharma, 2010) & (Trujillo, 2007)

## DESIGN PHILOSOPHY

### *Ethical Considerations*

In defining the ethical context and considerations for the project, the team used framework set forth by the American Society of Civil Engineers and the Santa Clara University School of Engineering vision. The ASCE code of ethics states that engineers are called to,

> *"…uphold and advance the integrity, honor and dignity of the engineering profession by using their knowledge and skill for the enhancement of human welfare and the environment."* (ASCE 2013)

Further, the Santa Clara University School of Engineering vision aims for students to practice engineering with intention and goal of improving the human condition.

Natural disasters in developing countries like the Philippines are an inevitable and unavoidable risk. This problem definition is by nature both ethical and scientific. Given the evidence supporting a clear need for effective disaster relief housing, a normative claim may be made that there is a moral responsibility that falls upon engineers to respond to this need.

This project aims to advance the engineering profession both technically and as a humanitarian effort by providing an innovative structural design for disaster relief housing.

***Sustainability***

A consideration salient in defining the overall design philosophy was designing with the intent of sustainability. In order to address the needs of sustainable development, an approach was defined under the guiding principles of cultural sensitivity, maximization of use, and cost effectiveness. These guidelines were applied to create a design that is accessible, durable, and a long-term solution.

***Design Criteria***

There are currently no accepted design criteria for bamboo in the International Building Code. The guidelines proposed by the International Network on Bamboo and Rattan (INBAR) and reviewed by the International Code Council Evaluation Service (ICC-ES) will be used as the primary design criterion in the structural portion of this project. Adjustments to the guidelines will be made as seen fit and will be supported by statistically significant test results.

The foundation will consist of reinforced concrete and the design will be as per the American Concrete Institute (ACI-318) code provision. The determination of required load resistance for the foundation and structural system designs will be taken primarily from ASCE 7-10, using LRFD/Strength design for the foundation and Allowable Stress Design (ASD) for the structure.

***Performance-Based Design***

Because there are no widely accepted codes or specifications for designing with bamboo, a performance-based approach was chosen for the structural design of the project.

In this approach, design features are specified in order to meet an intended performance. The intended performance protects against structural collapse and complete failure under the specified loading conditions. This is usually done through developing ductility in the system through excellent detailing. While this is the eventual aim, the project is currently in the developmental stages and ducitilities cannot be accurately predicted in a meaningful way. For this reason the design focused on material strength of bamboo and load path.

In order to do this, both the technical and practical limits of bamboo were considered. The material is highly inconsistent and therefore the main concern in the design was establishing a clear load path for resisting and transferring loads developed in the structure down to the foundation. The load path in a light-frame structure can be extremely complex due to the repetitive nature and requirements in design. The gravity and lateral systems were designed to avoid any unnecessary repetitiveness to simply the load path while still remaining conservative in design.

## STRUCTURAL DESIGN

### *Structural Design 2012*

The structural design of the 2012 Bamboo House was used as a guide in the 2013 Bamboo House development and design. The previous design was refined under the guiding design principles of accessibility, cost effectiveness, durability, and the need for a long-term solution. Changes were made to the previous design to implement a system that is simple for construction but also effectively resists site-specific design loads.

There were several design components and ideas that were kept from the previous design, including the use of built up members and multiple culm column components. These ideas were expanded and coupled with several new innovations in the design of the overall system.

***Figure 5.*** *2012 house design (lateral braces removed for clarity) (PECK/WALLACE 2012)*

### *Structural System*

In the development of the structural system both cultural and technical considerations were taken into account. In keeping with cultural norms, an open floor plan, a pitched roof and a large porch area were included in the design. The open floor plan allows for easy addition and removal of interior walls in a 441-ft$^2$ space. The outdoor covered porch area allows for just under 150-ft$^2$ of communal living space. The technical limits of bamboo were addressed by designing a simple system that could be easily analyzed and constructed. Taking into account these considerations, a structure that is constructible and culturally appropriate was designed.

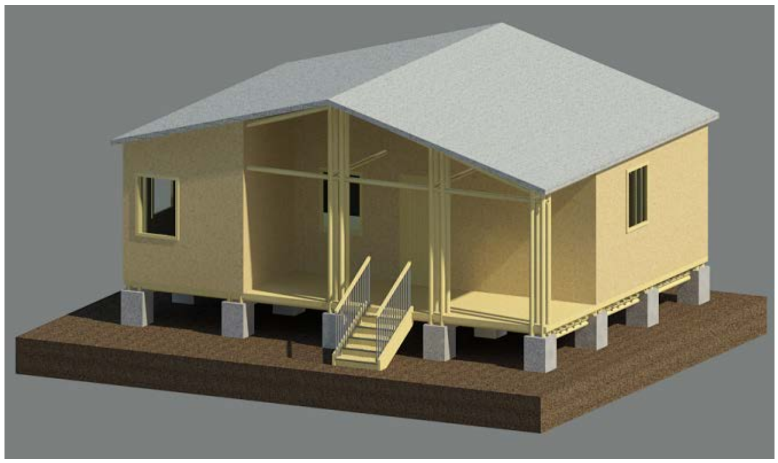


***Figure 6.*** *Theoretical structural system rendering*

***Gravity System***

**Methodology**

The gravity system was designed under the concepts of performance-based design to yield a system that has a clear load path and identifiable failure mechanisms. This was accomplished by simplifying the system as much as possible while still remaining appropriately conservative. In order to achieve this, built-up culm members were used when appropriate to increase the strength and also provide redundancy to implement a conservative system.

**Floor System**

The floor system consists of collecting girders and floor framing members. At the base of the floor system are built-up member collecting girders. These girders serve to transfer load from the system down to the foundation. Two bamboo culms bear directly on top of each other, effectively increase the moment of inertia. This decreases the deflection across the span between the foundation columns and allows for optimization of member spacing. The girders sit directly in the concrete foundation columns in a trough and are attached via an anchor bolt embedded into the foundation. This provides a sturdy base for the structural system that can effectively transfer loads. The trough detail

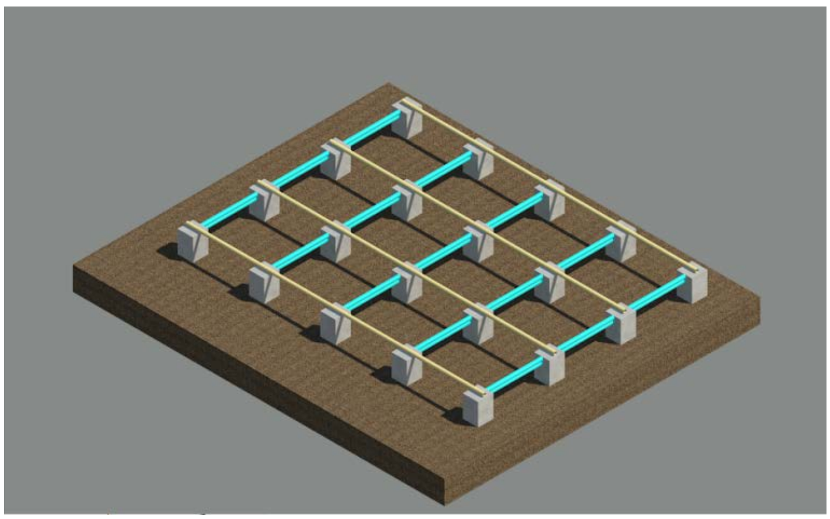


***Figure 7.*** *Built-up member collecting girders (all other framing removed for clarity)*

**Floor Framing**

The floor framing members sit directly on the collecting girders. Deflection limits specified for timber were used for guidance in determining our spacing, and spacing was calculated as 8-in. on center.

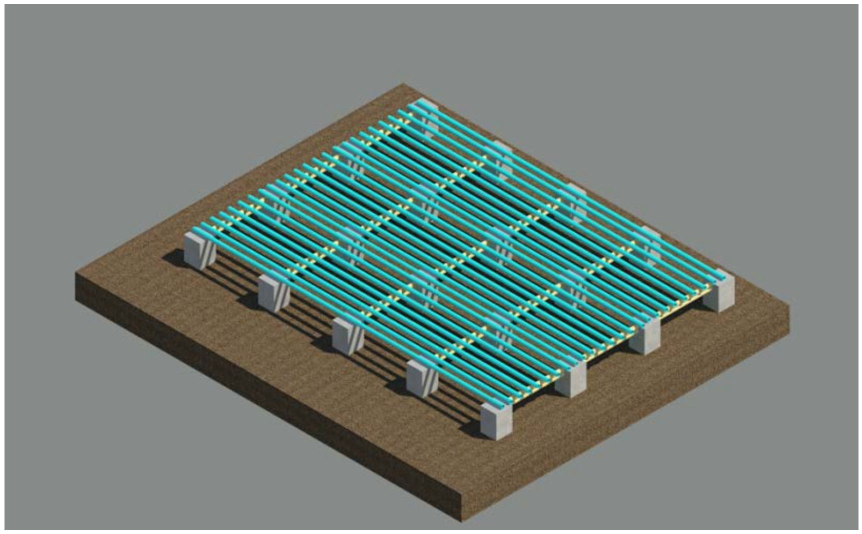


***Figure 8.*** *Floor framing members (other framing members have been removed for clarity)*

The simple grid layout of the floor system provides a clear load path to transfer loads to the foundation. The built-up girder members are salient in optimizing spacing and reducing excessive material use. By allowing the girders to sit directly in the foundation the strength of the system can be more accurately predicted.

### Load Bearing Columns

The load bearing columns were designed to allow for an easy later integration of the lateral system. Also considered in design was the integration of all floor framing members. In order to create a uniform and confined system, four culms were used for the design of each load bearing stud column. There are no interior columns in order to allow for an open floor plan.

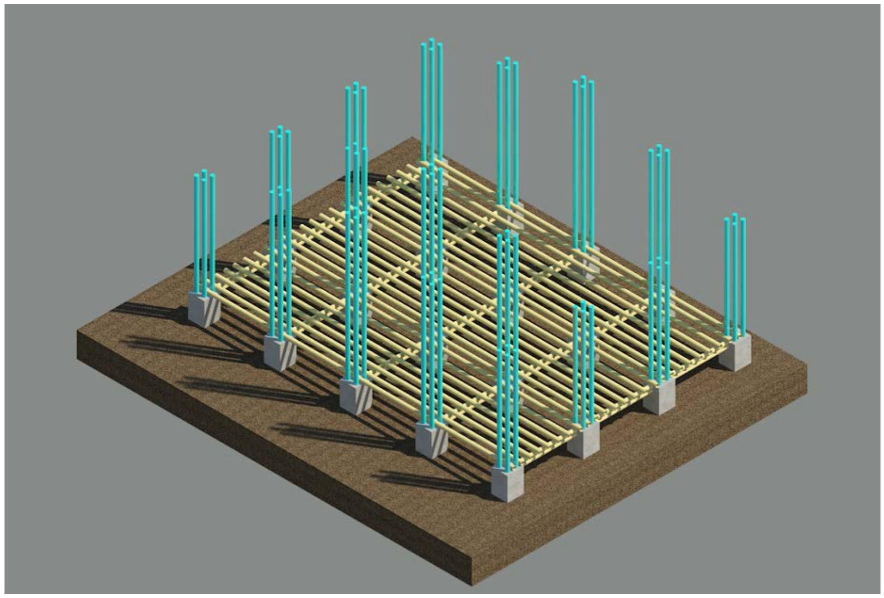


***Figure 9.*** *Stud column framing (other members removed for clarity)*

## Roof Framing

The roof framing sits directly in the gravity stud columns, which are dimensioned to accommodate the pitched roof. The roof height was kept below 15-ft. and the slope is less than 20-deg in order to simplify the load calculations, per ASCE 7-10. A steeper pitch requires more complex load calculations that were observed to be potentially problematic for a system with an already theoretical behavior. In keeping with the design philosophy of simplicity, the roof pitch and height were chosen to eliminate the need for complex load calculations.

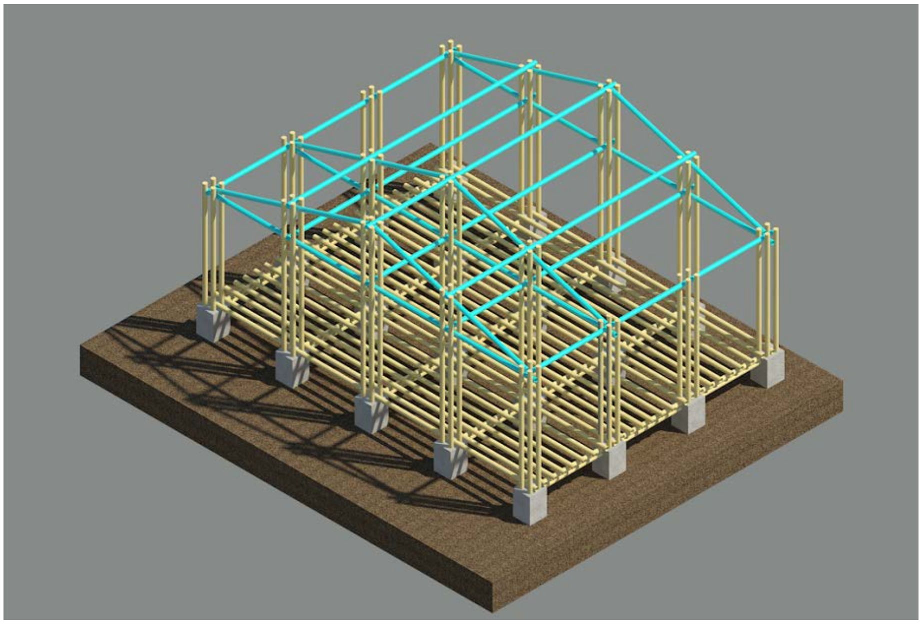


***Figure 10.*** *Roof framing (lateral system removed for clarity)*

### *Lateral System*

#### Methodology

The goal of the lateral system was to effectively transfer the high lateral loads caused by wind and seismic events down to the foundation. As with most structures, the lateral system is the most complex part of the structural design. For this reason, the team chose to design the lateral system as a separate component that could be later integrated. This was done to allow for better quality control, ease of construction, and minimizing site-specific work.

#### *Lateral System 2012*

The 2012 Bamboo House design called for a concentrically braced frame system, with braces placed in both exterior and interior walls. In keeping with the defined structural system, the team decided to eliminate all interior braces. This maintains an open floor plan and also eliminates the potential for inhabitants to knock down a wall with a lateral brace and compromise the overall system. The 2012 design also calls for the concentric brace to connect to the gravity system at the midpoint of the collecting girders. Although the bamboo girders may theoretically have the flexural strength to resist this load, the team decided to avoid putting bamboo members in bending in the design of the lateral system. This was done to avoid potential negative long term effects of creep or material degradation that result in a flexural bending or shear rupture of the collecting girder.

***Development of Lateral System 2013***

There were several different options considered in designing the lateral system. A cross brace would theoretically provide high strength, however in order for the cross-braces members to lie in-plane they must be notched to fit together. This poses a potential decrease in member capacity, requires a heavy amount of site work, and requires a high level of quality control. Because the properties of bamboo are relatively theoretical given the lack of a grading system and dimensional uniformity, the cross-brace decidedly increased the unknowns and variables in design too much to warrant use.

The second option, a shear wall also posed a great deal of site work. The culms would need to be shimmed to allow for the sheathing to lie flat on the culms. The grade of bamboo material in developing regions is generally poor and the individual culms are often already split. This poses potential problems with nailing or screwing sheathing directly into the culms. The already split culms in addition to shimming of the exterior will reasonably cause significant decrease in strength. Because a shear wall gains its capacity based on screw or nail spacing, an already split member will be inadequate in providing strength to support lateral loads.

**Diagonal Brace System**

In order to reduce the amount of site work and simplify the system, a single diagonal brace was chosen as the primary lateral force resisting system.

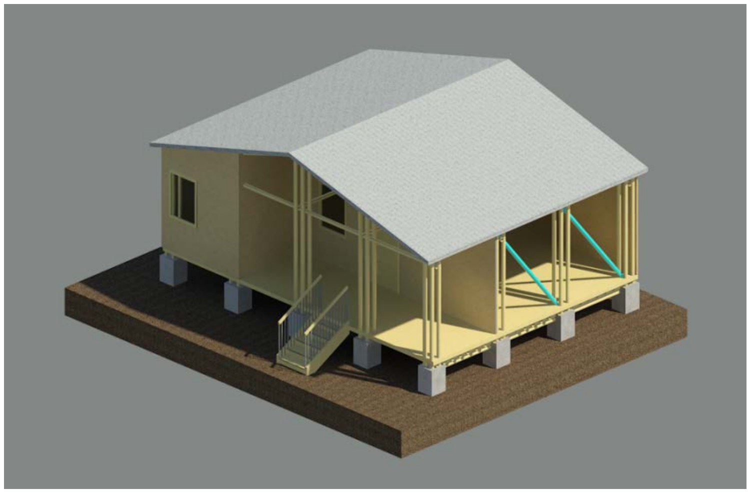


***Figure 11.*** *Diagonal braces in north direction*

The brace is designed with the same tension connection on each end, to allow for development of tensile and compressive strength in the brace. By designing a brace that can take lateral load in both tension and compression the number of braces needed in the structure was reduced, allowing for a more flexible layout of windows and doors. The tensile capacity of the brace also prevents racking in the structure during high winds or earthquake.

***Figure 12.*** *Lateral Brace System*

**Brace Integration**

The diagonal brace was designed as a separate component that could be later easily integrated into the gravity system. The brace consists of a single culm attached to a short end piece member on each side. The tension connection is achieved by embedding an anchor bolt in a brace internode and attaching the bolt end to the short end piece. The anchor bolt can then be tightened by hand. This end piece member sits on top of the gravity system and is integrated using two anchor bolts.

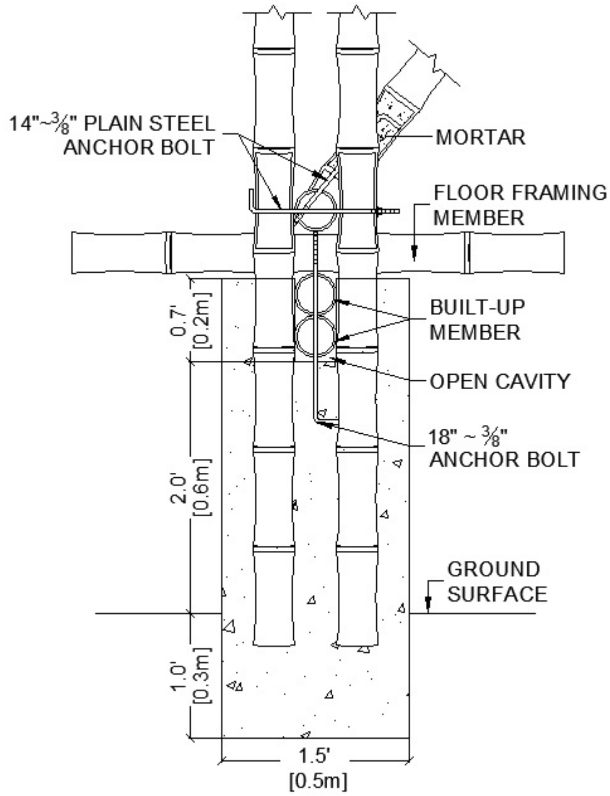



***Figure 13***. *Brace Integration*

By using two anchor bolts as a means for integration, the failure mechanism can be identified as the tension connection in the brace.

***Connections Details***

**Connection Design 2012**

The tension connections in the 2012 design involved bending rebar tightly around a piece of perpendicular rebar in order to transfer shear to the floor girder members. This design yielded a high capacity for the concentrically braced frames placed throughout the system. Although the connection detail had a high capacity, the 2013 Bamboo House Team decided that the constructability of the connection was limiting. The fairly complicated nature of the connection design would require an increase in quality control on-site to ensure the design was implemented properly.

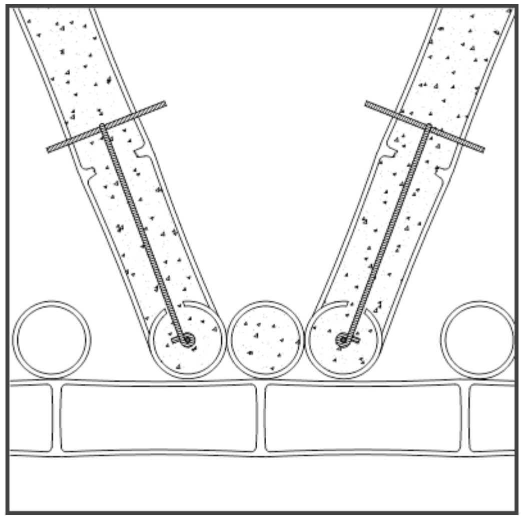


***Figure 14.*** *2012 Connection Design (PECK/WALLACE 2012)*

**Connection Details 2013**

In order to circumvent issues of quality control and constructability, the team decided on the innovative use of an anchor bolt in all connection details. While other connections using rebar or threaded rod were considered, anchor bolts offered the most economical and simple option. The anchor bolt effectively marries the advantageous properties of threaded rod and reinforcing bar. Threaded rod is relatively simple to implement in construction and demonstrates high capacity, however it is expensive and there is room for error in tightening the bolts on each end. Rebar is easily bent to provide shear reinforcing; however this introduces quality control and constructability issues.

