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Designing with bamboo: frames and connections in underdeveloped areas

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Santa Clara University

DEPARTMENT OF CIVIL ENGINEERING

Date: June 8, 2015

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Andrew Spencer
&
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ENTITLED

Designing With Bamboo: Frames and Connections in Underdeveloped Areas

BE ACCEPTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE IN CIVIL ENGINEERING

Tonya

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6/11/2015

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6/11/15

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Designing With Bamboo:
Frames and Connections in Underdeveloped Areas

by

Andrew Spencer
&
Bryson Kam

SENIOR DESIGN PROJECT REPORT

Submitted to
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Designing With Bamboo:
Frames and Connections in Underdeveloped Areas

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Abstract

Designing With Bamboo: Frames and Connections in Underdeveloped Areas focused on the construction and testing of specific components of a proposed structure utilizing bamboo. This structure, proposed by the Ecological Building Network, would primarily be used in Haiti and other developing countries that are prone to seismic activity. The components of this structure will consist of concrete masonry units, bamboo frames, and rebar for the connection. This project focuses specifically on the bamboo frame and it's connection to the concrete masonry wall. Tests were performed on isolated unit specimens to gain a sense of the behavior of this mechanism. Information gathered from these tests was used in the construction of a full-scale wall and helped to understand the behavior of the structure in a seismic scenario. Some factors that were considered throughout the progression of this project were the ease of construction and material availability. The main objective of this project was to provide specific design and construction standards for universal construction of bamboo frames and connections for those living in impoverished areas that have been affected by seismic activity.

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Introduction

Project Background

On January 12, 2010 a 7.0 M_W (Richter moment magnitude scale) earthquake struck the nation of Haiti just miles from the Haitian capital, Port-Au-Prince. A particular study showed that 28% of buildings had collapsed with an additional 33% damaged beyond repair. Over 3 million people were directly affected by this natural disaster including the 1.5 million Haitians that were immediately made homeless. 85,000 people still remain homeless as of September 2014.[1] A large factor in the destruction was the low building standards and absence of building codes in Haiti. Due to this, many homes were poorly built and performed poorly under seismic loads.

Following this, the Ecological Building Network (EBNet) designed and conceived a low-cost bamboo and concrete masonry unit structure that would fit the needs of the community and address seismic design concerns. Their design consists of a concrete masonry unit (CMU) plinth wall supporting bamboo frames. This project focuses of constructing and testing components of this structure, specifically the area between the bamboo frame and the CMU wall, known as the ductile hinge mechanism. Figure 1 shows the proposed structure and details of the wall frame.

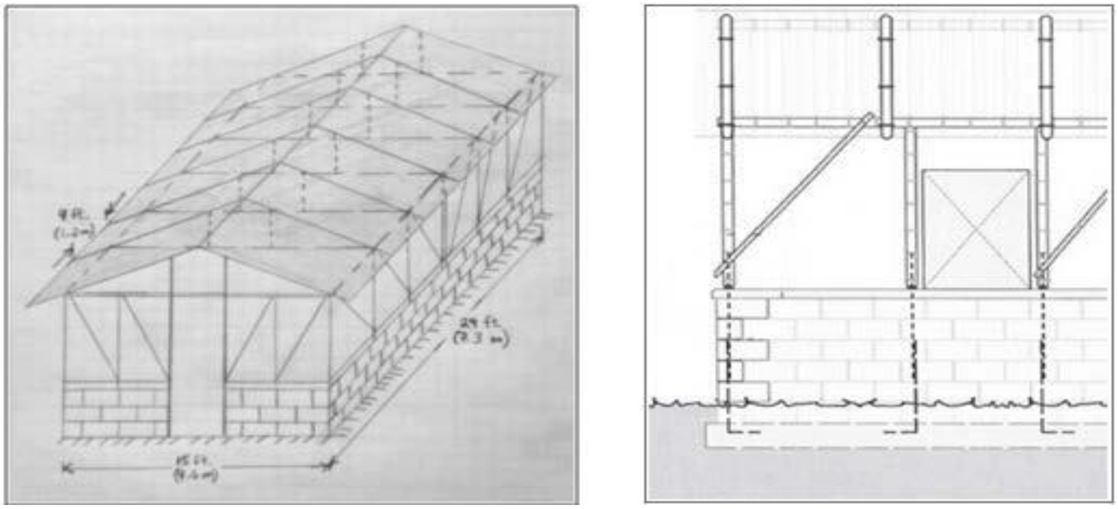

Figure 1: The wall frame and structure design from the Ecological Building Network

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[1] Data from http://pubs.usgs.gov/of/2010/1048/

Ethical Considerations

The focus of this project is to understand the behavior of the bamboo and CMU wall connection with the use of grout and rebar as the primary elements of design and construction but there are several social and environmental impacts that must be considered as well. These ethical concerns will need resolution for the future development of this project, the first being conflict of interest. Since Haiti is an underdeveloped area, there will be competition for the limited amount of resources that are available. This was made clear when relief efforts first began back in 2010 immediately following the earthquake. In the presence of panic and the natural instinct of self-preservation, the competition for goods delivered from Aid agencies was extremely high and lead to acts of violence among the survivors. To correct for this problem if the proposed design is implemented, negotiations will need to take place between the contractor and the resource providers prior to construction to ensure that everyone benefits.

Environmental Justice and Long-Term Sustainability are both important ethical considerations because of the environmental impact resulting from construction and the clearing of debris needed after the disaster. Waste and rubble disposal will need to be monitored and correctly deposited in order to limit the environmental impact. In addition, some land may need to be reserved specifically for bamboo growth in the future once the design is more widely implemented. This would mean that proper environmental provisions for land use must be followed and potential groundwater impacts will need to be assessed and limited. When it comes to sustainability, the most important issue is to provide a design that has low cost construction and uses materials that will last for a reasonable amount of time. Bamboo grows quickly and is abundant, which makes it a sustainable resource. Also, the proposed design solution must be able to prevent building failure in the event of another natural disaster, which is highly likely in that specific region of the world.

The final and most essential ethical consideration is Social Justice. After the earthquake, the resulting destruction and devastation called for immediate humanitarian action. Social Justice is the main objective of this project and of the design from EBNet because of the specific affected region and the number of lives that have been impacted by this event. Haiti was already an impoverished nation and the effects of the natural disaster only served to increase the suffering of its people. The goal of the design is to provide housing that is low cost but also high quality for the large amount of tragically affected people. There is a serious need to provide equitable distribution of goods and services so that as many people can be helped and have homes again; homes that are designed and constructed while keeping safety as the paramount principle.

Needs Assessment

This project consists of constructing and testing elements of the proposed structure from the Ecological Building Network, which was designed to serve several different needs in Haiti. The community need is the most pressing because it affects a large amount of people. The results from this project may satisfy this need if the bamboo frame and CMU wall components become readily producible. This design could be modified for different uses such as community centers and other types of public or communal structures. It can also be used in the retrofitting of both existing and damaged buildings.

In addition, our project covers so regulatory needs. Though no Haitian building codes currently exist, the government claims that it does employ some international code.[2] If these codes become more strictly enforced, then there could be a need for more earthquake-resistant structures such as the bamboo and CMU structure in this study.

Humanitarian needs are the main driving force of this project. After the 2010 earthquake, 1.5 million people became homeless.[3] The bamboo and CMU structure could be an effective solution to homelessness because of its low cost and high constructability. Also, these structures will be designed to perform more effectively in the event of a future earthquake, limiting damage to both the structure itself, and to inhabitants.

One of the beneficial aspects of this project is that it can be implemented anywhere that is prone to seismic natural disasters. Any country that is within the "Ring of Fire" as shown below in Figure 2, will find this design useful and applicable. This specific region in the Pacific Ocean is where 80% of the world's earthquakes occur. While this project was being completed, Nepal actually experienced an earthquake and faced similar levels of destruction to Haiti. This design should become an option for their future rebuilding efforts.

Figure 2: Ring of Fire[4]

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[2] Data from http://www.icfj.org/news/trouble-enforcing-building-codes-leads-dangers-haiti

[3] Data from http://www.dec.org.uk/haiti-earthquake-facts-and-figures

[4] Image from http://www.worldatlas.com/aatlas/infopage/ringfire.htm

Non-Technical Issues

There are various non-technical issues with every project and they are equally, if not more, important than the other aspects of the design. Some of these include any potential political issues that may arise, financial or economic issues that can occur from the project, potential safety issues once the project is completed, environmental and sustainability issues, and lastly any potential social justice issues.