The hooked end of the anchor bolt is used to develop tension in the connection design but does not require on-site bending like the rebar. Since only one end of the anchor bolt is threaded, there is also a reduction in the necessary hardware. Using the same anchor bolt throughout the entire system also eliminates potential confusion during construction.

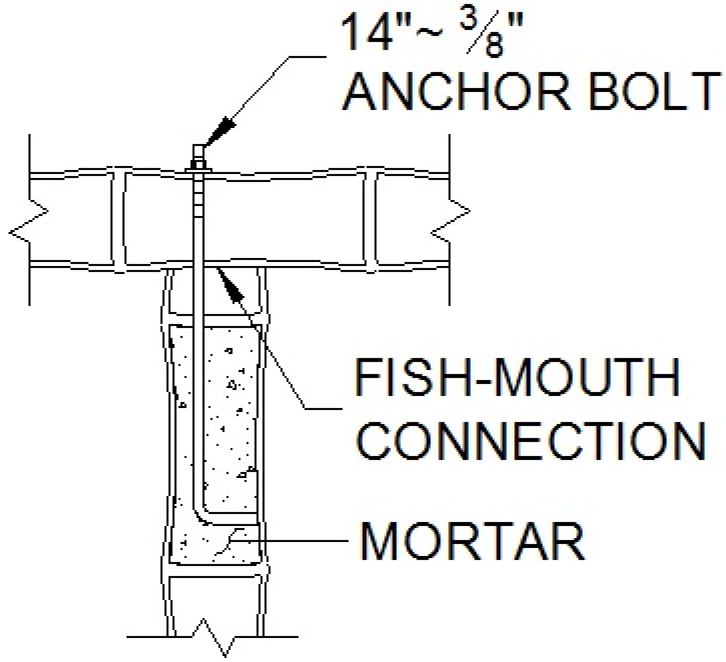



***Figure 15***. *Tension connection design*

The design calls for embedding the hooked end in concrete and bolting the free end to the perpendicular piece. Only one node is filled with concrete in order to reduce the amount of concrete used in overall construction. Testing showed that this connection design yielded a lower capacity than the 2012 design; however the strength was more than sufficient for the loads seen by the structure. Given the overall ease of construction, The 2013 Bamboo Team decided on the anchor bolt tension connection in the final design

**Gravity System Connections**

Anchor bolts were also used in connecting all gravity framing members. The length of the anchor bolt allows for the connection of up to three members at a time. This provided a simple solution for connecting multiple members at once, which frequently occurs in the structural system.

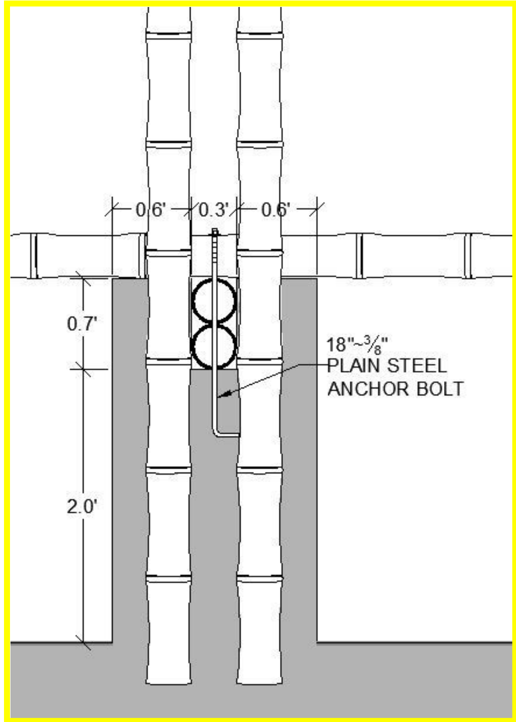



***Figure 16.*** *Anchor bolt gravity connection*

Natural fiber tie downs have been specified for connecting framing members to girder members for simplicity. The framing members are subject to relatively small loads and the natural fiber tie down offers an economical and structurally efficient solution.

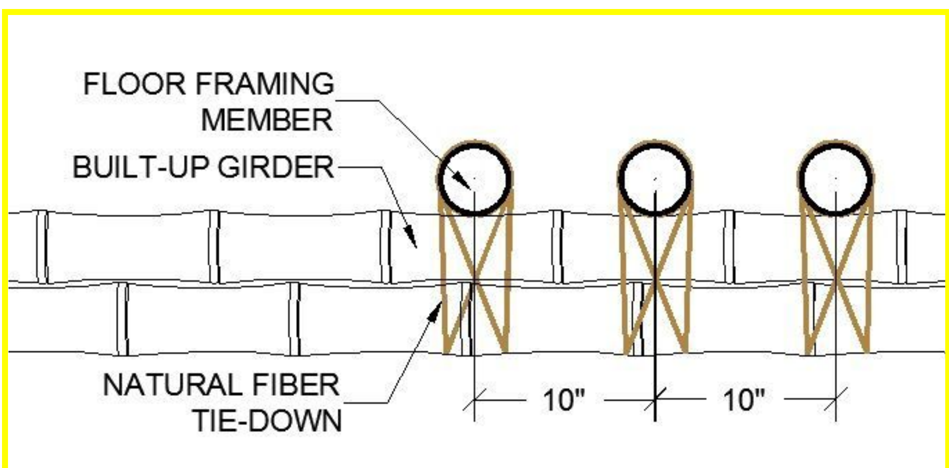



***Figure 17.*** *Natural fiber floor-framing connection*

## GEOTECHNICAL ANALYSIS AND DESIGN

The scope of 2012 Bamboo House project included a preliminary conceptual footing plan but did not include a geotechnical analysis or site-specific soil research. This design proposed embedding the bamboo columns into square shallow footing made out of reinforced concrete. The 2012 Bamboo House team did not size the footings, calculate the ultimate and allowable capacities and address the soil conditions in the Philippines.

The scope of the 2013 Bamboo House project includes a complete site-specific foundation design for the structure. One of the inherent challenges faced when building with bamboo is the load transfer from the bamboo structural system into the foundation. The proposed design aims to fully integrate the structural system into a reinforced concrete foundation. This design is a site-specific soil design for a typical site in the Cagayan Valley Region.

### *Soil Profile*

The design team will not personally perform in-situ site investigation due to the high cost and complexity of conducting this research in the Philippines; however, the team received in-situ test data from Jonathan Dungca, a professor of geotechnical engineering at De La Salle University in Manila, Philippines. Dungca provided the team with boring logs from a standard penetration test (SPT) and SPT N values corrected for field procedures ($N_{60}$) and the Unified Soil Classification System (USCS) group names for the soil. The design team used this field data as the basis for the geotechnical analysis and design. Dungca was unable to provide a soil profile for a site located in the Cagayan Valley and he did not believe that extensive geotechnical site exploration and testing had been performed in that region. However, he advised the team that that the soil profile information he provided was

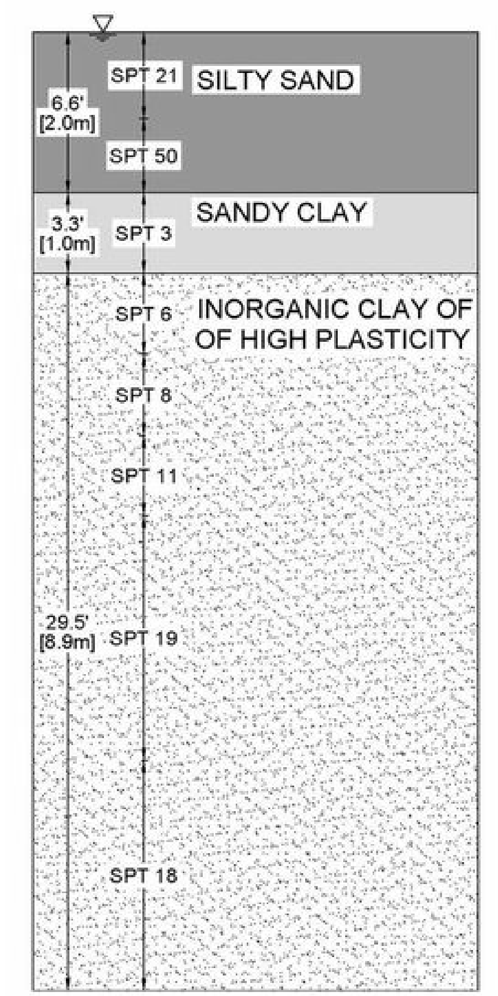



***Figure 18.*** *Soil profile based on the boring logs provided by Jonathan Dungca, 2013*

representative of a typical soil profile of a site located in the inland area of the Northern Philippines. The soil profile was developed from borings taken during the construction of the Maligay Park subdivision in Camarin, Caloocan City North, Metro Manila, Philippines.

The borings used to develop the site profile were taken to a depth of 12 meters (approximately 40 feet). The soil profile is shown in Figure 18. The uppermost layer of soil is a 6.6’ thick stiff silty sand (SM) layer. This layer is followed by a 3.3’ thick soft sandy clay layer and the rest of the profile is soft inorganic clay of high plasticity (CH).

Inorganic highly plastic clay shrinks and expands rapidly so the foundation should not be built in this layer. Since the sandy clay layer is soft and there is highly plastic clay right below it, the foundation should not be placed in this layer either because of settlement. The exact location of the bedrock is unknown since it occurs deeper than the 40' sample boring depth. Due to the high plasticity of the clay layers, the foundation must be located in the silty sand layer. The silty sand layer will experience the smallest amount of settlement out of the three layers and because the proposed structural system is a light-frame system, a shallow foundation design will be the most logical approach.

Additionally, Dungca noted that geotechnical engineers in the Philippines generally design foundations under the assumption that the groundwater table is at surface elevation. The water table changes depending on the wet and dry seasons. The presence of the groundwater table in a soil layer reduces the effective unit weight of the soil. Therefore, the assumption that the groundwater table is located at surface level leads to a more conservative design.

**Risk analysis of the potential for the occurrence of liquefaction**

The curves in figure 19 can be applied to silty sands provided the normalized standard penetration resistance, $N_1$, for the silty sand is increased by 7.5 before it is plotted on the chart. The Richter scale magnitude of the design earthquake is 8.5 as suggested by structural engineers in the Philippines. In figure 19 if the N1 and CSR for the soil layer plots above the curve then liquefaction is likely to occur at the given magnitude earthquake. If it plots below the curve then liquefaction is unlikely to occur at that magnitude earthquake.

Since the foundation is in a silty-sand layer, liquefaction is unlikely for the given soil properties. However, if the soil is sand and not silty sand then liquefaction is likely to occur. Since the soil profile is not for the exact site the house would be built on and due to the general inaccuracy of geotechnical calculations (the true precision of geotechnical computations may be up to ±50% of result of the calculation) the design team determined that while liquefaction seems unlikely to occur, the potential for liquefaction should be taken into account.

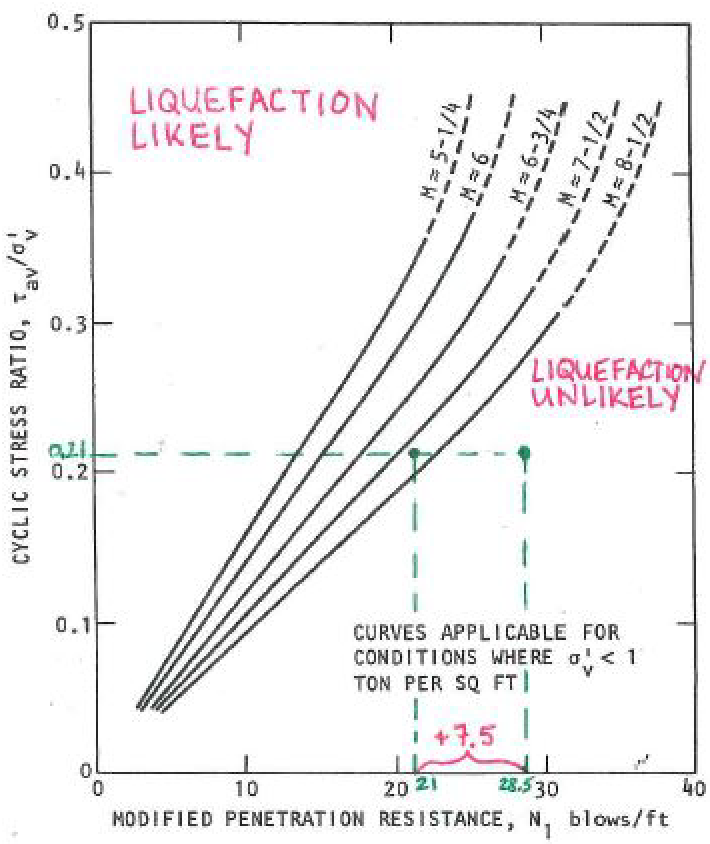



***Figure 19.*** *Chart for evaluation of liquefaction potential for sands for an 8.5 magnitude earthquake*

*Foundation Design Process and Considerations*

The final two alternatives considered for the foundation of the house were a shallow foundation option of reinforced concrete spread footings and a deep foundation option of bamboo piles.

**Shallow Foundation Option: Reinforced Concrete Spread Footings**

A single-family residential house is typically supported by a shallow reinforced concrete foundation. Since the house is a light-frame structure and the upper 2 meters (6.7 feet) of the soil profile is stiff silty sand both the bearing capacity and settlement should be sufficient for shallow spread footings. The loads are so light that a deep foundation is unnecessary. Concrete footings provide a stiffer floor diaphragm and would be more comfortable to walk on than the bamboo piles. The team's concern regarding square footing design is that differential settling will occur.

**Deep Foundation Option: Bamboo Piles**

The design team considered the use of bamboo as the primary structural material in the foundation. The use of bamboo in the foundation would allow for the structural system to tie into the foundation more effectively. Additionally, in the Philippines, bamboo is significantly cheaper than reinforced concrete and it is a locally sourced and renewable material whereas concrete and rebar must be imported.

The use of bamboo piles is a conventional building practice in Indonesia. Indonesia is a South East Asian country consisting of a group of islands and is located directly south of the Philippines; therefore, soil in Indonesia has similar soil properties to soil in the Philippines. A typical site in Indonesia rests on a layer of soft clay or peat that is often more than 30 meters thick. The soil profile from the Philippines is also mainly composed of soft clay. It is not economical to support a small, lightweight residential house on concrete or steel piles so bamboo provides a cost-effective alternative while still limiting the instability and settlement affects of the soft clays. Additionally the bamboo piles were still effective if the tips were placed in the soft clays; therefore there was no need to drive the piles all the way to a stiff soil or bedrock layer. Paulus P. Rahardijo, a professor of geotechnical engineering at Parahyangan Catholic University in Bandung Indonesia, observed that is was probably due to the buoyancy effect of the bamboo piles in the soft clay. Bamboo piles are also particularly useful in the event of a landslide, because they are not affected by soil removal and displacement in the event of a landslide. The bamboo piles were found to be durable if they were located underneath the groundwater table (Rahardijo, 2005). The bamboo piles can be installed by using a backhoe or a drop hammer.

**Selection of the final design**

The Bamboo House team determined that the most important influencing factors when choosing the final design were (1) the long-term performance and (2) the ease of construction of the foundation.

Bamboo piles have been found to be durable if they are located underneath the water table. In the Philippines, the water table varies greatly depending on the weather so the piles will experience different water table levels that can lead to rot developing in the bamboo over an extended period of time. Additionally, Rahardijo does not comment on how to protect the bamboo from insects in the soil such as ants or termites. Also there is no data available on the lifespan of bamboo piles or treatment methods to improve lifespan. Since a design goal is to create a durable and long-term structure, the uncertainty of the longevity of bamboo piles does not align with this design goal.

Bamboo piles are driven into the ground and therefore require heavy equipment to install. The shallow concrete footings required formwork to construct, but no heavy equipment or specialty tools are required to install the footings. In a poor, rural setting, a design that can be built with readily available equipment is essential to the practicality of the design.

***Proposed Footing Design***

The proposed foundation design was a shallow reinforced concrete footing. Four (4) full culm bamboo columns were embedded in a 2' tall square concrete column. Three additional concrete columns were placed in the middle of the floor diaphragm along line 2 to limit the deflection of the girders and floor-framing members. These were supported by square spread footings and the concrete columns supporting the exterior walls of the structure were supported by strap footings. The widths of the footings were 18 inches and the depth of the foundation was 12 inches.

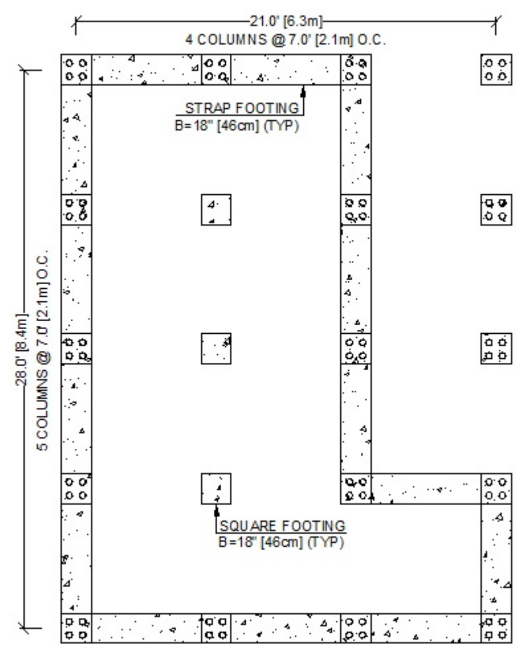



***Figure 20.*** *Footing plan view*

**Footing Cross-Sections**

The concrete footings and columns were reinforced with No. 3 rebar. The amount of reinforcement in the footings is controlled by AIC minimum reinforcement requirements instead of being controlled by tensile strain.

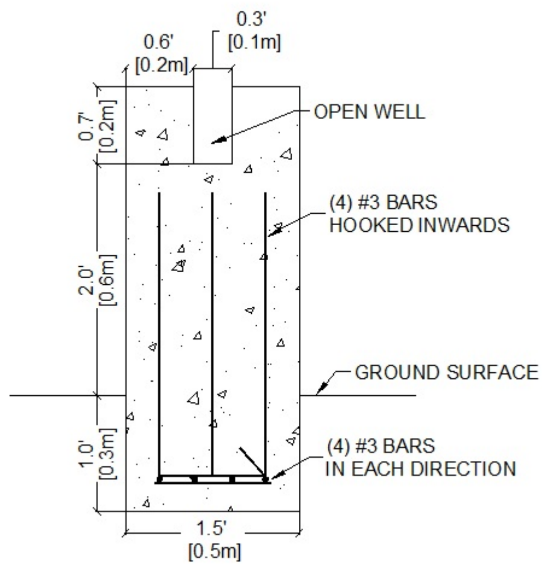



***Figure 21.*** *Typical cross-section of the proposed square spread footing*

***Analysis of soil capacity and foundation performance***

**Bearing capacity and settlement considerations**

ASD load combinations were used to calculate soil capacity, and LRFD load combinations were used to calculate the concrete footing capacity. Since the foundation will be built in the silty-sand soil layer, settlement limits will not control the foundation design unless liquefaction occurs due to lateral loads. The use of strap footings will restrict settlement and torsion caused by lateral loads. The bearing capacity was calculated using Vesic's equation. Both the bearing capacity and base shear capacity are sufficient to withstand the design loads.

Since the foundation was designed for a stiff silty-sand layer, settlement limits did not control the foundation design unless liquefaction occurs due to seismic loads. The square spread footings under the outer walls of the structure were strapped together with reinforced concrete beams to reduce differential settlement and torsional moments that result from liquefaction.

**COST ESTIMATE**

Douglas Fir Larch costs approximately $0.65 per linear foot for a 2x4 piece of sawn lumber. In contrast, In the Philippines, a 3.5” to 4.0” diameter full culm bambusa vulgaris costs approximately $0.01 per linear foot. The proposed structure requires approximately 2500 linear feet of bamboo. All of the bamboo for the structural system could be purchased for $250.

**PROTOTYPE CONSTRUCTION**

An important focus of the structural design in *A Light-Frame Approach to Disaster Relief Housing* was constructability of the system. In order to assess the ease of construction, the team built a prototype section of the house design. Figure X below shows a 3-Dimensional rendering of the section to be constructed.