Usually, permitting is a huge political issue for projects but our project will be implemented in other countries besides the United States so the same regulations may not be applicable. The volunteer organization has oversight for the project locations so they handle that part of the selection. However, political support is hugely important for this design because it will help the concept be more widely accepted and eventually implemented. There has been a political push towards supporting bamboo design in Haiti since the earthquake. For support from outside the country, there are numerous disaster relief organizations that help with political connections and discussions.

The first and most important financial issues will be the affordability of the project. It is the main priority because the design needs to be constructed with renewable, low cost, sustainable materials. Ideally, the future home or business owners will do most of the construction and preparation to help keep costs at a minimum. They may even help to grow some of the bamboo for their structure, which will help with the sustainability of the project. The next issue will be finding funding sources for the project. These sources would be organizations that deal with relief funds and dispersing them whenever needed. The last financial issue is capital costs. The relief funds have already been completely spent used since the earthquake occurred in 2010, nearly five years ago, and these organizations are constantly looking for donations and other funding to help the existing need.

Worker safety is the most common safety issue for most projects. This will be applicable for the design and construction of this project as well since some of these structures will be used for community structures as well as residential units. Once the building is fully operational, inspection and maintenance standards will need to be upheld by a governing agency that will be responsible for maintaining building standards and inspecting any failing elements.

There are also impacts to the current culture and demographics that must be considered. Bamboo is seen as a weak material to some Haitians. So, it may take some time and experimentation to convince the locals that they should use this design when building their structures. Through the design, testing and results of this project, it can be analytically shown that this design and its components are stronger than their current materials and construction methods. There are financial impacts that may be applicable as well. Members of the community may need to devote resources towards growing bamboo and processing it for construction. If there is no land available, some crops in certain areas may need to be moved or stopped from producing so that bamboo can be planted instead, which can impact the farmers financially. On the other hand, there may be some financial gain for bamboo farmers as well as for construction workers that are trained in this specific construction. The last social issue is the aesthetics of the structure. Part of our design requires applying a plaster to the outside wall so that the bamboo is hidden and the structure resembles the traditional architecture of the area. There may also be other methods to disguise the bamboo framing so that the public does not question the structural integrity.

Bases for Design

Why Use Bamboo?

Bamboo was chosen as the main building material for this design for several reasons, which include its availability, sustainability and favorable mechanical properties. Bamboo is one of fastest growing plants in the world. It is abundant and grows in a multitude of climates. For this project, the specific species named Guadua Angustifolia was used. This species can grow at a remarkable rate of nearly four inches a day and can begin harvesting at the age of six years. Bamboo is a grass, which means that it will continue to grow after being harvested, making it an incredibly sustainable material.

There are many different species of bamboo, like Guadua Angustifolia, that can be stronger than concrete in compression, which is a favorable structural property for uses in construction. The most important mechanical property of bamboo is that it has a similar strength to weight ratio as steel in tension, which is ideal for its use in frames like the ones in this project. From the environmental side, bamboo can sequester carbon from the atmosphere similar to timber. The bamboo plant stores the carbon in its biological structure, which helps to improve the surrounding environment since there will be less carbon dioxide in the atmosphere.

Why Use Concrete Masonry Units?

Concrete masonry units are the most popular building material for homes in Haiti. Unfortunately, these structures are not seismically safe due to their large amount of weight and poor design. During an earthquake, the ground underneath the structure as well as the structure itself is accelerated. From Newton's second law, force is equal to mass times acceleration. Therefore, the mass of the structure is the key component to the calculating the resulting forces created during an earthquake. These concrete masonry units weigh about 25 pounds per block. If built without proper reinforcing and detailing methods, the number of blocks it takes to build a house makes the weight of the total structure extremely high and dangerous in the event of an earthquake. However, the International

Code Council has produced ICBO Uniform Building Codes that provide safe construction of these structures.

For this design, the height is limited to three feet above the ground for safety and structural performance under seismic conditions. This is a safer alternative to their current building practices but still incorporates a building material that is common in that region.