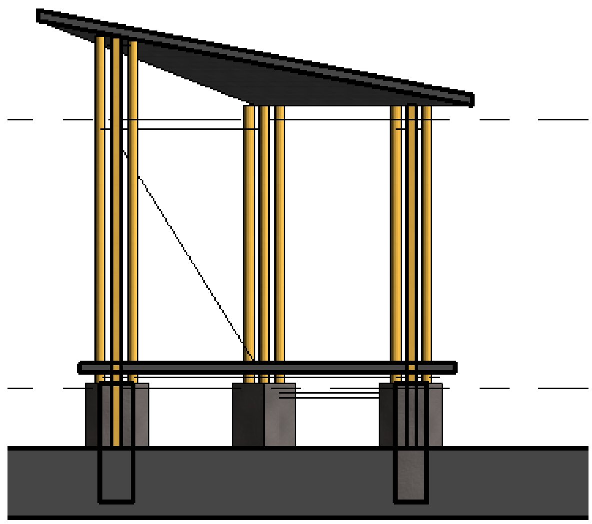


***Figure 22.*** *3D rendering of prototype section*

The prototype included all key anchor bolt connections from the structural design. Also included in the prototype was the lateral brace, important for assessing the ease at which the brace could be integrated into the system. The brace was constructed separately, as specified in the theoretical structural design. The brace was then integrated into the already built gravity system and bolted together.


***Figure 23.*** *Fully constructed brace frame integration*

***Assessment of Construction***

The prototype was successfully built by the team with limited experience in construction. The design required only a very limited use of power tools, theoretically making it constructible in a developing region with limited access to power. Fish mouth connection were done using a jig saw, however this could also be done using traditional chisel methods. The only additional power tool used was a cordless drill. The battery powered drill can easily be used in a region with unreliable power and is simple for someone with limited construction experience to use. Figure X below shows the finished prototype section.

***Figure 24.*** *Completed prototype section*

## CONCLUSION

### *Design Summary*

The goal of *A Light-Frame Approach to Disaster Relief Housing* was to expand on and improve the preliminary 2013 design for the Philippines. This was done by including a full foundation design and a complete conceptual structural design. A specific focus was placed on designing a structure that would fit in architecturally with the community in the Cagayan Valley region in the Philippines. The team focused on bringing important cultural aspects to the design including an open floor plan, pitched roof, and large porch area. The design focused on a structure that could be resilient in multiple extreme flood, monsoon and earthquake loading conditions. This was done by providing sufficient lateral bracing in the structure and a foundation design that could accommodate the potential effects of liquefaction and flood loads. In addition to cultural considerations, the design was made as simple as possible. Constructability of the design was an important aspect of the design, and the team aimed to create a system that could be easily understood and implemented by those with limited or no technical backgrounds.

### *Next Design Steps*

Due to the highly variable and fairly unknown material properties of bamboo, the 2013 Bamboo House design is still in a fairly conceptual stage. The construction of a prototype section proved that the design is constructible. The team recommends a next step of full-scale testing of the lateral brace system. Though design calculations showed that the structure is theoretically overdesigned, the interaction of the different components in a real-world setting needs further investigation. In addition to further testing, the team recommends investigation into creating a grading system for full-culm bamboo. A grading system similar to rough-sawn lumber would be ideal for structural design and constructing a reliable system.

Beyond the structural design, the team recommends a full investigation into sheathing the system. The anisotropic qualities of bamboo require special attention in sheathing to create smooth and level surfaces in the system. In order to properly address the stigma that bamboo has in the developing world, a complete system including sheathing should be designed to look like a modern home.

### ***Further Applications***

*An Approach to Light-Frame Disaster Relief Housing* designed both the geotechnical and structural systems as an example of how bamboo can be integrated into modern construction. The site investigated in the Philippines provides essentially the worst-case scenario loading conditions for design. The team believes that any system that can effectively withstand these conditions can be used around the world in other countries as disaster relief housing. The focus on a permanent solution rather than a temporary fix furthers the investigation of bamboo as a sustainable and resilient material that can be effectively used in modern construction.

**REFERENCES**

Bakun, William H., and William H. Prescott. (2010) "Professional Paper 1550 – Earthquake Occurrence." *Loma Prieta Earthquake Professional Papers*. N.p., n.d. Web. 4 June 2013.

Ghavami, K. (2008). "Bamboo: Low cost and energy saving construction materials." Pontificia Universidade Catolica, Rio de Janeiro, Brasil. 5-21.

Holzer, Thomas L. (2013) "Performance of the Built Environment." *Loma Prieta Earthquake Professional Papers*. USGS, n.d. Web. 4 June 2013.

Nichols, Michael K. (2007) 1989 Loma Prieta Earthquake. Digital image. *National Geographic*. National Geographic. Web. 4 June 2013.

Peck, Quinn, and Wallace, Scott. (2012) "A Sustainable Approach to Disaster Relief Housing." *Santa Clara University School of Engineering*, June 2012. 4 June 2013.

Rahardjo, Paulus P. (2005). "Chapter 31: The use of bamboo and bakau piles for soil improvements and application of pile raft system for the construction of embankment on peats and soft soils". *Elsevier Geo-Engineering Book Series*, Vol. 3, p 899-921.

Republic of the Philippines's National Statistics Office (NSO). "Cagayan Valley: Nine in Ten Households Owned/Amortized Their Housing Units". June 27, 2003. Accessed April 2013. <www.census.gov.ph>

Republic of the Philippines's National Statistics Office (NSO). "Philippine Population went up by 12 million persons (results from the 2007 census of population)". November 25, 2010. Accessed October 2012. <www.census.gov.ph>

Republic of the Philippines's National Statistics Office (NSO). "QuickStat on Region II – Cagayan Valley: May 2013". Accessed June 2013. <www.census.gov.ph>

Schroder, Stephane. “Bambusa Vulgaris (Common Bamboo)” Guadua Bamboo. Accessed May 2013. <www.guaduabamboo.com>

Seed, H. B. & I.M. Idriss. (1982). *Ground Motions and Soil Liquefaction During Earthquakes*. Earthquake Engineering Research Institute.

Sharma, B. (2010). Seismic Performance of Bamboo Structures. University of Pittsburgh. 1 178.

Trujillo, D. (2007). “Bamboo structures in Colombia.” *The Structural Engineer*. 85(6): 25-30.

Trujillo, D. (2009). “Axially Loaded Connections in Guadua Bamboo.” *Non-conventional Materials and Technologies*. 1-8.

# APPENDIX A

# CONNECTION TESTING

## Testing

### *Evaluation of Lateral Force-Resisting System*

The most difficult part of designing with bamboo is integrating the various systems of the design. Due to the unique material and geometric properties of bamboo, the connection of the structural members is most often the first area to experience engineering failure. By designing durable and strong connections with limited quality control, the overall safety and effectiveness of the structure can be dramatically increased. *An Approach to Light-Frame Disaster Relief Housing* designed and constructed two connection types: a tension connection for the integration of the lateral and gravity systems, and a bolted connection for the connection of the members of the gravity force resisting system.

The capacity of the brace frame connection was analyzed through three simple test procedures: internode direct shear, node interior fiber crushing and testing of the connection prototype in tension. The experimental data collected from these tests was then used to verify the theoretical strength and failure method of the design.

The results of testing showed that in a high seismic loading event the connecting members of the lateral brace would likely split and experience failure of the concrete inside the nodes before the members experiences compressive failure of the node interior fibers or the shear failure of the internode fibers. These results partially depend on the strength of the concrete inside the nodes as well as the length of the members of the tested connection prototype. For further applications, full scale testing of the lateral force resisting systems need to be performed in order to better evaluate the performance of the constructed design during a significant seismic event.

### *Tensile Testing of Connection Prototype*

Materials and Methods

1. Procedure

a. Cut one bamboo piece with at least two full nodes. Cut one end of the bamboo five inches from the internode. Cut the other end about halfway through the node.

b. Cut a shorter bamboo piece with one full node. Leave at least three inches of bamboo culm on either side of the full node.

c. Create a fishmouth connection by fishmouthing the longer bamboo piece. Fishmouth the end of the sample that was cut five inches from the internode. This can be done using a jigsaw or a chisel.

d. Drill a 2” diameter hole into the full node that is closest to the fishmouth end of the sample. This can be done with a holesaw or a chisel. This hole will be used to fill the node with concrete.

e. Take the shorter bamboo piece and drill and ⅜” diameter hole through the center of the node so that the drill is perpendicular to the fibers of the bamboo piece. This hole should continue through both sides of the bamboo. This can easily be done using a drill bit that is at least 6” long.

f. Take the long bamboo piece and insert a 14” anchor bolt into the 2” diameter hole so that the bent end of the anchor bolt is restrained by the internode of the culm. Then, thread the other end of the anchor bolt through the hole in the center node of the shorter bamboo piece.

g. Secure the shorter bamboo piece by attaching a washer and nut to the end of the anchor bolt.

h. Prepare a concrete mix. Due to the time restraints for these tests, quikrete was used. Combine the quikrete and water with a 4:1 ratio.

i. Once the concrete mix has been prepared, completely fill the node with the 2" diameter hole with the mix. Ensure that the mix is compact by using a vibrator or metal rod to release any air bubbles in the node. Allow the concrete to set in the bamboo for at least 7 days. The final connection sample should look like this:

Fig. 1: Anchor bolt connection of the brace frame

j. Once the concrete has set, the samples are ready to test. Secure the shorter piece of the bamboo with two straps to the bottom part of the testing machine. Make sure that the straps completely restrain the bottom segment from moving during the test. Attach clamps to the other end of the long bamboo piece at the top of the testing machine.

k. Load the sample in tension so that the machine physically pulls the two bamboo members apart. Measure the peak load and note any physical changes to the sample before and after testing.

2. Raw Data

| Connection Tension Test | |
|---|---|
| Test | Peak Load (lbs) |
| 1 | 721.1 |
| 2 | 661.8 |

Table 1: Raw data for the tensile connection test

3. Results

Both samples experienced failure at tensile strengths above 661.8 lbs. Both sample connections failed with full splitting of the fish-mouthed member and crumbling of the concrete in the node.

4. Discussion

The tensile strength of the connection prototype was determined in order to further predict the failure method of the brace frame connection. These results must be analyzed with the results of node interior fiber crushing tests and the internode direct shear tests in order to determine the failure method of the brace frame during a significant loading event

### *Internode Direct Shear*

Materials and Methods

1. Procedure

a. Cut a section of a bamboo culm so that there is one whole internode sample. Leave at least three inches of bamboo culm on both exterior sides of the sample.

b. Weigh the sample, and measure the length of the internode, as well as the thickness of the walls of the culm in four places.

c. Restraint the sample using straps on either side of the interior node to a compression testing machine. Leave the internode undisturbed for testing.

d. Apply a 1” load applicator to the sample at the center of the internode to that the fibers of the culm run perpendicular to the load applicator. The testing sample should look like this:

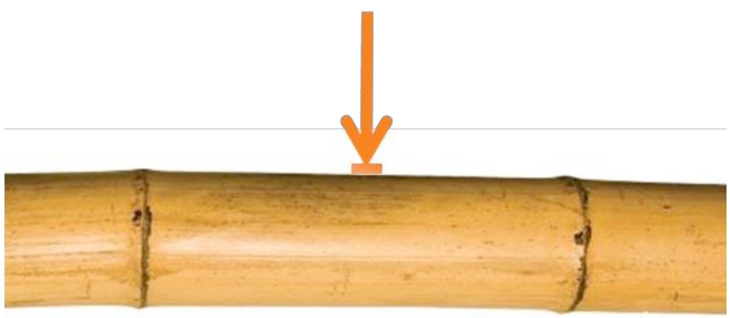


Fig. 2. Simulation test for internode direct shear


Fig. 3. Internode direct shear test using 10-kip machine.

e. Load the sample in compression with the vertical load directly applied to the perpendicular fibers of the culm. Measure the peak capacity and note any noticeable physical changes of the sample during and after the testing.

2. Raw Data

| Direct Shear | | | | | | | |
|---|---|---|---|---|---|---|---|
| Test | $t_1$ (mm) | $t_2$ (mm) | $t_3$ (mm) | $t_4$(mm) | Node Spacing (in) | Peak Load (lbs) | Outer Diameter of Culm (in) |
| 1 | 9.52 | 12.8 | 10.3 | 12.38 | 10.75 | 1121 | 3.743 |
| 2 | 11.4 | 11.38 | 11.65 | 10.66 | 8.375 | 1482 | 4.213 |
| 3 | 14.76 | 14.32 | 12.84 | 12.89 | 6.75 | 1223 | 3.954 |

Table 2: Raw data for the simulation for the internode direct shear

3. Results

All three samples experienced shear failure at stresses higher than 350 psi. The first sample had a capacity of 356.82 psi. The second sample had a capacity of 471.73 psi, and the third had a capacity of 389.29 psi. The average shear capacity of the internode of guadua bamboo from these test results is 405.95 psi.

4. Discussion

The shear strength of the internodes of guadua bamboo culms was determined in order to further predict the failure method of the brace frame connection. These results must be analyzed with the results of node interior fiber crushing tests and the tensile testing of the connection prototype in order to determine the failure method of the brace frame during a significant loading event.

### *Node Interior Fiber Crushing*

Materials and Methods

1. Procedure

a. Prepare a sample by cutting a bamboo culm on both sides of an internode. Leave at least two inches on each side of the node.

b. Weigh the sample, and measure the length of the internode, as well as the thickness of the walls of the culm in four places.

c. Secure a 2” diameter load applicator directly to the fibers of internode. The test apparatus should look as follows:

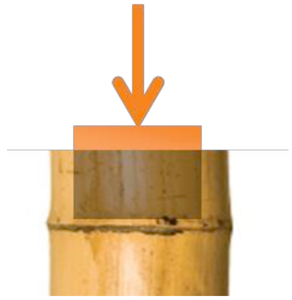


Fig. 4. Simulation test for node interior fiber crushing

Fig. 5. Test specimen and node fibers before node crushing.

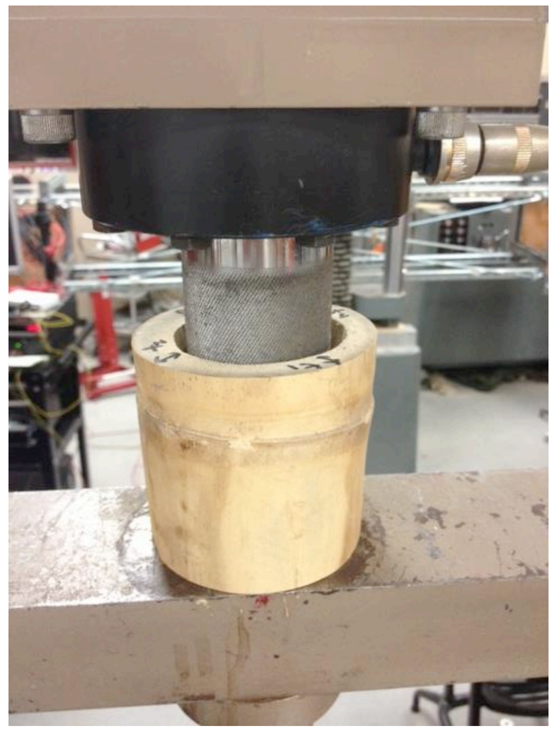


Fig. 6. 10-kip machine applying load to inner node fibers.

d. Load the sample in compression with the vertical load directly applied to the fibers of the internode. Measure the peak capacity and note any noticeable physical changes of the sample during and after the testing.

2. Raw Data

| Node Crushing | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Test | Area of Load Applicator $in^2$ | Load | Stress (psi) | $t_1$ (mm) | $t_2$ (mm) | $t_3$ (mm) | $t_4$(mm) | Inner Diameter of Node (in.) |
| 1 | 2.76 | 3095.34 | 1121.5 | 12.18 | 11.92 | 10.25 | 12.77 | 2.5 |
| 2 | 2.76 | 3570.06 | 1293.5 | 11.2 | 12.45 | 12.05 | 10.92 | 2.125 |
| 3 | 2.76 | 2975.28 | 1078 | 13.05 | 14.31 | 16.67 | 14.83 | 2.375 |

Table 3: Raw data for the simulation for node interior fiber crushing

3. Results

All three samples experienced compressive failure at stresses higher than 390. The first sample had a capacity of 406.34 psi. The second sample had a capacity of 468.66 psi, and the third had a capacity of 390.58. The average compressive capacity of the node interior fibers of guadua bamboo from these test results is 421. 86 psi.

4. Discussion

The compressive strength of node interior fibers of guadua bamboo culms was determined in order to further predict the failure method of the brace frame connection. The test was performed three times in order to determine the compressive strength of the interior node fibers of guadua bamboo. In order to eliminate the possibility of column buckling, the samples were kept very short. This ensured that the samples would experience failure at the nodes. With these results, the bamboo team can better predict the loading at which the nodes containing would experience compressive failure in a high loading event.

By evaluating the results of the node interior fiber crushing and the internode direct shear, the capacity of guadua bamboo in the lateral brace connection can be more critically analyzed. The connection is more likely to fail by method of direct shear to the internodes rather than crushing of the interior node fibers.

# APPENDIX B

# BORING LOG

**Boring Log**

Received from Dr. Jonathan Dungca, a professor of geotechnical engineering at De La Salle University in Manila, Philippines

| | |
|---|---|
| Project Site: | Sampaguita Street, Maligay Park Subdivision, Camarin, Caloocan City |
| Water Level: | 0 m |

| DEPTH1 | DEPTH2 | SPT/RQD | SPT or RQD | INPUT | USCS NAME |
|---|---|---|---|---|---|
| 0 | 1 | 21 | SPT | 4 | Silty Sand |
| 1 | 2 | 50 | SPT | 4 | Silty Sand |
| 2 | 3 | 3 | RQD | 11 | Sandy Clay |
| 3 | 4 | 6 | RQD | 13 | Inorganic Clay of High Plasticity |
| 4 | 5 | 8 | RQD | 13 | Inorganic Clay of High Plasticity |
| 5 | 6 | 11 | RQD | 13 | Inorganic Clay of High Plasticity |
| 6 | 7 | 19 | RQD | 13 | Inorganic Clay of High Plasticity |
| 7 | 8 | 19 | RQD | 13 | Inorganic Clay of High Plasticity |
| 8 | 9 | 19 | RQD | 13 | Inorganic Clay of High Plasticity |
| 9 | 10 | 18 | RQD | 13 | Inorganic Clay of High Plasticity |
| 10 | 11 | 18 | RQD | 13 | Inorganic Clay of High Plasticity |
| 11 | 12 | 18 | RQD | 13 | Inorganic Clay of High Plasticity |

# APPENDIX C

# CONTACTS

| Contact | Company | Position | Email | Website | Notes/Comments |
|---|---|---|---|---|---|
| DeBoer, Darrel | DeBoer Architects | Architect | darrel@deboerarchitects.com | deboerarchitects.com | Meeting first week in February to discuss building with bamboo and foundation designs |
| René Vignos | Forell/Elsesser Engineers | Structural Engineer | R.Vignos@forell.com | forell.com | Meeting on 1/30 to discuss Haiti reconstruction project |
| Loomis, Michael | | Structural Engineer | mloomis@gmail.com | | -Planning to meet 1/23 to discuss Quinn and Scotts design |
| | Association of Structural Engineers of | | aseponline@gmail.com | aseponline.org | |
| Balili, Alden | Association of Structural Engineers of the Philippines | Director of ASEP, professor at DLSU in Manila | alden.balili@gmail.com | | -Currently helping with the structural design |
| Carlson, Grace | Casa Bayanihan (Philippines Study abroad program) - Ataneo de Manila University | | carlson.go@gmail.com | | Put us in contact with Praxis site leaders |
| Eder, Cathy | Casa Bayanihan (Philippines Study abroad program) - praxis site leader | | cathyllaveeder@yahoo.com | | Nonprofit, "Lingap Pangkabataan" - Baseco and Mindanao are communities for potential housing project (affected by typhoon) |
| Dungca, Jonathan | DLSU Manila | Professor | jonathan.dungca@dlsu.edu.ph | | Currently helping with the foundation design (soil information) |

# APPENDIX D

# CALCULATIONS PACKAGE

An Approach to Light-Frame Disaster Relief Housing

# STRUCTURAL CALCULATIONS

submitted
by

Hayley Dickson
Megan Cronan

## DESIGN CRITERIA SUMMARY

| | |
|---|---|
| Project: | An Approach to Light-Frame Disaster Relief Housing<br>Cagayan Valley Region, Philippines |
| Designers: | M. Cronan and H. Dickson |
| Project Number: | CENG 193 – Spring 2013 |
| Jurisdiction: | Republic of the Philippines |
| Code, Specifications and Standards: | *ASCE/SEI 7-10, ACI 318-11, Acceptance Criteria for Structural Bamboo* (ICC-ES), *National Building Code of the Philippines* |
| Software Used: | AutoCAD 2012, SAP 2000 |

Basic Loads:

Gravity Dead Loads:

| | |
|---|---|
| Floor | 25 PSF |
| Roof | 10 PSF |

Gravity Live Loads:

| | |
|---|---|
| Roof | 20 PSF |
| Floor | 40 PSF |

Deflection Limits:

| | |
|---|---|
| Total Load | L/360 |
| Live Load | L/480 |

Lateral Load:

Wind Criteria

| | |
|---|---|
| Wind Speed | 125 MPH |
| Wind Exposure | B |
| Importance Factor | 1.00 |

Seismic Criteria

| | |
|---|---|
| Method | Equivalent Lateral Force |
| SDC | D |
| Site Class | D |
| Importance Factor | 1.00 |
| R | 1.50 |
| $C_s$ | 0.49 |
| Seismic Weight | 26 KIPS |
| $\rho$ | 1.3 |

Flood Load

| | |
|---|---|
| Still water depth | 2.0 FT |
| Coefficient of drag | 2.25 |
| $F_a$ | 360 LBS |

Soils:
*(Per soil Report provided by Dr. Jonathan Dungca, January 2013)*

| | |
|---|---|
| Bearing Pressure | 5000 psf |

Materials:

| | |
|---|---|
| Bamboo | Full Culm |
| Species | Guadua Angustifolia |
| Average Diameter | 3 ½" - 4" |
| | |
| Concrete | |
| Compressive strength | 2000 psi |
| Reinforcing steel | #3 bar |
| | |
| Anchor Bolts | Steel |
| Nominal Diameter | 3/8" |

## DESIGN LOAD CALCULATIONS

The design loads for the structure were determined using *ASCE/SEI 7-10*. In this section, all references will refer to tables in *ASCE/SEI 7-10* unless noted otherwise.