Why Use Rebar?

Steel rebar has many mechanical properties that make it an ideal building material. Steel is commonly used in construction in America because of its high strength to weight ratio compared to other materials. This means that much less material can be used to resist the same loads in the structure, which reduces the overall weight. In addition, rebar is essential for this project because its efficient use in the design can limit the cost of construction, while providing the necessary strength at the same time.

The mechanical property of ductility is the key element in this project. When loaded, steel exhibits ductile behavior after yielding. This means that the steel member will deform for a long time before failure is experienced. In a seismic application, steel will become ductile after yielding and the structure will begin to move, which will give the people inside that building a chance to escape before the structure ultimately fails. Other materials, such as concrete, have a brittle mode of failure, which means that a building will suddenly collapse under seismic conditions. Unfortunately, this brittle mode of failure was exactly what the buildings in Haiti experienced and explains why there were so many casualties.

Proposed Solution

The proposed solution comes from a design concept by the Ecological Building Network. The design concept is for a low-cost housing system for use in tropical countries, which is comprised of a low (CMU) plinth wall supporting a bamboo frame, which can be seen in Figure 1. These components make up the structure of the housing system. According to the Ecological Building Network, the finished product would consist of plastered walls covering the CMU plinth wall and the bamboo frame. This would support a lightweight bamboo truss roof supporting a corrugated metal roof as seen in Figure 3 below. The structure's dimensions correlate with a single family home and may be a rectangular single-story house around 360 square feet, though this value along with the length and width of the structure may be modified.

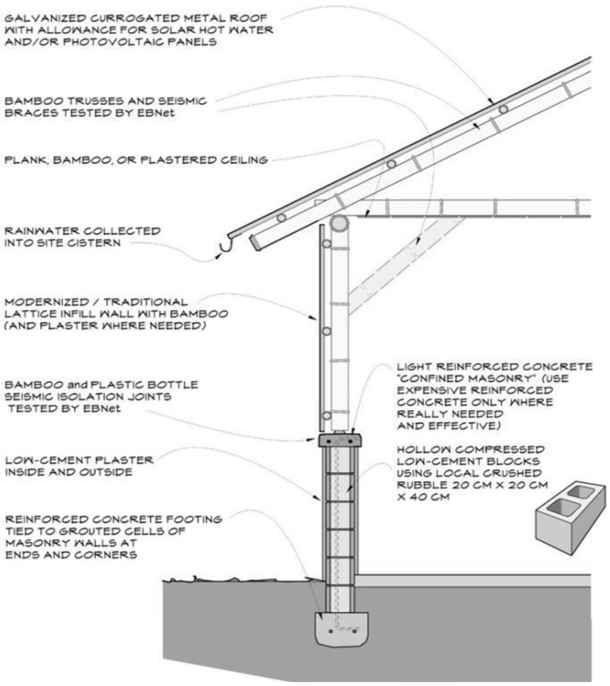

Figure 3: Section View Showing Ecological Building Network's Proposed Structure

To provide seismic resistance, the design consists of ductile hinge mechanisms, which connect the bamboo frame to the CMU plinth wall. These mechanisms provide seismic resistance to the structure and will be discussed further in the following section.

Introduction to the Ductile Hinge Mechanism

The ductile hinge mechanism, which can be seen in Figure 4, below, is Santa Clara University's contribution to the bamboo braced frame design proposed by the Ecological Building Network. The purpose of the ductile hinge mechanism is to increase the system's ductility and to provide a controllable "weak link" within the system that limits the forces that may be experienced by other components of the system. These components include the bamboo frame, bamboo frame connections, and the CMU plinth wall. By doing this, favorable ductile behavior under seismic loading can be achieved. Ductility, provided by the steel rebar, prevents against catastrophic failure that would otherwise occur if the system failed in the CMU plinth wall, or by failure in the bamboo braced frame through bamboo culm failure or bolt shear in the connections joining bamboo culms.

Figure 4 below, shows the location of the Ductile Hinge Mechanisms within a wall in the proposed structure. Ductile hinge mechanisms may occur where the bamboo braced frame connects to the CMU plinth wall.