The design loads calculated are specifically for the proposed structure and the proposed site location of the Cagayan Valley Region in the Philippines.

The loads considered in the design were dead loads, live loads, flood loads, seismic loads and wind loads.

Static loads due to snow, ice and rain were neglected because the pitch of the roof prevents the accumulation of snow, ice and rain on the roof.

### Gravity Loads

**Dead Load**

The dead load was calculated based on the total weight of the bamboo used in the design.

The proposed structure required approximately 2500 LF of bamboo. For design purposes the typical cross-section of the bamboo was assumed to have an outer diameter of 4" and an inner diameter of 3.75". This resulted in a bamboo cross-sectional area of 0.0106 $ft^2$.

The average density of guadua bamboo is 600 $kg/m^3$ (Schroder 2013). This is equivalent to 37.5 $lb/ft^3$.

The total weight of the structure is equal to

$$W := \rho \cdot A \cdot L = 994\,lb$$

where

*W = total weight of the structure*
*ρ = material density*
*A = cross-sectional area*
*L = length of material*

Given that the floor plan of the structure is 21' by 28', the total area of the structure is 588 $ft^2$. This translates to a structure dead load of 1.7 psf.

To account for the added weight of mortar and anchor bolts in the connections and any components and cladding that may be added to the structure, the dead load for design was assumed to be 25 psf and the roof dead load is assumed to be 10 psf.

**Live Load**

Since the proposed structure is a single-family residence, the live load was taken as 40 psf and the roof live load was taken as 20 psf (*Table 4-1).*

## Lateral Loads

**Flood Load**
The Cagayan Valley Region was defined as a non-coastal A-Zone. The Association of Structural Engineers of the Philippines (ASEP) advises the use of a design flood elevation (DFE) of 1.0ft and a base flood elevation (BFE) of 2.0ft.

Due to the base flood elevation height, the concrete columns will be the only part of the structural system that will resist flood loads.

The local still water depth was taken as 2.0ft to be conservative. The breaking wave height is calculated as

$$H_b = 0.78d_s = 1.56\,ft \qquad \text{(Eq 5.4-2)}$$

where
*$H_b$ = breaking wave height*
*$d_s$ = local still water depth*

Since the concrete columns have a square cross-section, the coefficient of drag for the breaking waves was taken as 2.25 (Section 5.4.4.1). The flood load was calculated as

$$F_D = 0.5\gamma_w C_D D H_b^2 = 360\,lbs \qquad \text{(Eq 5.4-4)}$$

where
*$F_a$ = net force on the top of each column*
*$\gamma_w$ = unit weight of water*
*$C_D$ = coefficient of drag of breaking wave*
*$H_b$ = breaking wave height*
*$D$ = column diameter*

**Seismic Load**
Based on the soil profile provided by Dungca, the soil site class is D for the upper 10' of the profile and F at depths great than 10'. A shallow foundation is used in the design so site class D is used for the seismic load analysis.

The proposed use of the structure is single-family residential; therefore the building is risk category II which corresponds to an importance factor of 1.0 (Table 1.5-2).

The structure's lateral force resisting system is bamboo concentrically-braced frames. ASCE/SEI 7-10 does not provide prescriptive design for bamboo braced frames. To be conservative, a response modification coefficient, R, of 1.50 was used in this design. This was because 1.50 is the smallest R value listed in ASCE/SEI 7-10.

The spectral response acceleration parameters for the Cagayan Valley Region of the Philippines were derived from the region's peak ground acceleration (PGA) using Lubkowski & Aluisi's method (2012). The PGA was taken as 0.43g (Torregosa et al, 2001).

$$\frac{S_s}{PGA} = 0.3386PGA + 2.1696$$ (Lubkowski & Aluisi, 2012)

$$\frac{S_1}{PGA} = 0.5776PGA + 0.5967$$ (Lubkowski & Aluisi, 2012)

The following calculations were used to determine that the Seismic Design Category (SDC) and the building period.

*Short Period*

| | | |
|---|---|---|
| $S_s$ (g) | 1.00 | |
| $F_a$ | 1.1 | (Table 11.4-1) |

$S_{MS} = F_a S_S$ (11.4-1)

| | | |
|---|---|---|
| $S_{MS}$ (g) | 1.10 | |

$S_{DS} = \frac{2}{3} S_{MS}$ (11.4-3)

| | | |
|---|---|---|
| $S_{DS}$ (g) | 0.73 | |
| SDC | D | (Table 11.6-1) |

*1-Second Period*

| | | |
|---|---|---|
| $S_1$ (g) | 0.36 | |
| $F_v$ | 1.8 | (Table 11.4-2) |

$S_{M1} = F_v S_1$ (11.4-2)

| | | |
|---|---|---|
| $S_{M1}$ (g) | 0.65 | |

$S_{DS} = \frac{2}{3} S_{MS}$ (11.4-4)

| | | |
|---|---|---|
| $S_{D1}$ (g) | 0.44 | |
| SDC | D | (Table 11.6-1) |

*Building Period*

| | | |
|---|---|---|
| $h_n$ (ft) | 14 | |
| $C_t$ | 0.02 | (Table 12.8-2) |
| x | 0.75 | (Table 12.8-2) |

$T = C_t h_n^x$ (12.8-7)

| | |
|---|---|
| T (s) | 0.14 |

The equivalent lateral force procedure was used to determine the base shear.

*Equivalent Lateral Force Procedure*
*Seismic Response Coefficient*

$C_s = \frac{S_{DS}}{\left(\frac{R}{I_e}\right)}$ (12.8-2)

Cs = 0.48671

The long-period transition period, $T_L$, is unknown for the site.
It is reasonable to assume that $T<T_L$

$$C_s \le \frac{S_{D1}}{T\left(\frac{R}{I_e}\right)}$$ for $T \le T_L$ (12.8-3)

Cs ≤ 2.00828

$$C_s \ge 0.044 S_{DS} I_e \ge 0.01$$ (12.8-5)

Cs ≥ 0.03212

*Seismic Dead Load*

| | |
|---|---|
| D (psf) | 30 |
| $D_r$ (psf) | 15 |
| A ($ft^2$) | 588 |
| $W_D$ (kips) | 17.64 |
| $W_{Dr}$ (kips) | 8.82 |
| W (kips) | 26.46 |

*Base Shear*

$$V = C_s W$$

| | |
|---|---|
| V (kips) | 12.88 |

*Seismic Load Effect*

$$E = E_v + E_h$$ (12.4-1)

$$E_h = \rho V$$ (12.4-3)

$$E_v = 0.2 S_{DS} W$$ (12.4-3)

| | |
|---|---|
| ρ | 1.3 |
| $E_h$ (kips) | 16.7417 |
| $E_v$ (kips) | 3.86347 |

| | |
|---|---|
| E (kips) | 20.6052 |

Symbol definitions:

*$R$ = response modification coefficient*
*$I_e$ = importance factor*
*PGA = peak ground acceleration*
*$S_s$ = spectral response acceleration parameter at short periods*
*$S_1$ = spectral response acceleration parameter at a period of 1 second*
*$F_a$ = short-period site coefficient*
*$F_v$ = long-period site coefficient*
*$S_{MS}$ = spectral response acceleration parameter at short periods, adjusted for site parameters*
*$S_{M1}$ = design, spectral response acceleration parameter at a period of 1 second, adjusted for site parameters*
*$S_{DS}$ = design, spectral response acceleration parameter at short periods*
*$S_{D1}$ = design, spectral response acceleration parameter at a period of 1 second*
*SDC = seismic design category*

**Wind Load**

*Site Parameters*

Flat Topography

Location: Cagayan Valley Region, Philippines

*Structure Parameters*

| | | |
|---|---|---|
| Risk Category II | | *(Table 1.5-1)* |
| Low-Rise Building | | *(Section 26.2)* |
| Enclosed Building | | *(Section 26.2)* |
| Regular-Shaped | | *(Section 26.2)* |
| Light-Frame Construction | | |
| Mean roof height, h (ft) | 13.2 | |
| Roof slope (degrees) | 16 | |
| Basic Wind Speed, V (mph) | 125 | *(Per ASEP)* |
| $K_d$ | 0.85 | *(Table 26.6-1)* |
| Surface roughness | B | *(Section 26.7.2)* |
| Exposure category | B | *(Section 26.7.3)* |
| $K_{zt}$ | 1 | *(Section 26.8.2)* |
| G | 0.85 | *(Section 26.9.1)* |
| Gcpi (±) | 0.18 | *(Table 26.11-1)* |

**MWFRS: Directional Procedure**

Maximum height is less than 15 ft; therefore, Kz equals Kh which equals 0.57 *(Table 27.3-1)*

This is an enclosed building; therefore, qi equals qh at all surfaces. *(Section 27.4-1)*

| | | |
|---|---|---|
| $K_h$ | 0.57 | *(Table 27.3-1)* |
| $q_h$ (psf) | 19.38 | *(Equation 27.3-1)* |

$$q_h = 0.00256 K_h K_{zt} K_d V^2 \quad (psf) \qquad (27.3\text{-}1)$$

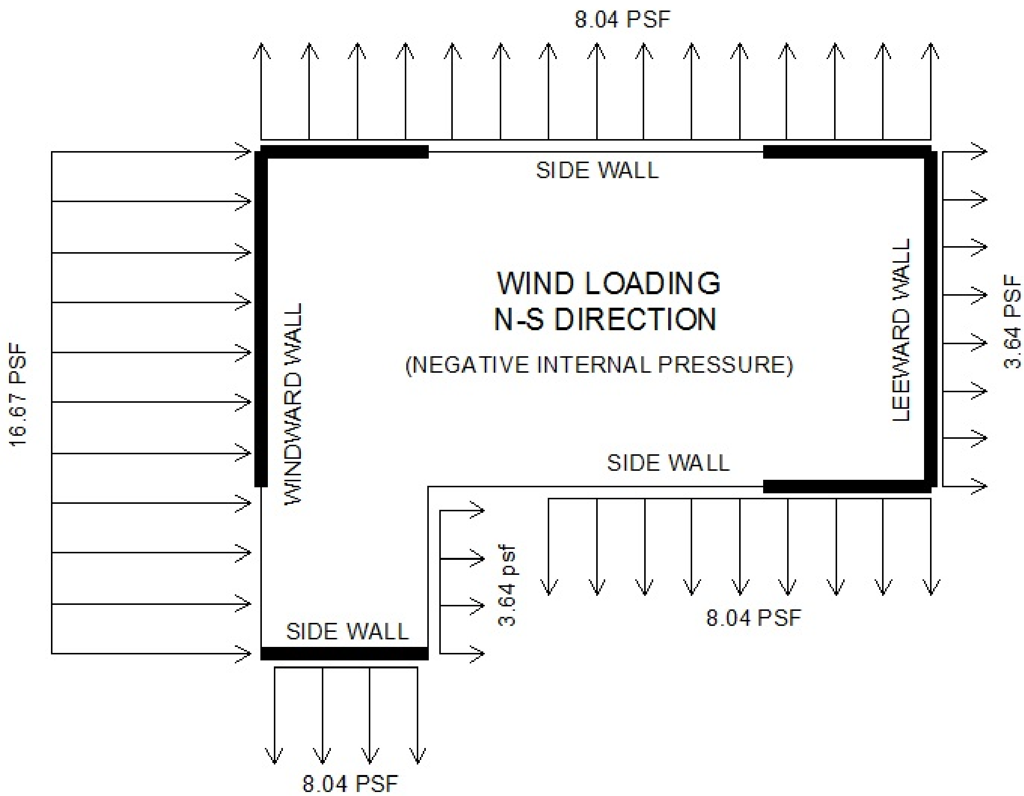
| **Design Parameters** | |
|---|---|
| **V (mph)** | 125 |
| **$K_d$** | 0.85 |
| **$K_{zt}$** | 1 |
| **G** | 0.85 |
| **($GC_{pi}$) (±)** | 0.18 |
| **$K_h$** | 0.57 |
| **$q_h$ (psf)** | 19.38 |

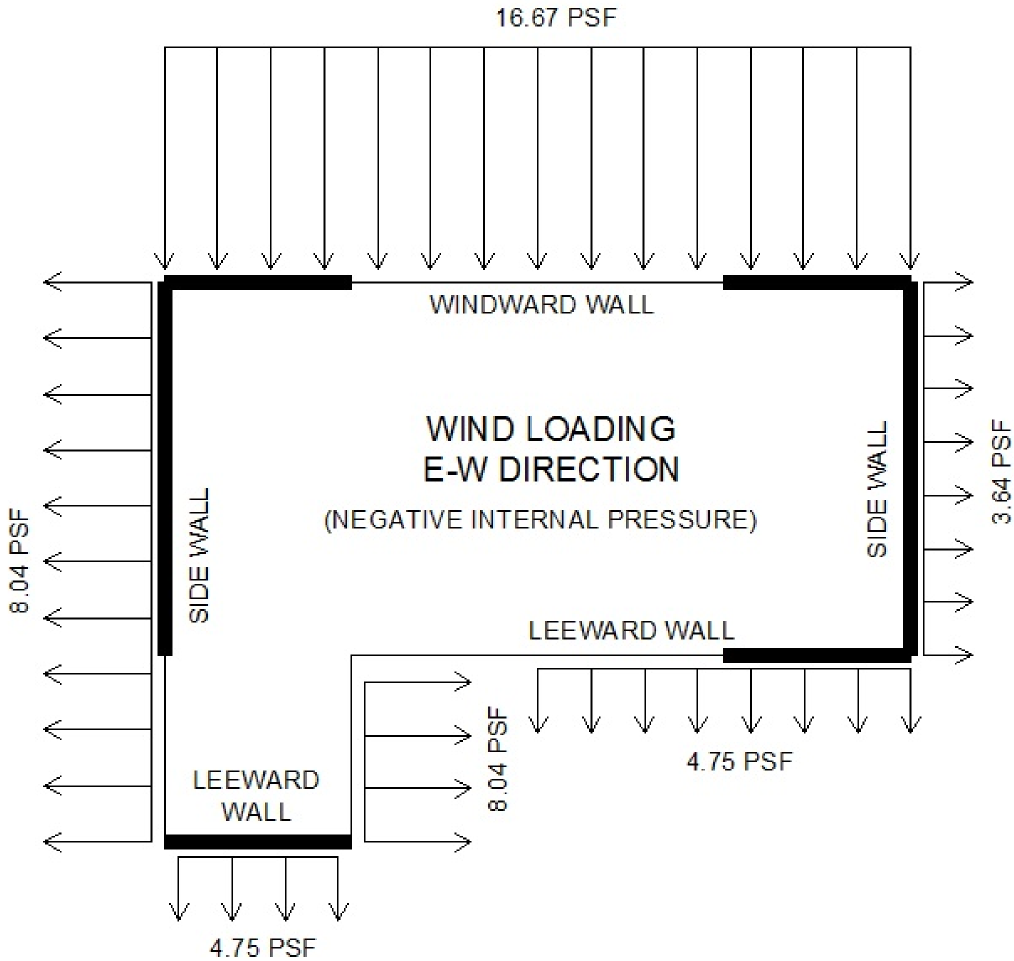
| **Walls: Wind in N-S Direction (when L=28' & B=21')** | | | | | | |
|---|---|---|---|---|---|---|
| **Location** | **$C_p$** | **$qGC_p$ (psf)** | **$q_h$(Gcpi) (psf)** | **$q_h(GC_{pi})$ (psf)** | **$p_1$ (psf)** | **$p_2$ (psf)** |
| **Windward Wall** | 0.8 | 13.18 | 3.49 | -3.49 | 9.69 | 16.67 |
| **Leeward Wall** | -0.4 | -7.13 | 3.49 | -3.49 | -10.62 | -3.64 |
| **Side Wall** | -0.7 | -11.53 | 3.49 | -3.49 | -15.02 | -8.04 |

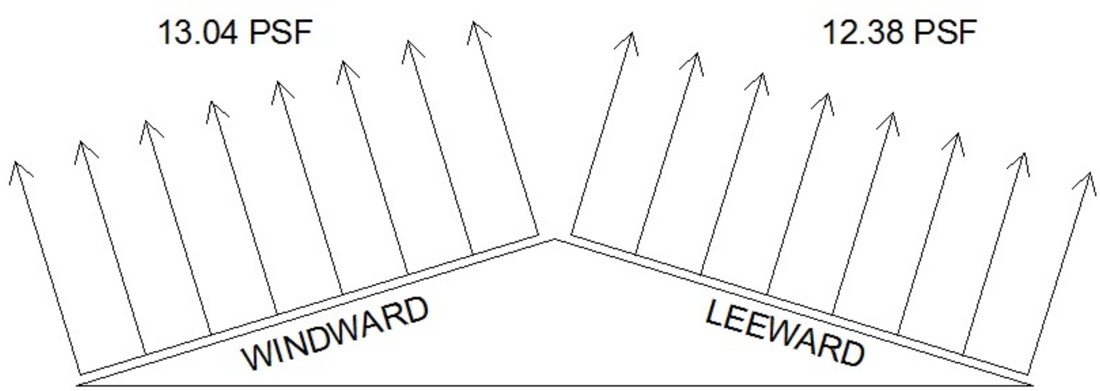
| **Roof: Wind in N-S Direction (when L=28')** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Location** | | **$C_p$** | **$qGC_p$ (psf)** | **$q_h$(Gcpi) (psf)** | **$q_h(GC_{pi})$ (psf)** | **$p_1$ (psf)** | **$p_2$ (psf)** |
| **Windward Roof** | *Inward* | -0.108 | -1.78 | 3.49 | -3.49 | -5.27 | 1.71 |
| | *Outward* | -0.580 | -9.55 | 3.49 | -3.49 | -13.04 | -6.07 |
| | *Overhang* | 0.800 | 13.18 | 3.49 | -3.49 | 9.69 | 16.67 |
| **Leeward Roof** | *Outward* | -0.540 | -8.90 | 3.49 | -3.49 | -12.38 | -5.41 |

| **Walls: Wind in E-W Direction (when L=21' & B=28')** | | | | | | |
|---|---|---|---|---|---|---|
| **Location** | **$C_p$** | **$qGC_p$ (psf)** | **$q_h$(Gcpi) (psf)** | **$q_h(GC_{pi})$ (psf)** | **$p_1$ (psf)** | **$p_2$ (psf)** |
| **Windward Wall** | 0.8 | 13.18 | 3.49 | -3.49 | 9.69 | 16.67 |
| **Leeward Wall** | -0.5 | -8.24 | 3.49 | -3.49 | -11.72 | -4.75 |
| **Side Wall** | -0.7 | -11.53 | 3.49 | -3.49 | -15.02 | -8.04 |

| Roof: Wind in E-W Direction (when L=21') | | | | | | |
|---|---|---|---|---|---|---|
| **Horiz Distance from Windward Edge (ft)** | **$C_p$** | **$q_hGC_p$ (psf)** | **$q_h$(Gcpi) (psf)** | **$q_h(GC_{pi})$ (psf)** | **$p_1$ (psf)** | **$p_2$ (psf)** |
| 0' to 6.6' | -0.90 | -14.83 | 3.49 | -3.49 | -18.31 | -11.34 |
| | -0.18 | -2.97 | 3.49 | -3.49 | -6.45 | 0.52 |
| 6.6' to 13.2' | -0.90 | -14.83 | 3.49 | -3.49 | -18.31 | -11.34 |
| | -0.18 | -2.97 | 3.49 | -3.49 | -6.45 | 0.52 |
| 13.2' to 21.0' | -0.50 | -8.24 | 3.49 | -3.49 | -11.72 | -4.75 |
| | -0.18 | -2.97 | 3.49 | -3.49 | -6.45 | 0.52 |
| Overhang | 0.80 | 13.18 | 3.49 | -3.49 | 9.69 | 16.67 |




16.67 PSF
WINDWARD WALL
WIND LOADING
E-W DIRECTION
(NEGATIVE INTERNAL PRESSURE)
SIDE WALL
8.04 PSF
SIDE WALL
3.64 PSF
LEEWARD WALL
8.04 PSF
4.75 PSF
LEEWARD
WALL
4.75 PSF


13.04 PSF
12.38 PSF
WINDWARD
LEEWARD

**FOUNDATION DESIGN**

**Column Design Loads**

ASD load combinations were used for the foundation design. The following was used to determine the loads that would be applied to each column.

| Column Gravity Load Tributary Areas | |
|---|---|
| $A_a$ (sf) | 12.25 |
| $A_b$ (sf) | 24.50 |
| $A_c$ (sf) | 49.00 |

| | |
|---|---|
| D (psf) | 25.00 |
| L (psf) | 40.00 |
| $L_r$ (psf) | 20.00 |
| $E_{N2}$ (kips) | 13.70 |
| $E_{N4}$ (kips) | 6.90 |
| $E_S$ (kips) | 10.30 |
| $E_{E\text{-}W}$ (kips) | 10.30 |
| $W_{E\text{-}w}$ (kips) | 3.08 |
| $W_{N\text{-}S(1AB)}$ (kips) | 2.31 |
| $W_{N\text{-}S(2DE)}$ (kips) | 3.08 |
| $W_{N\text{-}S(4AB)}$ (kips) | 1.54 |
| $W_{N\text{-}S(4DE)}$ (kips) | 2.31 |
| $F_a$ (kips) | 0.36 |

| ASD Load Combinations (Gravity Loads) | |
|---|---|
| $ASD_1$ (psf) | 25.0 |
| $ASD_2$ (psf) | 65.0 |
| $ASD_3$ (psf) | 45.0 |
| $ASD_4$ (psf) | 56.5 |

| Column Point Loads (Controled by Dead & Live) | |
|---|---|
| $P_{A\text{-}4}$ (kips) | 0.8 |
| $P_{B\text{-}1}$ (kips) | 1.6 |
| $P_{B\text{-}2}$ (kips) | 3.2 |
| $P_{B\text{-}3}$ (kips) | 3.2 |

| | |
|---|---|
| $P_{C-1}$ (kips) | 1.6 |
| $P_{C-2}$ (kips) | 3.2 |
| $P_{C-3}$ (kips) | 3.2 |
| $P_{C-4}$ (kips) | 1.6 |
| $P_{D-1}$ (kips) | 1.6 |
| $P_{D-2}$ (kips) | 3.2 |
| $P_{D-3}$ (kips) | 3.2 |
| $P_{E-1}$ (kips) | 0.8 |

| Column Point Loads (Wind, N-S direction) | | | |
|---|---|---|---|
| | $ASD_5$ | $ASD_{6a}$ | $ASD_7$ |
| $P_{A-1}$ (kips) | 2.0 | 2.2 | 1.8 |
| $P_{B-4}$ (kips) | 1.8 | 2.7 | 1.6 |
| $P_{D-4}$ (kips) | 2.3 | 3.0 | 2.0 |
| $P_{E-2}$ (kips) | 2.7 | 3.4 | 2.5 |

| Column Point Loads (Earthquake, N-S direction) | | | |
|---|---|---|---|
| | $ASD_5$ | $ASD_{6b}$ | $ASD_7$ |
| $P_{A-1}$ (kips) | 7.5 | 6.1 | 7.4 |
| $P_{B-4}$ (kips) | 5.4 | 5.0 | 5.0 |
| $P_{D-4}$ (kips) | 7.8 | 6.8 | 7.4 |
| $P_{E-2}$ (kips) | 10.2 | 8.5 | 9.8 |

| Column Point Loads (Wind, E-W direction) | | | |
|---|---|---|---|
| | $ASD_5$ | $ASD_{6a}$ | $ASD_7$ |
| $P_{A-2}$ (kips) | 2.7 | 3.4 | 2.5 |
| $P_{A-3}$ (kips) | 2.7 | 3.4 | 2.5 |
| $P_{E-3}$ (kips) | 2.7 | 3.4 | 2.5 |
| $P_{E-4}$ (kips) | 2.7 | 3.4 | 2.5 |

| Column Point Loads (Earthquake, E-W direction) | | | |
|---|---|---|---|
| | $ASD_5$ | $ASD_{6b}$ | $ASD_7$ |
| $P_{A-2}$ (kips) | 7.8 | 6.8 | 7.6 |
| $P_{A-3}$ (kips) | 7.8 | 6.8 | 7.6 |
| $P_{E-3}$ (kips) | 7.8 | 6.8 | 7.6 |
| $P_{E-4}$ (kips) | 7.5 | 6.1 | 7.4 |

**Bearing Capacity**

Vesic's equation was used to calculate bearing pressure given the following values:

| Vesic Computation | |
|---|---|
| Nc | 46.12 |
| sc | 1.72 |
| dc | 1.27 |
| Nq | 33.30 |
| sq | 1.70 |
| dq | 1.17 |
| N gamma | 48.03 |
| s gamma | 0.60 |
| d gamma | 1.00 |
| B/L | 1 |
| k | 0.666667 |

This resulted in an ultimate bearing capacity of 5000 psf.

The allowable bearing capacity was calculated by

$$P_u := 3.2\text{kip}$$
$$B := 1.5\text{ft}$$
$$q_a := \frac{P_u}{B^2} = 1422 \cdot \text{psf}$$

**Shear Capacity and Liquefaction Risk Analysis**

| Soil Properties | |
|---|---|
| $\gamma$ (lb/ft$^3$) | 120.0 |
| $N_{60}$ | 21.0 |
| $\phi$ (degrees) | 35.0 |
| $\beta$ (degrees) | 0.0 |
| $K_p$ | 3.7 |
| H (ft) | 6.6 |
| **Footing Dimensions** | |
| $D_f$ (ft) | 1.0 |
| B (ft) | 1.5 |
| **Design Loads** | |
| $P_{D+L}$ (kips) | 3.2 |
| $V_{max}$ (kips) | 3.4 |
| W (kips) | 24.5 |

## Passive Pressure

$$P_p = \frac{\gamma H^2 K_p}{2}$$

When β = 0,

$$K_p = \tan^2\left(45 + \frac{\phi}{2}\right)$$

| | |
|---|---|
| $P_p$ (kips) | 9.6 |

## Sliding Friction

$$P_{sf} = P_{D+L}\,\mathrm{B}\tan\phi$$

| | |
|---|---|
| $P_{sf}$ (kips) | 3.4 |

## Factor of Safety due to Shear

| | |
|---|---|
| $V_s$ (kips) | 3.0 |

$$FS = \frac{P_p + P_{sf}}{V_s}$$

| | |
|---|---|
| **FS** | **3.8** |

## Cyclic Stress Ratio (CSR)

$$\tau_{av} = 0.65\frac{\gamma H}{g}a_{max}r_d$$

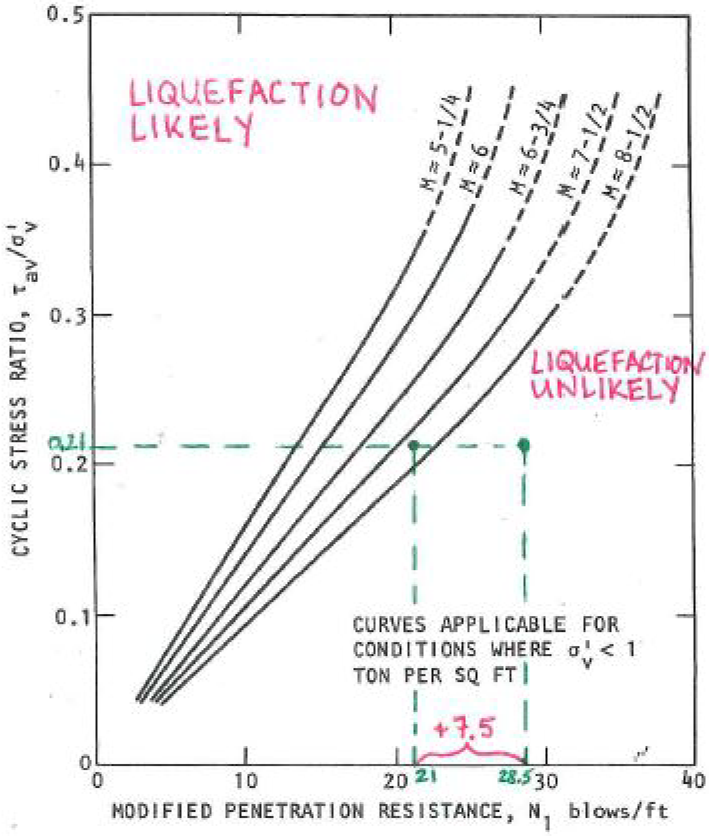
| | |
|---|---|
| $(S_a)_{max}$ (g) | 0.140 |
| $(a_{max})_{mean}$ (g) | 0.041 |
| $\tau_{av}$ (psf) | 21.2 |

Shallow foundation so assume $r_d = 1$

$$\sigma'_v = z(\gamma - \gamma_w)$$

$$CSR = \frac{\tau_{av}}{\sigma'_v}$$

| | |
|---|---|
| z (ft) | 3.3 |
| $\sigma'_v$ (psf) | 190.1 |
| CSR | 0.112 |

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## Concrete Column Analysis and Reinforcement Sizing

### Footing Dimensions

$f'_c := 2000 \frac{lb}{in^2}$

$B := 18in$

$h := 12in$

$c := 12in$

$d := 6in$

(minimum acceptable d according to ACI 318-11)

$b_0 := c + d = 18 \cdot in$

### Two-Way Shear

$$V_{uc} := \left(\frac{P_u}{4}\right) \cdot \left[\frac{B^2 - (b_0)^2}{B^2}\right] = 0 \frac{s^2}{m} \cdot kip$$

$V_{nc} := 4 \cdot b_0 d \cdot \sqrt{f'_c \cdot (psi)} = 6.169 \frac{s}{m^{0.5}} \cdot kip$

$\phi V_{nc} := 0.85 \cdot V_{nc} = 5.244 \frac{s}{m^{0.5}} \cdot kip$

$T := d + 4in = 10 \cdot in$

Therefore,

$T := 12in$

(minimum acceptable T according to ACI 318-11)

**Required Reinforcement**

$f_y := 60000 \frac{lb}{in^2}$

$\phi := 0.9$

$l := \frac{(B - c)}{2} = 3 \cdot in$

$M_{uc} := \frac{\left(P_u \cdot l^2\right)}{2B} = 1.05 \times 10^3 \cdot lb \cdot in$

$A_{req} := \frac{\left(f'_c \cdot B\right)}{1.176 \cdot f_y} \cdot \left(d - \sqrt{d^2 - \frac{2.353 \cdot M_{uc}}{0.9 \cdot f'_c \cdot B}}\right) = 3.244 \times 10^{-3} \cdot in^2$

$A_{min} := 0.002 \cdot B \cdot h = 0.432 \cdot in^2$

*Use 4 #3 bars each way*

$A_s := 0.44in^2$

$d_b := 0.375in$

$\rho := \frac{A_s}{B \cdot d} = 4.074 \times 10^{-3}$

**Development Length**

$l_d := \frac{1}{50} \cdot \frac{f_y}{\sqrt{f'_c \cdot lb}} \cdot \left(d_b\right)^2 = 3.773 \cdot in$

**Strap Footing Sizing and Analysis**

Section Properties

$f'_c := 2000psi$

$E_c := 57000\sqrt{f'_c} \cdot \left(\sqrt{psi}\right) = 2549 \cdot ksi$

$f_y := 60ksi$

$E_s := 29000ksi$

$n := \frac{E_s}{E_c} = 11.376$

$l := 7ft$

$h_{min} := \frac{l}{16} = 5.25 \cdot in$

*(ACI 318-11 Table 9.5a)*

$h := 12in$

$b := 12in$

$d := h - 3in = 9 \cdot in$

$M_{max} := 5.6kip \cdot in$

*(From SAP Analysis)*

$\phi := 0.65$

$A_{calc} := \frac{M_{max}}{0.81 \cdot f_y \cdot b} = 9.602 \times 10^{-3} \cdot in^2$

*<u>Choose 1 No. 3 bar</u>*

$A_s := 0.11 \cdot in^2$

$M_u := \phi \cdot A_s \cdot f_y \cdot b \cdot \left(1 - \frac{0.59 \cdot A_s \cdot f_y}{b \cdot d \cdot f'_c}\right) = 50.552 \cdot kip \cdot in$

Un-cracked Stresses

$A_{tot} := h \cdot b + (n - 1) \cdot A_s = 145.141 \cdot in^2$

$y_{bar} := \frac{\left[\frac{b \cdot h^2}{2} + (n - 1)A_s \cdot d\right]}{A_{tot}} = 6.024 \cdot in$

$I_{gtr} := \left(\frac{1}{12}\right) b \cdot h^3 + b \cdot h \cdot \left(y_{bar} - \frac{h}{2}\right)^2 + (n - 1) \cdot A_s \cdot \left(d - y_{bar}\right)^2 = 1.738 \times 10^3 \cdot in^4$

$f_r := 7.5 \cdot \sqrt{f'_c} \cdot \left(\sqrt{psi}\right) = 335.41 \cdot psi$

$M_{cr} := \frac{\left(\phi \cdot f_r \cdot I_{gtr}\right)}{h - y_{bar}} = 63.408 \cdot kip \cdot in$

The strap footings were analyzed in SAP 2000. The straps were assumed to behave as fixed beams. The following data was obtained from the program.

**TABLE: Joint Reactions**

| Joint | OutputCase | CaseType | F1 | F2 | F3 | M1 | M2 | M3 |
|---|---|---|---|---|---|---|---|---|
| Text | Text | Text | Kip | Kip | Kip | Kip-in | Kip-in | Kip-in |
| 1 | DEAD | LinStatic | 0.731 | 0.719 | 0.079 | 0 | 0 | 0 |
| 2 | DEAD | LinStatic | -0.174 | -0.171 | 5.494 | 0 | 0 | 0 |
| 3 | DEAD | LinStatic | 0.688 | -0.732 | 0.079 | 0 | 0 | 0 |
| 4 | DEAD | LinStatic | -0.163 | 0.174 | 3.594 | 0 | 0 | 0 |
| 5 | DEAD | LinStatic | -0.027 | -0.016 | 0.079 | 0 | 0 | 0 |
| 6 | DEAD | LinStatic | 0.006343 | 0.003836 | 3.594 | 0 | 0 | 0 |
| 7 | DEAD | LinStatic | 0.027 | 0.015 | 0.079 | 0 | 0 | 0 |
| 8 | DEAD | LinStatic | -0.006478 | -0.003674 | 3.594 | 0 | 0 | 0 |
| 9 | DEAD | LinStatic | -0.704 | 0.702 | 0.079 | 0 | 0 | 0 |
| 10 | DEAD | LinStatic | 0.167 | -0.167 | 5.794 | 0 | 0 | 0 |
| 11 | DEAD | LinStatic | -0.704 | -0.702 | 0.079 | 0 | 0 | 0 |
| 12 | DEAD | LinStatic | 0.167 | 0.167 | 4.294 | 0 | 0 | 0 |
| 13 | DEAD | LinStatic | 0.704 | -0.704 | 0.079 | 0 | 0 | 0 |
| 14 | DEAD | LinStatic | -0.167 | 0.167 | 1.194 | 0 | 0 | 0 |
| 15 | DEAD | LinStatic | -0.026 | -0.016 | 0.079 | 0 | 0 | 0 |
| 16 | DEAD | LinStatic | 0.006238 | 0.00377 | 5.794 | 0 | 0 | 0 |
| 17 | DEAD | LinStatic | -4.578E-07 | -0.0007143 | 0.079 | 0 | 0 | 0 |
| 18 | DEAD | LinStatic | 1.088E-07 | 0.0001697 | 1.994 | 0 | 0 | 0 |
| 19 | DEAD | LinStatic | 0.026 | -0.016 | 0.079 | 0 | 0 | 0 |
| 20 | DEAD | LinStatic | -0.006241 | 0.003764 | 5.794 | 0 | 0 | 0 |
| 21 | DEAD | LinStatic | 0.016 | 0.027 | 0.079 | 0 | 0 | 0 |
| 22 | DEAD | LinStatic | -0.003856 | -0.006485 | 4.594 | 0 | 0 | 0 |
| 23 | DEAD | LinStatic | 0.017 | -0.028 | 0.079 | 0 | 0 | 0 |
| 24 | DEAD | LinStatic | -0.003999 | 0.006618 | 4.594 | 0 | 0 | 0 |
| 25 | DEAD | LinStatic | 0 | 0 | 0.472 | 0 | 0 | 0 |
| 26 | DEAD | LinStatic | 0 | 0 | 3.672 | 0 | 0 | 0 |
| 27 | DEAD | LinStatic | 0 | 0 | 0.472 | 0 | 0 | 0 |
| 28 | DEAD | LinStatic | 0 | 0 | 3.672 | 0 | 0 | 0 |
| 29 | DEAD | LinStatic | 0 | 0 | 0.472 | 0 | 0 | 0 |
| 30 | DEAD | LinStatic | 0 | 0 | 3.672 | 0 | 0 | 0 |
| 31 | DEAD | LinStatic | 0 | 0 | 0.472 | 0 | 0 | 0 |
| 32 | DEAD | LinStatic | 0 | 0 | 2.072 | 0 | 0 | 0 |
| 33 | DEAD | LinStatic | 0 | 0 | 0.472 | 0 | 0 | 0 |
| 34 | DEAD | LinStatic | 0 | 0 | 2.072 | 0 | 0 | 0 |
| 35 | DEAD | LinStatic | -0.717 | 0.746 | 0.079 | 0 | 0 | 0 |
| 36 | DEAD | LinStatic | 0.17 | -0.177 | 1.994 | 0 | 0 | 0 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 37 | DEAD | LinStatic | -0.557 | -0.548 | 1.927 | 0 | 0 | 0 |
| 38 | DEAD | LinStatic | -0.013 | 0.021 | 1.957 | 0 | 0 | 0 |
| 39 | DEAD | LinStatic | -0.012 | -0.021 | 1.956 | 0 | 0 | 0 |
| 40 | DEAD | LinStatic | -0.536 | 0.536 | 1.913 | 0 | 0 | 0 |
| 41 | DEAD | LinStatic | 0.02 | 0.012 | 1.957 | 0 | 0 | 0 |
| 42 | DEAD | LinStatic | 0.000000349 | 0.0005446 | 1.941 | 0 | 0 | 0 |
| 43 | DEAD | LinStatic | -0.02 | 0.012 | 1.957 | 0 | 0 | 0 |
| 44 | DEAD | LinStatic | 0.537 | 0.536 | 1.913 | 0 | 0 | 0 |
| 45 | DEAD | LinStatic | 0.024 | -2.292E-07 | 1.972 | 0 | 0 | 0 |
| 46 | DEAD | LinStatic | 0.537 | -0.536 | 1.913 | 0 | 0 | 0 |
| 47 | DEAD | LinStatic | -0.021 | -0.012 | 1.957 | 0 | 0 | 0 |
| 48 | DEAD | LinStatic | 0.02 | 0.012 | 1.956 | 0 | 0 | 0 |
| 49 | DEAD | LinStatic | -0.525 | 0.558 | 1.928 | 0 | 0 | 0 |
| 50 | DEAD | LinStatic | 0.546 | -0.569 | 1.942 | 0 | 0 | 0 |
| 51 | DEAD | LinStatic | 0 | 0 | 0.472 | 0 | 0 | 0 |
| 52 | DEAD | LinStatic | 0 | 0 | 1.272 | 0 | 0 | 0 |
| 53 | DEAD | LinStatic | -0.032 | 3.006E-07 | 0.079 | 0 | 0 | 0 |

STRUCTURAL DESIGN

FLOOR SYSTEM

**Load Summary**

$D := 25psf$

$L := 40psf$

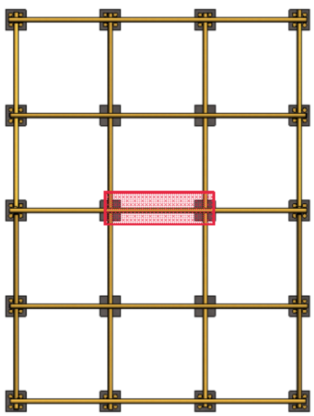
**Load Combinations**
**(ASD from ASCE 7-10)**

$\omega_1 := D = 25 \cdot psf$

$\omega_2 := D + L = 65 \cdot psf$

...