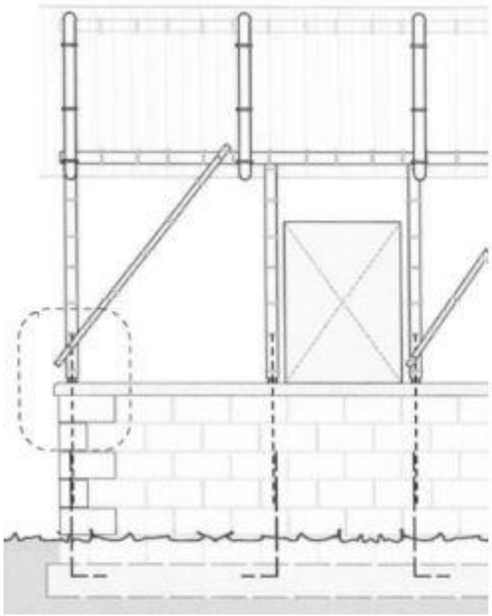

Figure 4: Ductile Hinge Mechanism Circled Within a Wall

The ductile hinge mechanism includes a steel rebar dowel as seen in Figure 4. This dowel serves as the “weak link” in the system by acting as a fixed, guided (rotation restrained) member similar to that in Figure 5, below. Each ductile hinge mechanism in the structure will have a yield strength that is equal to the force required to yield its rebar dowel. A ductile hinge mechanism’s yield strength will represent the lateral force that it can resist without experiencing plastic or permanent deformation. The yield strength of the ductile hinge mechanism can be designed by manipulating three variables within the fixed, guided rebar dowel:

1. Material property (type of steel)
2. Cross sectional geometry (rebar size)
3. Effective length of the rebar dowel (exposed rebar length)

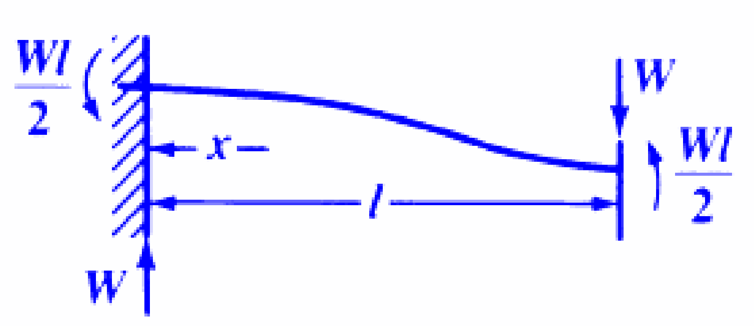

Figure 5: Fixed, Guided Beam Diagram[5]

The designed value for the strength of the ductile hinge mechanism is constrained by three factors:

1. It must be lesser than the strength of all other component in the system in order to assure system failure results from yielding in the rebar dowel
2. It must satisfy system strength requirements regarding seismic loads
3. It must satisfy system deflection requirements for resisting wind loads

With regard to the second and third factors, system strength and deflections are dependent upon the strength of each rebar dowel, and also the total number of rebar dowels included in a system. Theoretically, a system will be a full structure or house consisting of many ductile hinge mechanisms.

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[5] Image from: http://www.engineersedge.com/beam_bending/beam_bending13.htm

Theory and Predicted Behavior

Lateral Force Required for Yielding of Rebar Dowel

(Yield Strength of Ductile Hinge Mechanism)

For a fixed, guided beam like that in Figure 5, the maximum bending stress, which occurs at each end can be calculated using Equation 1:

$$\sigma_b = \frac{Wl}{2Z} \tag{1}$$

Where:

σ_b = maximum bending stress in the beam (psi)

W = lateral force (lbs)

l = effective length of the rebar dowel (in)

Z = section modulus of the cross section of the beam (in^3)

Solving for W, we get:

$$W = \frac{2\sigma_b Z}{l} \tag{2}$$

Substituting σ_y for σ_b gives the lateral force required for yielding, W_y:

$$W_y = \frac{2\sigma_y Z}{l} \tag{3}$$

Where:

σ_y = tensile yield strength (psi)

W_y = lateral force required for yielding (lbs)