$\omega := \max(\omega_1, \omega_2) = 65 \cdot psf$



**Typical floor girder member**

**Material & Section Properties**

$E := 1797ksi$

$L := 7ft$

$F_t := 6.67ksi$

$d := 4in$

$I := 2 \cdot 6.25in^4$

$w_t := 7ft$

$w := \omega \cdot w_t = 455 \cdot plf$

**Check Max Deflection (Fixed-Fixed end condition)**

$\Delta_{max} := \frac{w \cdot L^4}{384 \cdot E \cdot I} = 0.219 \cdot in$

$\frac{L}{360} = 0.233 \cdot in$

(deflection limit for timber construction)

$Demand := \Delta_{max} = 0.219 \cdot in$

## Check Bending

$$M_{max} := \frac{w \cdot L^2}{12} = 22.295 \cdot kip \cdot in$$

$$M_{demand} := M_{max}$$

$$M_c := \frac{F_t \cdot L \cdot d}{12 \cdot I} = 1.413 \times 10^9 \frac{1}{m^5} \cdot kip \cdot in$$

$$\frac{M_{demand}}{M_c} = 1.578 \times 10^{-8} m^5$$

**Typical Floor Framing Member**

**Material & Section Properties**

(Spacing @ 8in o.c.)

$E = 1797 \cdot ksi$

$L = 7 \cdot ft$

$I := 6.25in^4$

$w_t := 8in$

$w := \omega \cdot w_t = 43.333 \cdot plf$

**Check Max Deflection (Pin-Pin end condition)**

$$\Delta_{max} := \frac{5w \cdot L^4}{384 \cdot E \cdot I} = 0.208 \cdot in$$

$$\frac{L}{360} = 0.233 \cdot in$$

**(deflection limit for timber construction)**

$$L := \left( \frac{\Delta_{max} \cdot 384 \cdot E \cdot I}{5 \cdot w} \right)^{\frac{1}{4}} = 7 \cdot ft$$

***okay, because E is conservatively estimated**

## ROOF FRAMING

## Load Summary

$L_r := 20psf$

$D_r := 10psf$

$\omega := L_r + D_r = 30 \cdot psf$

## 7ft Span

$E = 1797 \cdot ksi$

$L := 7ft$

$I := 6.25in^4$

$w_t := 10in$

$w := w_t \cdot \omega = 25 \cdot plf$

**Deflection Check - Pin-pin end condition**

$$\Delta_{max} := \frac{5w \cdot L^4}{384 \cdot E \cdot I} = 0.12 \cdot in$$

$$\frac{L}{180} = 0.467 \cdot in$$

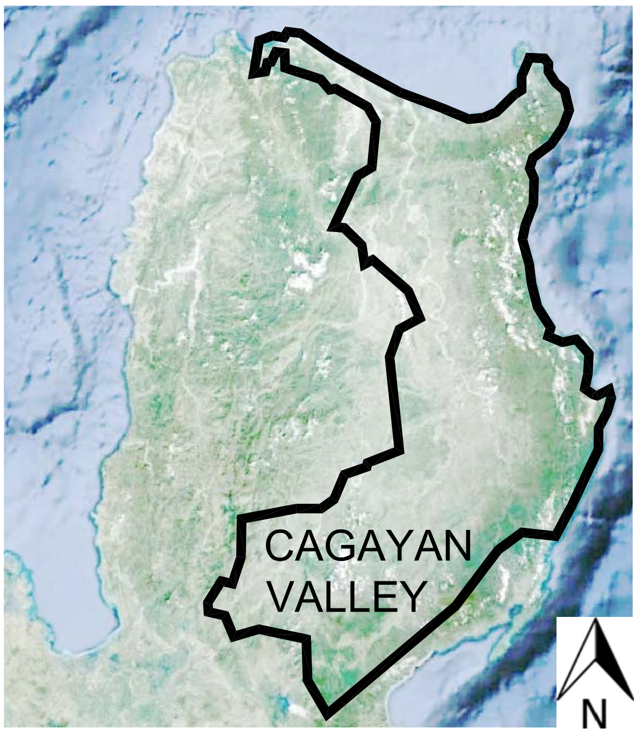
# APPENDIX E

# STRUCTURAL DRAWINGS AND DETAILS

# AN APPROACH TO LIGHT-FRAME DISASTER RELIEF HOUSING

*CAGAYAN VALLEY, PHILIPPINES*

## SITE MAP




## PAGE INDEX

T1 - TITLE SHEET

*FOUNDATION DRAWINGS*

G1 - FOOTING PLAN
G2 - TYPICAL FOOTING CROSS-SECTIONS
G3 - N-S (NORTH-SOUTH) FOOTING ELEVATIONS
G4 - E-W (EAST-WEST) FOOTING ELEVATIONS

*STRUCTURAL DRAWINGS*

S1 - FLOOR DIAPHRAGM
S2 - FLOOR FRAMING
S3 - ROOF PLAN
S4 - LATERAL FORCE-RESISTING SYSTEM
S5 - ELEVATIONS AT LINES A&E
S6 - ELEVATIONS AT LINES 1&3
S7 - ELEVATIONS AT LINE 4

*STANDARD DETAILS*

D1 - DETAILS 1 & 2
D2 - DETAILS 3,4,5 & 6

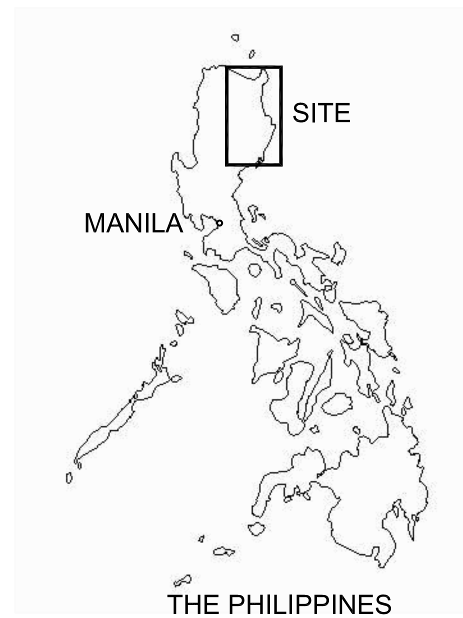
## GENERAL NOTES

1. ALL CONCRETE COLUMNS HAVE A SQUARE CROSS-SECTION OF 1.5' BY 1.5'
2. CONCRETE HAS A MINIMUM YIELD STRENGTH OF 2000 PSI
3. ALL BAMBOO MEMBERS ARE ASSUMED TO HAVE A NOMINAL DIAMETER OF 4"
4. ALL DIMENSIONS RELATED TO THE LOCATION OF BAMBOO MEMBERS REFER TO THE CENTERLINE OF THE MEMBER
5. ALL BAMBOO MEMBERS ARE ASSUMED TO BE PERFECTLY STRAIGHT
6. BAMBOO MEMBERS SHOULD BE INSPECTED PRIOR TO USE TO ENSURE THAT THOSE WITH EXTREME CURVATURES ARE AVOIDED
7. BAMBOO WITH SIGNIFICANT SPLITTING OR TAPERING SHOULD NOT BE USED

## LEGEND

BAMBOO MEMBER
CONCRETE
NATIVE SOIL
BRACE LOCATION
DETAIL NUMBER — 1
SHEET NUMBER — D1

## VICINITY MAP




AN APPROACH TO LIGHT-FRAME DISASTER RELIEF HOUSING

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TITLE SHEET

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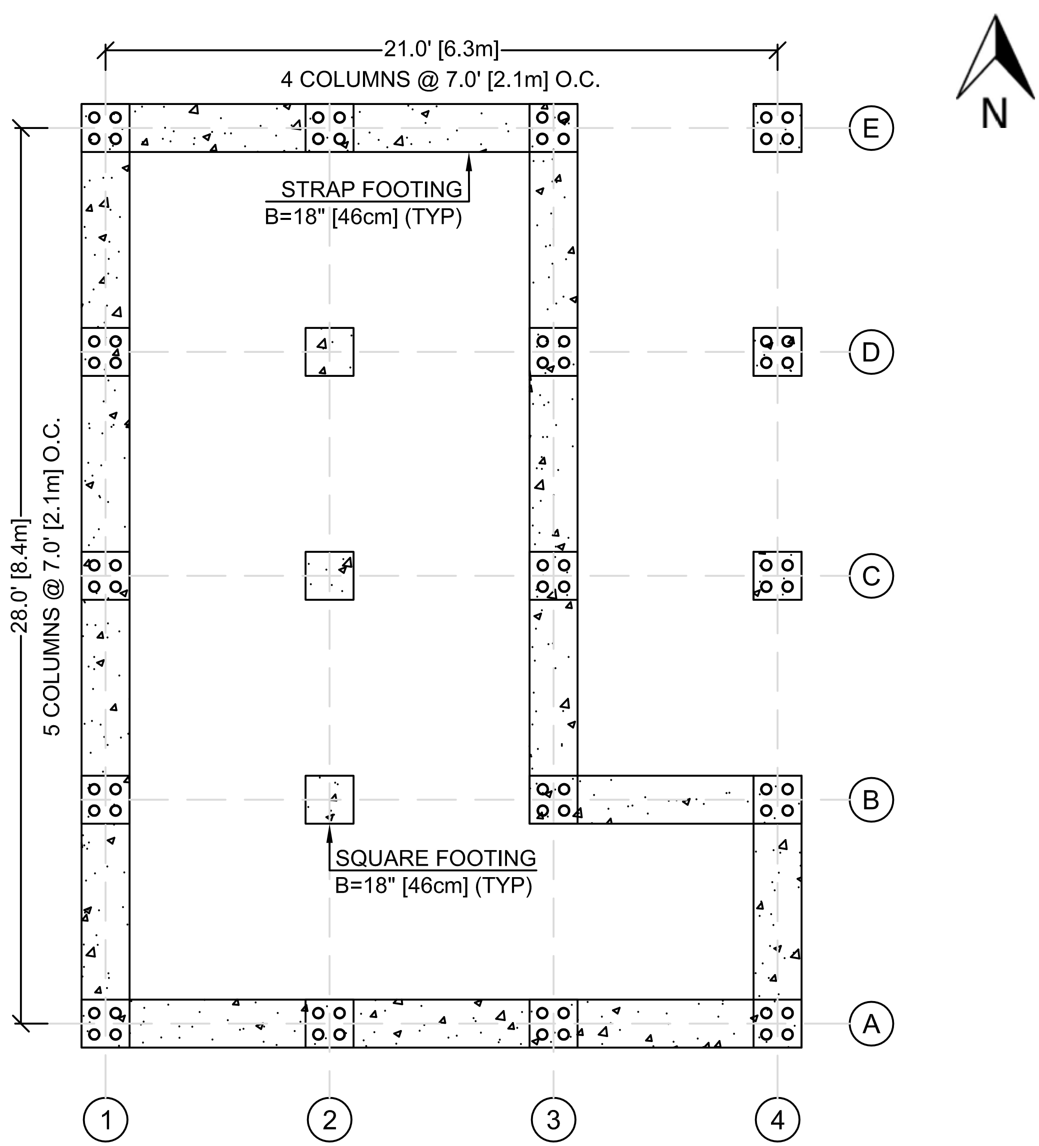
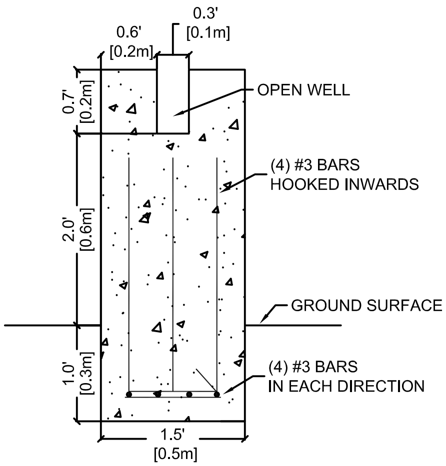
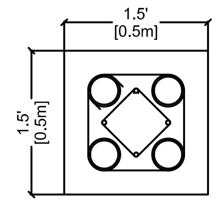
DATE: SPRING 2013
SCALE: NTS

T1



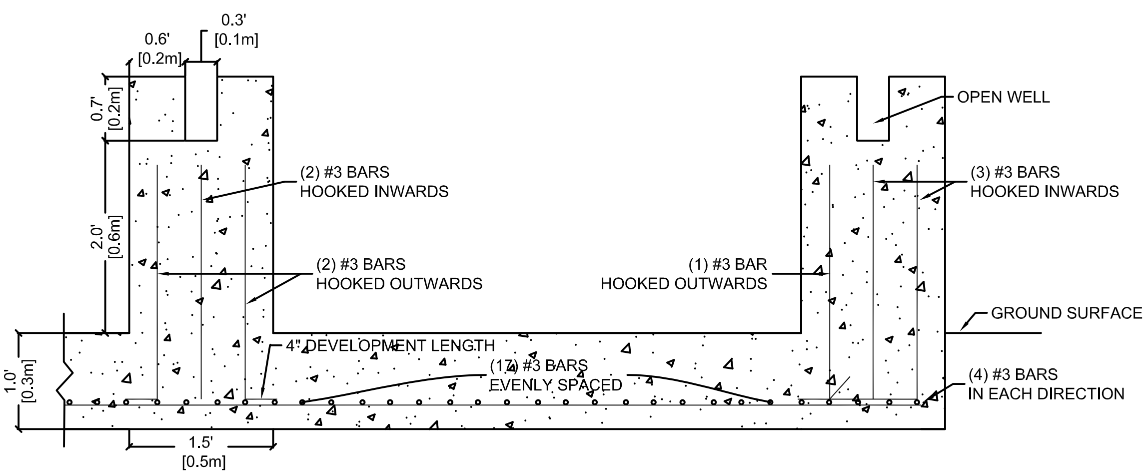

| | |
|---|---|
| AN APPROACH TO LIGHT-FRAME DISASTER RELIEF HOUSING | |
| Santa Clara University School of Engineering | FOOTING PLAN |
| | DESIGNED BY: HD & MC<br>REVIEWED BY: RS & SS<br>DATE: SPRING 2013<br>SCALE: 1 to 6 |
| | G1 |




NOTES:

1. ALL CONCRETE STRAPS HAVE A WIDTH OF 1.5'
2. REBAR HAS A MINIMUM COVER OF 3"
3. BAMBOO CULMS IMBEDDED IN CONCRETE HAVE A 3" COVER
4. BAMBOO CULMS HAVE A DEVELOPMENT LENGTH OF 3' INTO THE CONCRETE COLUMNS
5. REBAR IS NOT SHOWN TO SCALE
6. CONCRETE ON THE SIDES OF THE WELL IS NOT STRUCTURAL. THE LOADS ARE ASSUMED TO BE TRANSFERRED INTO THE MAIN CONCRETE COLUMN BY THE BAMBOO MEMBERS AND ANCHOR BOLTS




AN APPROACH TO LIGHT-FRAME DISASTER RELIEF HOUSING

TYPICAL FOOTING CROSS-SECTIONS

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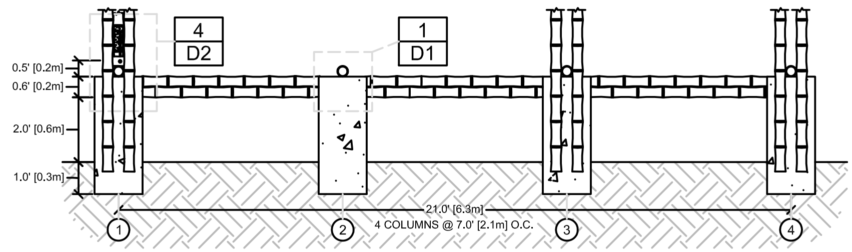
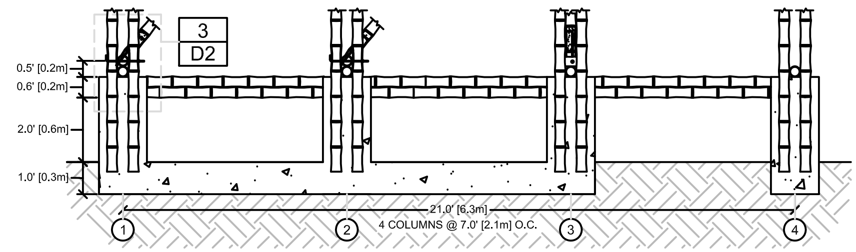
SCALE: 1 to 2

G2

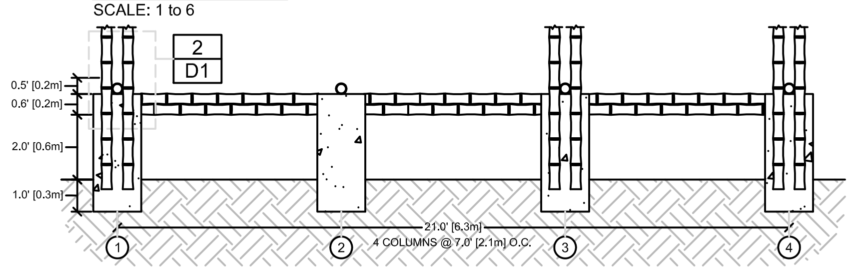
## LINE D ELEVATION
SCALE: 1 to 6



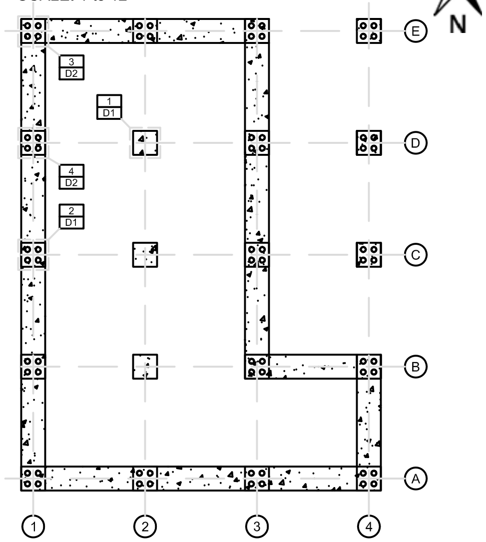

## LINE E ELEVATION
SCALE: 1 to 6



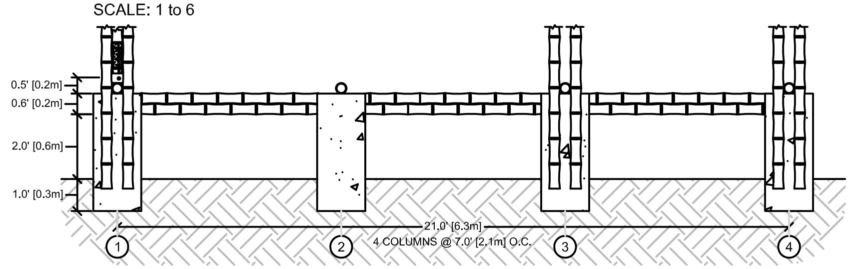

## LINE C ELEVATION
SCALE: 1 to 6



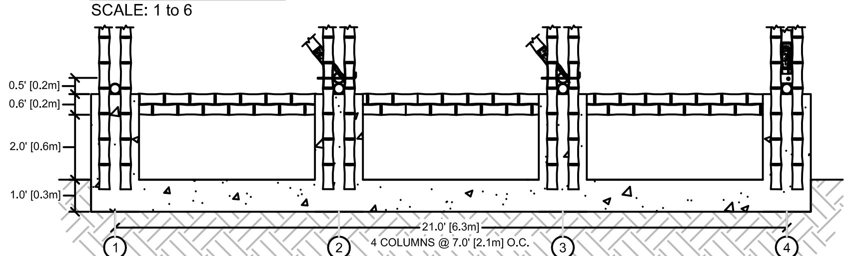

## FOOTING PLAN
SCALE: 1 to 12




## LINE B ELEVATION
SCALE: 1 to 6




## LINE A ELEVATION
SCALE: 1 to 6




NOTES:
1. ALL CONCRETE STRAPS HAVE A WIDTH OF 1.5'
2. BAMBOO CULMS IMBEDDED IN CONCRETE HAVE A 3" COVER
3. BAMBOO CULMS HAVE A DEVELOPMENT LENGTH OF 3' INTO THE CONCRETE COLUMNS

AN APPROACH TO LIGHT-FRAME DISASTER RELIEF HOUSING

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N-S FOOTING ELEVATIONS

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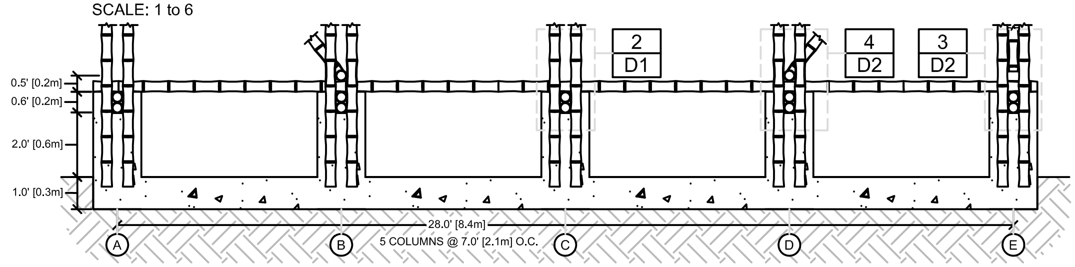
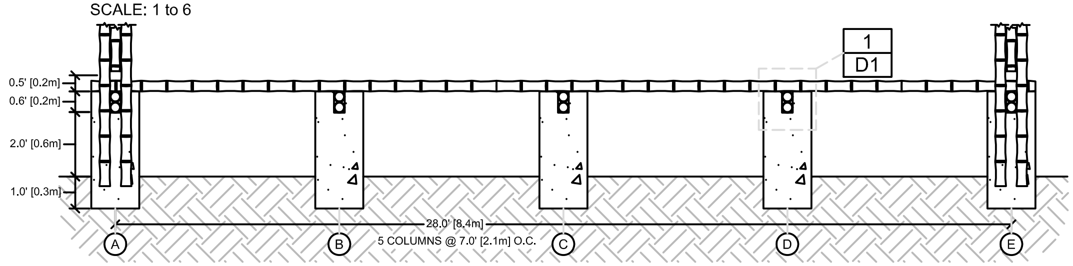
REVIEWED BY: RS & SS
DATE: SPRING 2013
SCALE: AS SHOWN

G3

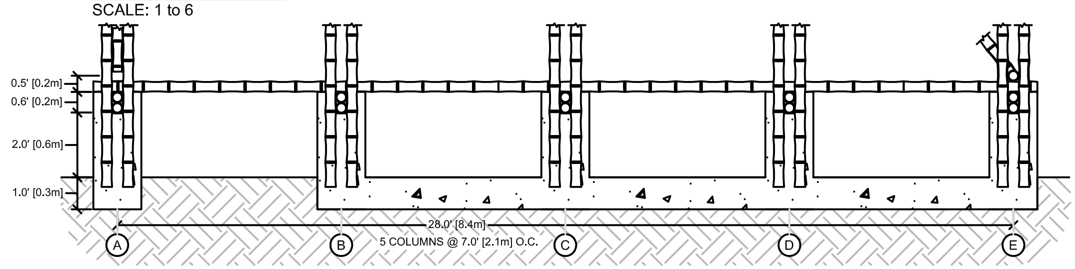
## LINE 1 ELEVATION
SCALE: 1 to 6



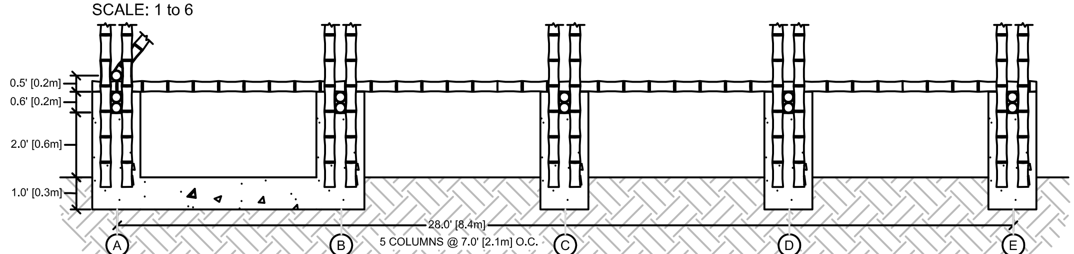

## LINE 2 ELEVATION
SCALE: 1 to 6



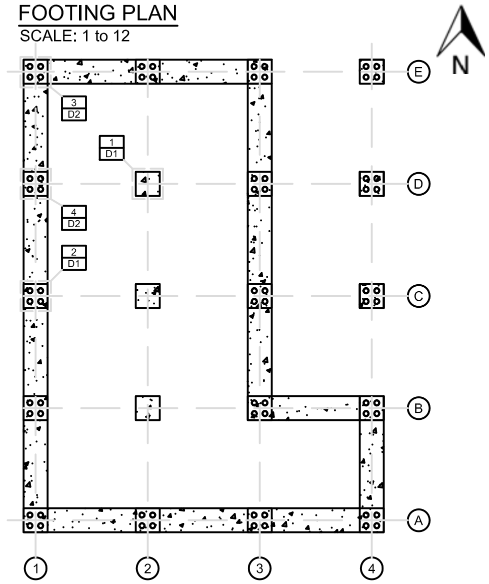

## LINE 3 ELEVATION
SCALE: 1 to 6




## LINE 4 ELEVATION
SCALE: 1 to 6




## FOOTING PLAN
SCALE: 1 to 12




NOTES:
1. ALL CONCRETE STRAPS HAVE A WIDTH OF 1.5'
2. BAMBOO CULMS IMBEDDED IN CONCRETE HAVE A 3" COVER
3. BAMBOO CULMS HAVE A DEVELOPMENT LENGTH OF 3' INTO THE CONCRETE COLUMNS

AN APPROACH TO LIGHT-FRAME DISASTER RELIEF HOUSING

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E-W FOOTING ELEVATIONS

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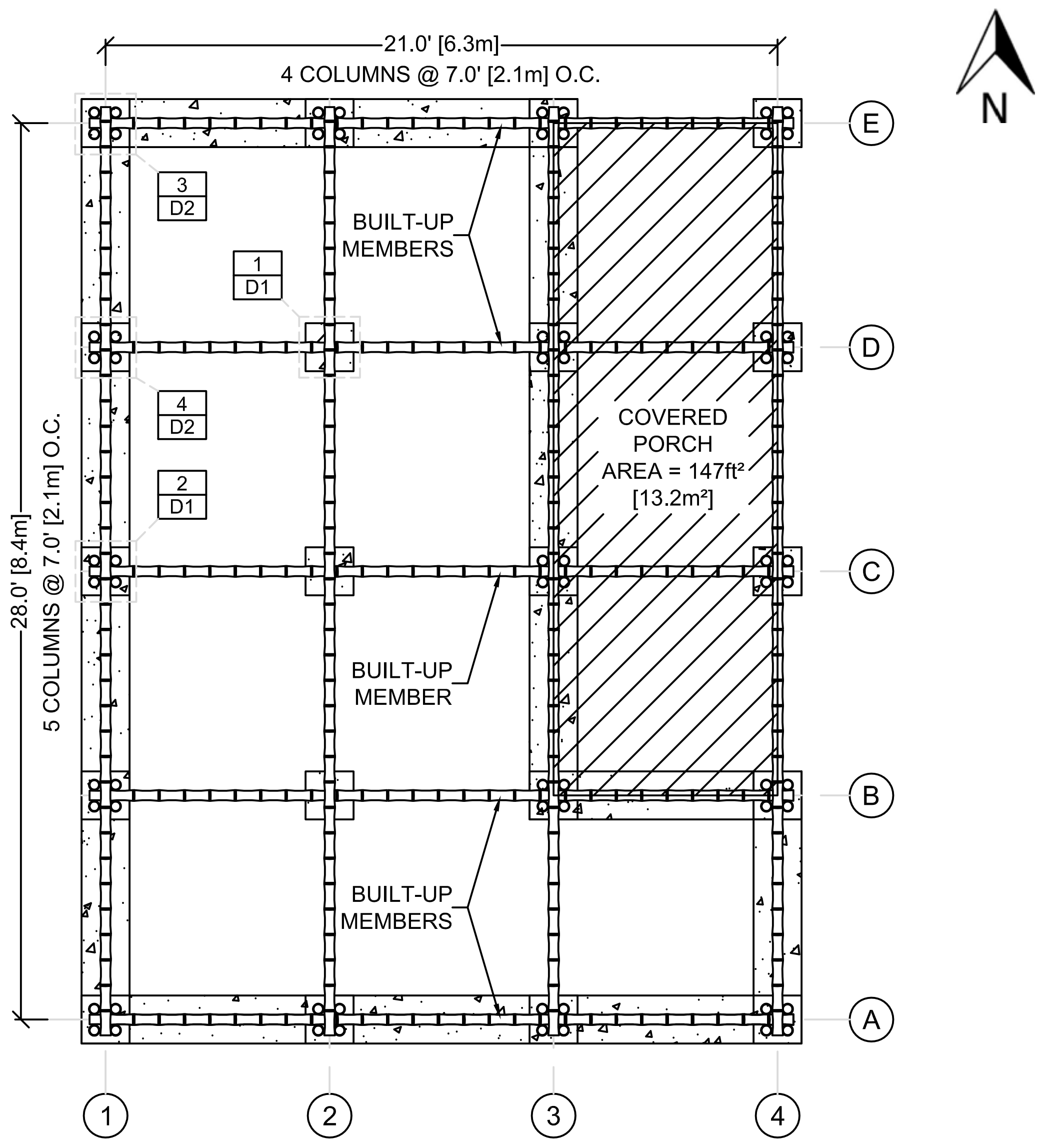
DATE: SPRING 2013
SCALE: AS SHOWN

G4




NOTES:

1. Detail 1 applies to joints at locations B2, C2 & D2
2. Detail 2 applies to joints at locations A1, B3, B4, C1, C3, C4, D3, D4 & E4
3. Detail 3 applies to joints at locations A2, A3, E1 & E2
4. Detail 4 applies to joints at locations A4, B1, D1 & E3

AN APPROACH TO LIGHT-FRAME DISASTER RELIEF HOUSING

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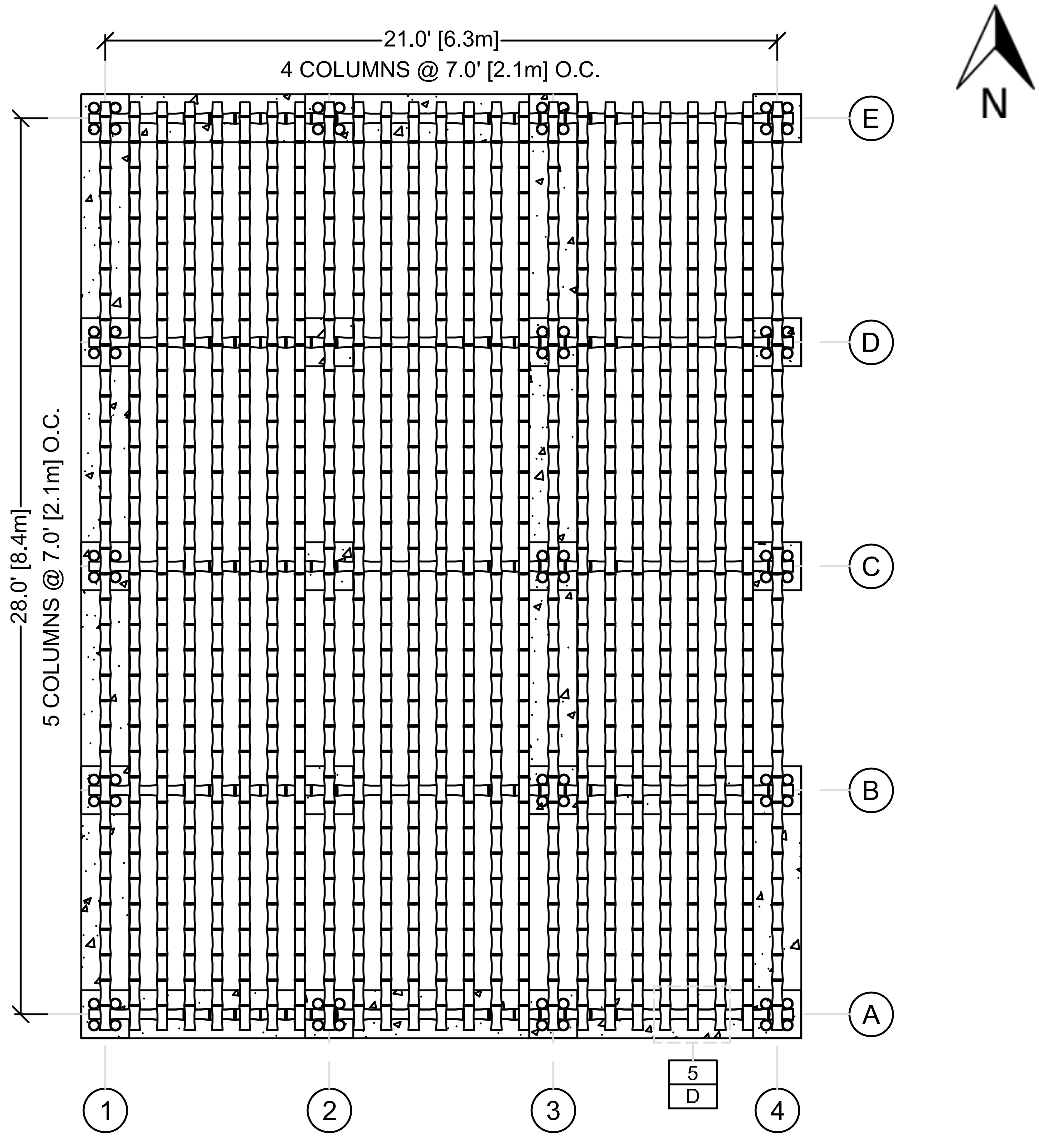
FLOOR DIAPHRAGM

DESIGNED BY: HD & MC
REVIEWED BY: RS & SS
DATE: SPRING 2013
SCALE: 1 to 6

S1




NOTES:

1. THERE ARE 7 FRAMING MEMBERS BETWEEN EACH COLUMN
2. FRAMING MEMBERS ARE EVENLY SPACED ON CENTER STARTING AND ENDING WITH A FRAMING MEMBER BETWEEN EACH COLUMN

AN APPROACH TO LIGHT-FRAME DISASTER RELIEF HOUSING

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FLOOR FRAMING

DESIGNED BY: HD & MC
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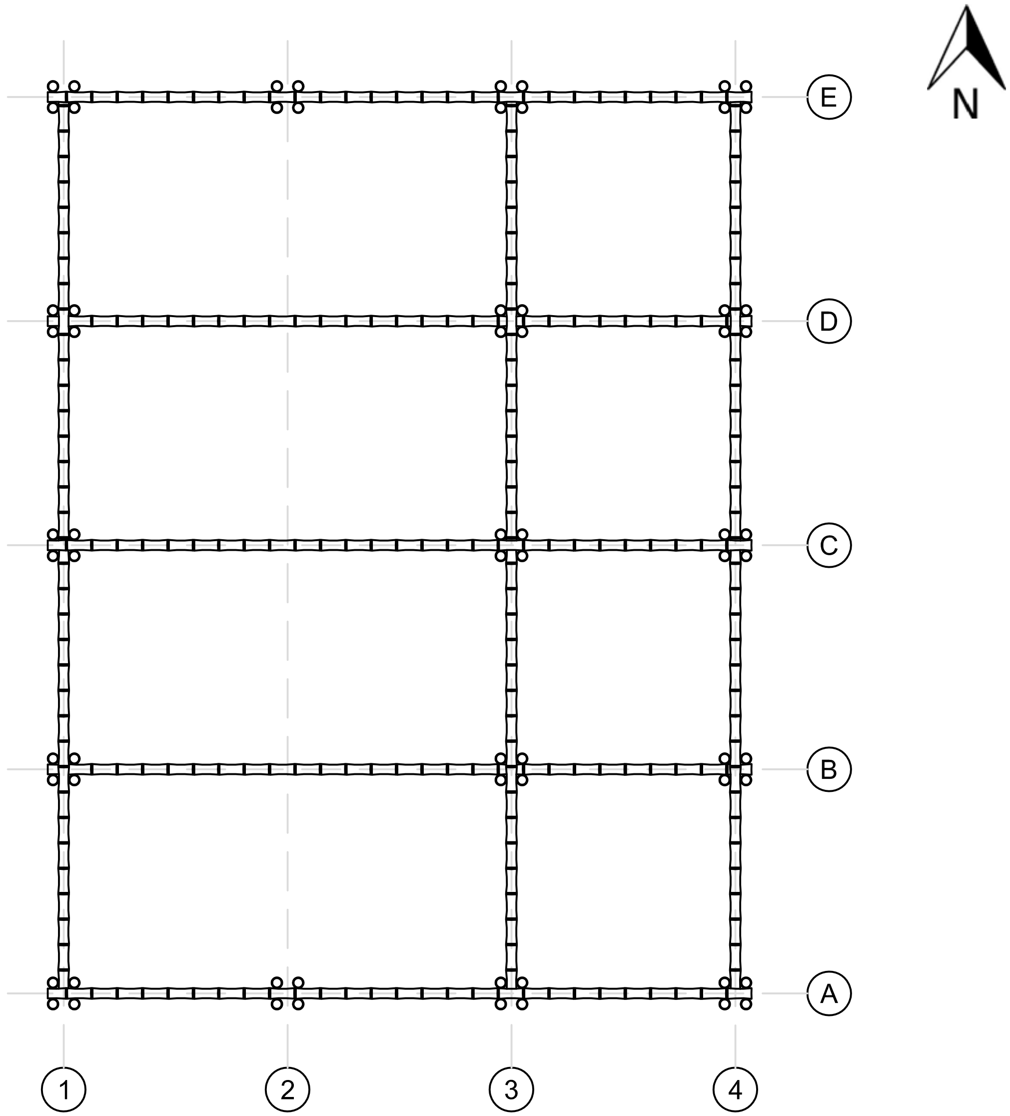
DATE: SPRING 2013
SCALE: 1 to 6

S2




AN APPROACH TO LIGHT-FRAME DISASTER RELIEF HOUSING

ROOF PLAN

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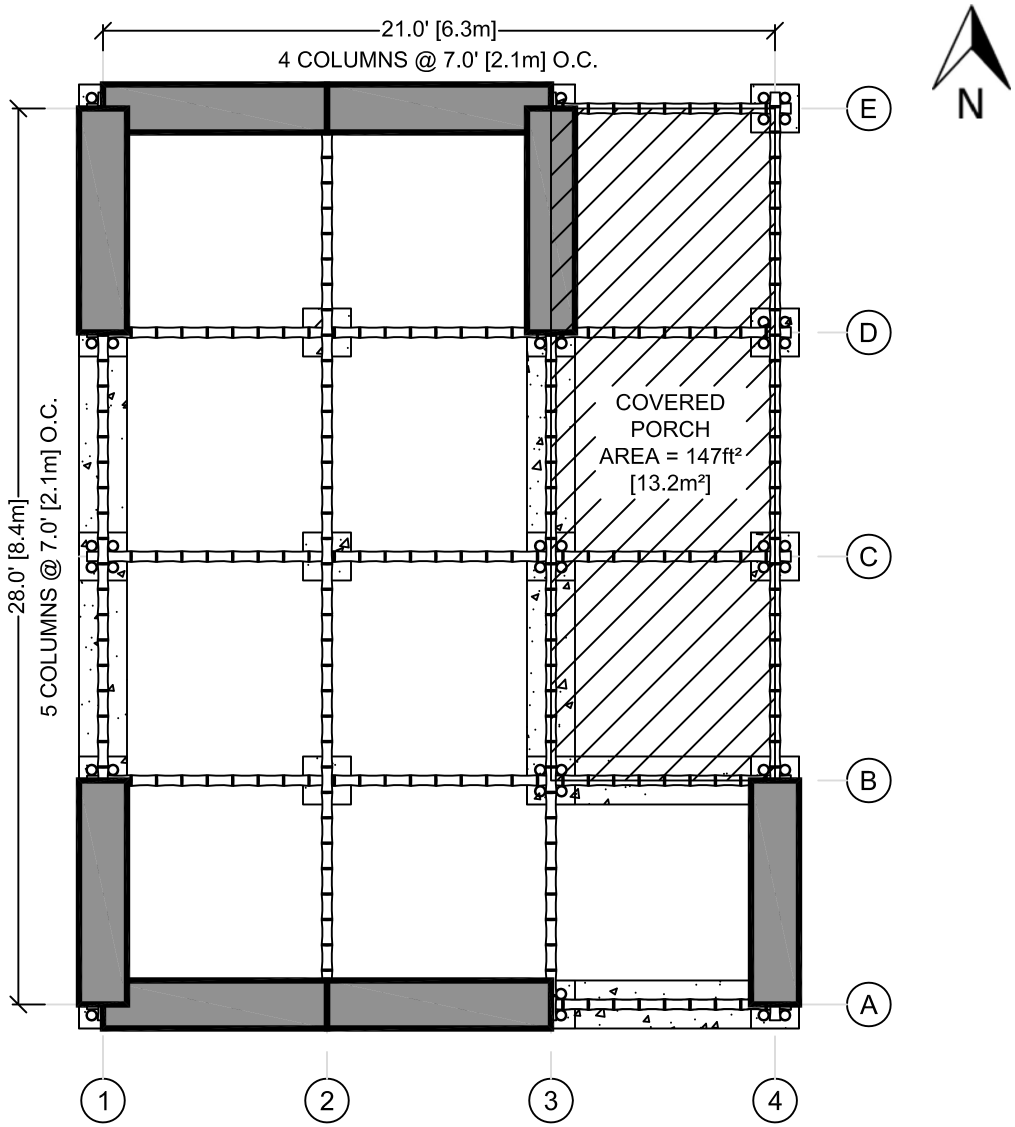
DATE: SPRING 2013
SCALE: 1 to 6