Lateral Deflection at Yielding of Rebar Dowel

Lateral deflection, Δ, due to lateral force, W, may be calculated using Equation 4 below:

$$\Delta = \frac{Wl^3}{12EI} \tag{4}$$

Where:

E = modulus of elasticity (psi)

I = cross sectional moment of inertia (in^4)

Substituting Equation 2 into Equation 4 gives:

$$\Delta = \frac{2\sigma_b Z l^2}{12EI} \tag{5}$$

Substituting σ_y for σ_b gives the lateral yield deflection, Δ_y :

$$\Delta_y = \frac{2\sigma_y Z l^2}{12EI} \tag{6}$$

For a circular cross section:

$$Z = \frac{\pi}{4} \cdot r^3 \tag{7}$$

Project Context and Scope

This project addressed the need to provide connections of bamboo frames to a CMU plinth wall structure for areas with high seismic activity. To address this need, several isolated unit specimens were created to simulate the ductile hinge mechanism in the full wall frame, which occur wherever the bamboo frame is connected to the CMU wall. The improvements in the design of the unit specimens was a critical part of our project since Senior Design projects from the past had problems with accurately simulating the ductile hinge mechanism.

The next part of our project consisted of constructing a full-sized wall frame with a 5 foot bay. For its construction, we incorporated several past projects with our new design of the ductile hinge mechanism to produce a final product. We read the recommendations from the past groups and followed their suggestions in order to create the strongest connections and grout as well as the most efficient ductile hinge mechanism for our expected behavior. The Full-Scale Wall combined all of these elements and was then tested under cyclic loading. This testing allowed us to measure the deflection from the loads and compare those values to the expected deflections from calculations.

There were a number of factors that we considered when analyzing the proposed structure and its ability to resists the various loads that it will encounter. The most crucial load combinations for our project are due to earthquakes and wind. Through our project and the experimental testing that we performed, we strived to provide detailed design criteria for future bamboo and CMU structures. One of our main driving objectives was to standardize the mix designs for all elements made from concrete as well as the construction of the wall frame in order for our results to be replicated in the future. We had to consider the available materials in underdeveloped areas and how their standards differ greatly from those in America. We also had to consider the ease of construction since construction tools and manufactured materials are limited in these areas, which made our process of construction critical to its future implementation.

Theoretical Results for Strengths of Ductile Hinge Mechanisms

Using Equation 3, theoretical lateral forces required for yielding could be calculated for ductile hinge mechanisms based on rebar dowel effective length and rebar size. The rebar dowel effective length was constrained between 1” and 3” and the rebar size was limited to No. 3 and No. 4 rebar sizes per recommendations from the Ecological Building Network. For the sake of theory, Grade 40 steel rebar was assumed. Therefore, 40,000 psi was used as the value for tensile yield strength, σ_y , in these calculations. Theoretical values for force required for yielding can be seen in Table 1 below.

Table 1: Theoretical strength values for ductile hinge mechanisms with σy = 40,000 psi

Effective Length of Rebar Dowel, l (in)	**No. 3 rebar: Lateral Force Required for Yielding, W_y (lbs)**	**No. 4 rebar: Lateral Force Required for Yielding, W_y (lbs)**
1	414	982
1.5	276	655
2	207	491
2.5	166	393
3	138	327

The Isolated Unit Specimen

Introduction and Purpose

Isolated unit specimens as seen in Figure 6, were constructed and tested in order to isolate the ductile hinge mechanism and to observe its behavior removed from a full-scale wall setting. This was done mainly to obtain stress-strain data pertaining only to the ductile hinge mechanism alone, which includes a single CMU node filled with the high-strength grout, No. 3 or No. 4 rebar, and the grouted portion of the bamboo column.

Figure 6: Isolated unit specimens in curing process

The purpose for fabricating and testing isolated unit specimens was to prove that the ductile hinge mechanism could behave predictably and similarly to the theoretical model of the fixed, guided member. Therefore, this would prove that the actual end conditions are comparable to those in theory. With regards to the isolated unit specimen, this means that grout-filled ends provide adequate fixity and do not experience spalling.