S3




AN APPROACH TO LIGHT-FRAME DISASTER RELIEF HOUSING

BRACE-FRAME LOCATIONS

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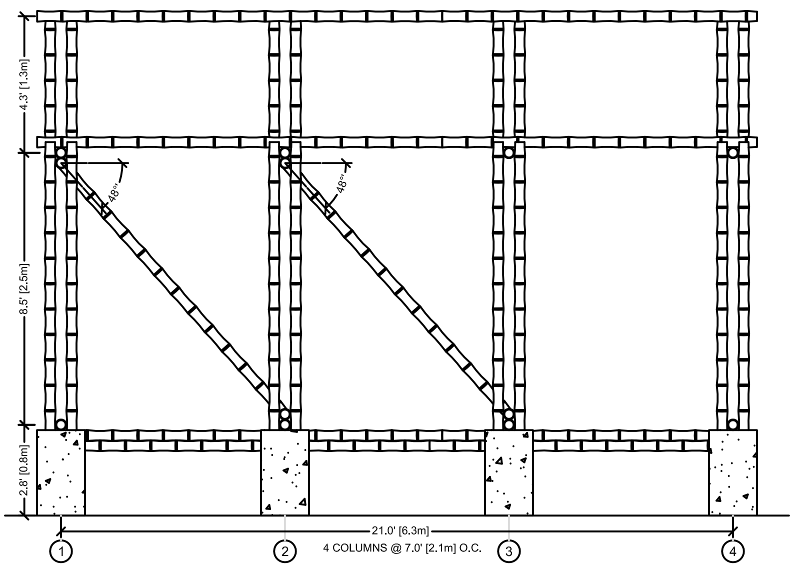
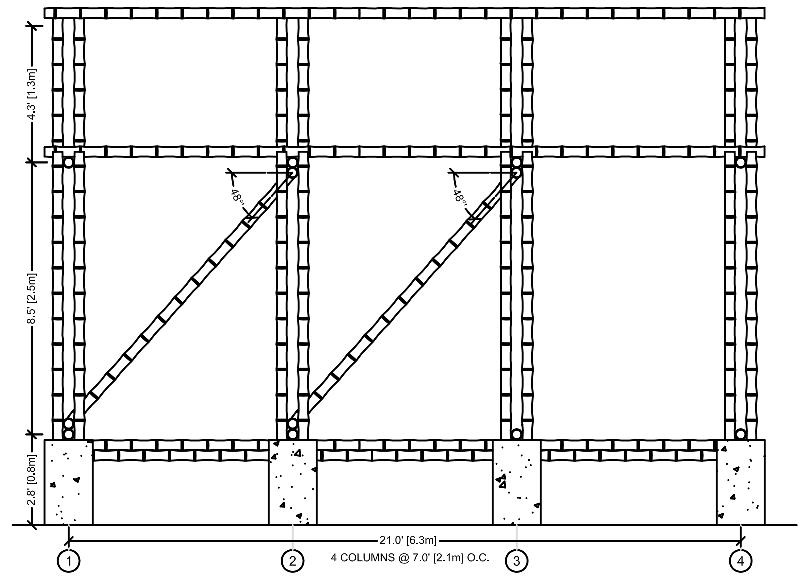
REVIEWED BY: RS & SS
DATE: SPRING 2013
SCALE: 1 to 6

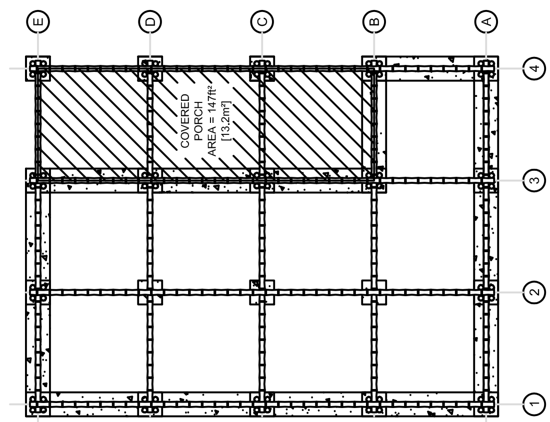
S4

## LINE A ELEVATION
SCALE: 1 to 6




## LINE E ELEVATION
SCALE: 1 to 6




## FLOOR DIAPHRAGM
SCALE: 1 to 12

NOTES:
1. SEE DETAIL 6 FOR BRACE FRAME CONNECTION

# AN APPROACH TO LIGHT-FRAME DISASTER RELIEF HOUSING

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## ELEVATIONS: LINES A & E

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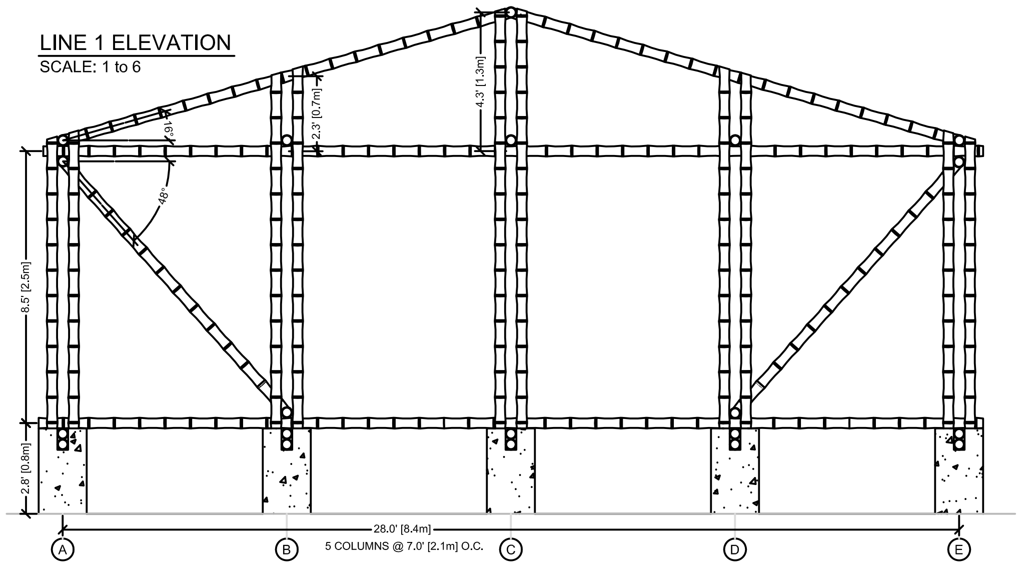
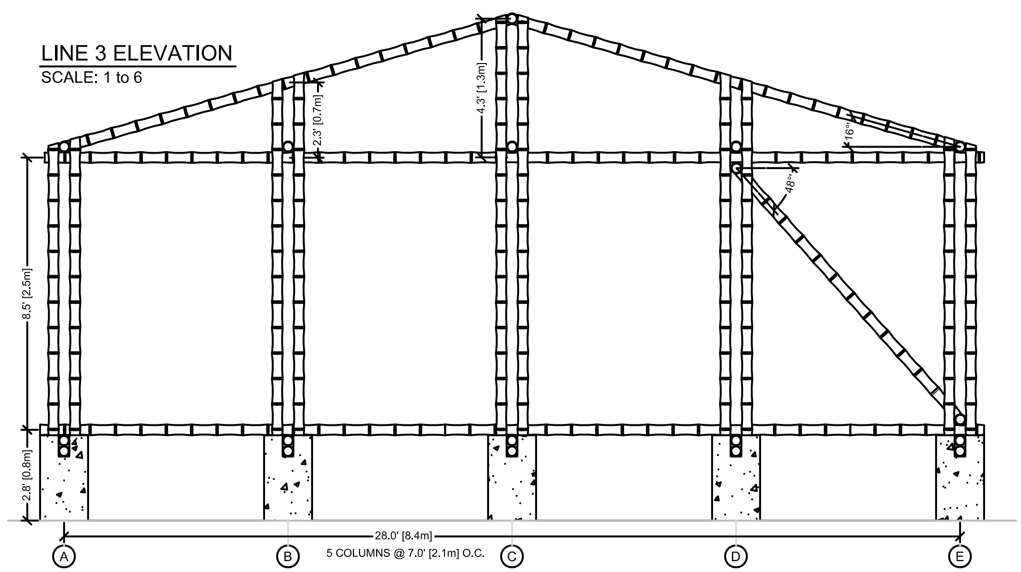
REVIEWED BY: RS & SS
DATE: SPRING 2013
SCALE: VARIES

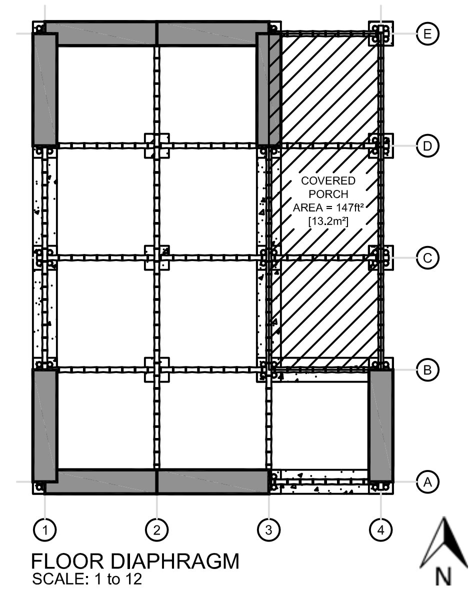
S5

LINE 1 ELEVATION
SCALE: 1 to 6




LINE 3 ELEVATION
SCALE: 1 to 6




FLOOR DIAPHRAGM
SCALE: 1 to 12

AN APPROACH TO LIGHT-FRAME DISASTER RELIEF HOUSING

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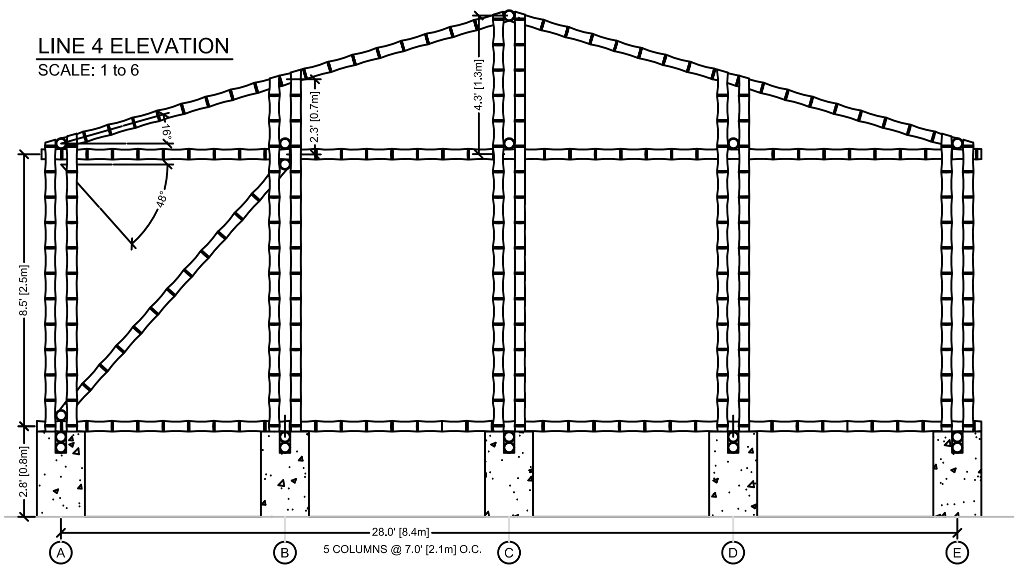
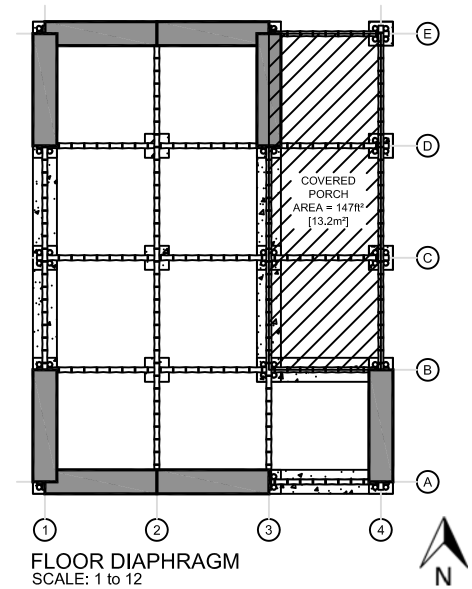
ELEVATIONS: LINES 1 & 3

DESIGNED BY: HD & MC
REVIEWED BY: RS & SS
DATE: SPRING 2013
SCALE: VARIES

S6




LINE 4 ELEVATION
SCALE: 1 to 6




FLOOR DIAPHRAGM
SCALE: 1 to 12

AN APPROACH TO LIGHT-FRAME DISASTER RELIEF HOUSING

ELEVATION: LINE 4

Santa Clara University
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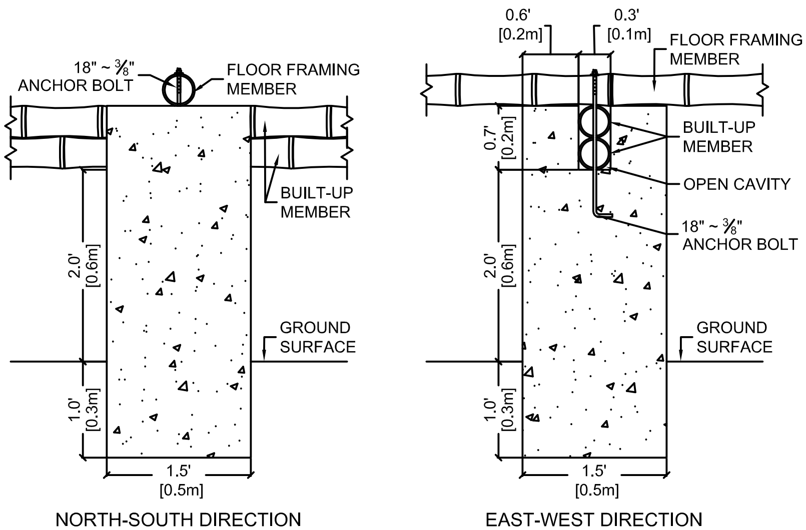
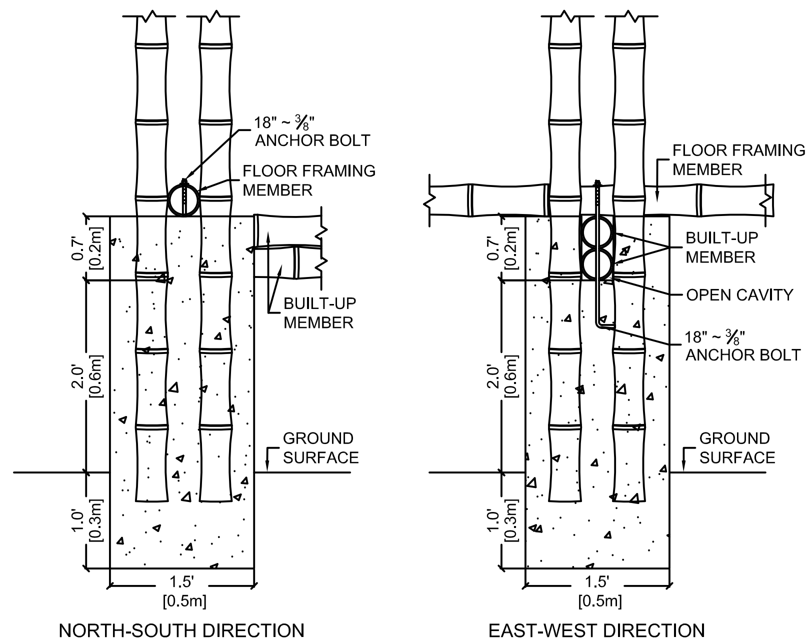
DESIGNED BY: HD & MC
REVIEWED BY: RS & SS
DATE: SPRING 2013
SCALE: VARIES

S7




| 1 | CONNECTION BETWEEN FOUNDATION AND FLOOR DIAPRAGHM |
|---|---|
| D1 | SCALE: 1 to 2 |




| 2 | CONNECTION BETWEEN FOUNDATION AND COLUMNS |
|---|---|
| D1 | SCALE: 1 to 2 |

AN APPROACH TO LIGHT-FRAME DISASTER RELIEF HOUSING

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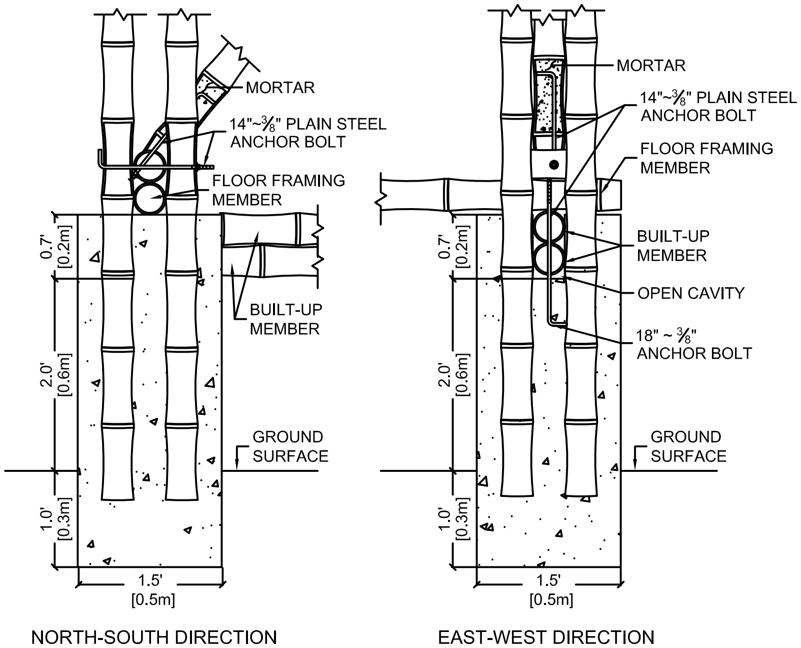
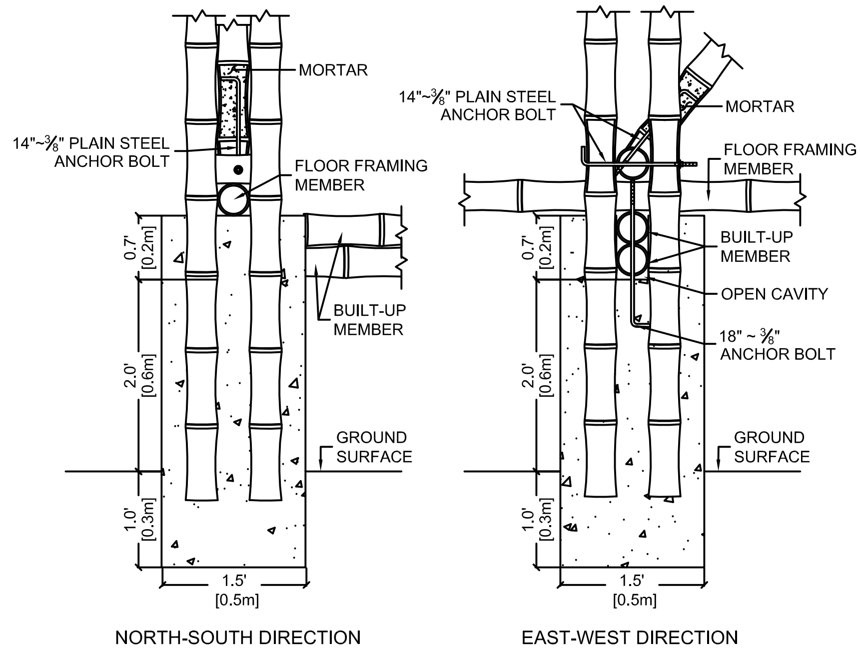
DETAILS 1 & 2

DESIGNED BY: HD & MC
REVIEWED BY: RS & SS
DATE: SPRING 2013
SCALE: 1 to 2

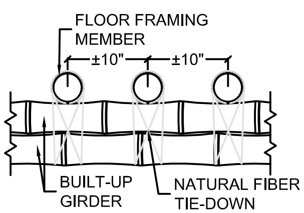
D1



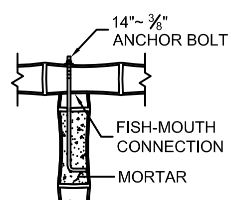

3 | D1 BRACE INTEGRATION - EAST-WEST BRACES
SCALE: 1 to 2




4 | D2 BRACE INTEGRATION - NORTH-SOUTH BRACES
SCALE: 1 to 2




5 | D2 FLOOR FRAMING
SCALE: 1 to 2




6 | D2 BRACE CONNECTION
SCALE: 1 to 2

AN APPROACH TO LIGHT-FRAME DISASTER RELIEF HOUSING

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School of Engineering

DETAILS 3,4,5 & 6

DESIGNED BY: HD & MC
REVIEWED BY: RS & SS
DATE: SPRING 2013
SCALE: 1 to 2

D2