Design Philosophy and Demand

In order to promote the yielding of rebar for favorable behavior under seismic loading, the exposed rebar dowel length as seen in Figure 7, must behave similarly to a fixed, guided (rotation-restrained) member. This implies that the end conditions in the rebar dowel within the ductile hinge mechanism must be such that one end is fixed with respect to the CMU block, and the other is fixed with respect to the bamboo column. This fixity is determined by the rigidity in the grout. Spalling within the grout will lead to an increase in the effective length of the rebar dowel, which leads to decreased strength. An increase in the effective length of the rebar dowel that is dictated by spalling in the grout ends would also lead to uncertainty and unpredictability with regard to yield strength, since it would be unlikely that the grout failure and resulting increase in the rebar dowel's effective length be consistent and predictable.

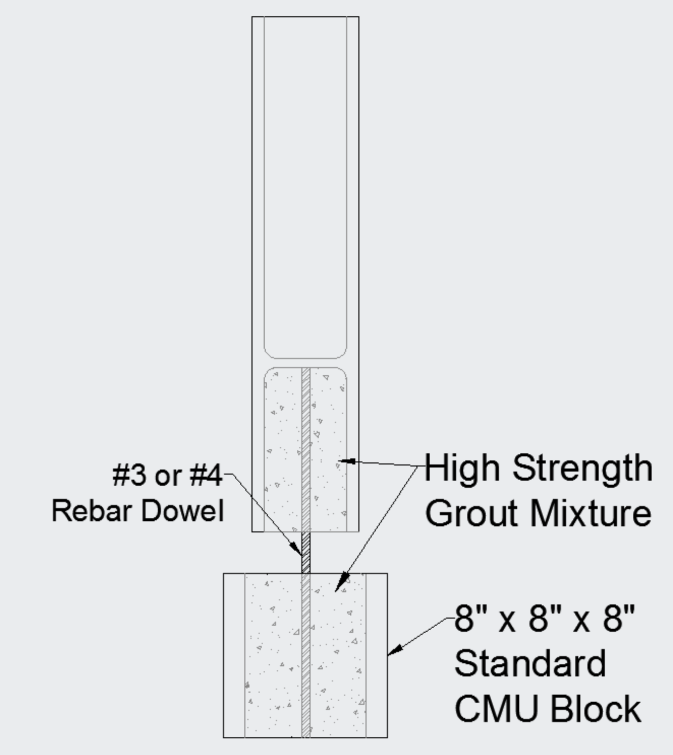

Figure 7: Isolated Unit Specimen diagram

Design of Specimen

The design of the isolated unit specimen was conducted according to recommendations provided by previous senior design projects, which addressed the ductile hinge mechanism. The recommendations called for a high-strength grout mixture to be used in order to prevent spalling in the grout during loading. Doing this would increase rigidity in the grout ends of the rebar dowel.

The grout mixture was designed in accordance with ASTM C 476. Through compression testing, it was found that the grout had a 28 day compressive strength of 4960 psi.

The rebar dowel was designed with an exposed length of 3” in order to prevent spalling within the grout since a longer effective length would theoretically produce lesser forces in the grout while still providing adequate strength. Modeling the rebar dowel as a fixed, guided member as seen in Figure 5, the yield strengths were predicted using measured values for tensile yield strengths for the rebar. The predicted values for yield strength of the ductile hinge mechanism for different rebar dowel lengths of No. 3 and No. 4 rebar can be seen below in Table 2.

Table 2: Predicted yield strength of isolated unit specimens

Rebar Size	Rebar Dowel Length (in.)	Actual Rebar Yield Strength (psi)	New Predicted Lateral Yield Strength (lbs)
No. 3	3”	46617	161
No. 4	3”	65061	532

Method of Testing and Testing Apparatus

Figure 8: MTS Testing Apparatus

The isolated unit specimens were tested in an MTS machine with the apparatus in Figure 8. The lower MTS grip held a steel T-beam, while the upper grip held a steel welded beam as seen in Figure 9. Both the T-beam and the welded beam were fixed with respect to its corresponding grip. The single CMU block component of each isolated unit specimen was affixed to the T-beam with four steel clamps. The bamboo culm component of each isolated unit specimen was affixed to the welded section using a combination of ratchet tie down straps and steel clamps. The goal was to prevent slip in any of the components within the test apparatus. This would provide that measured deflection in the system was attributed solely to the isolated unit specimen.

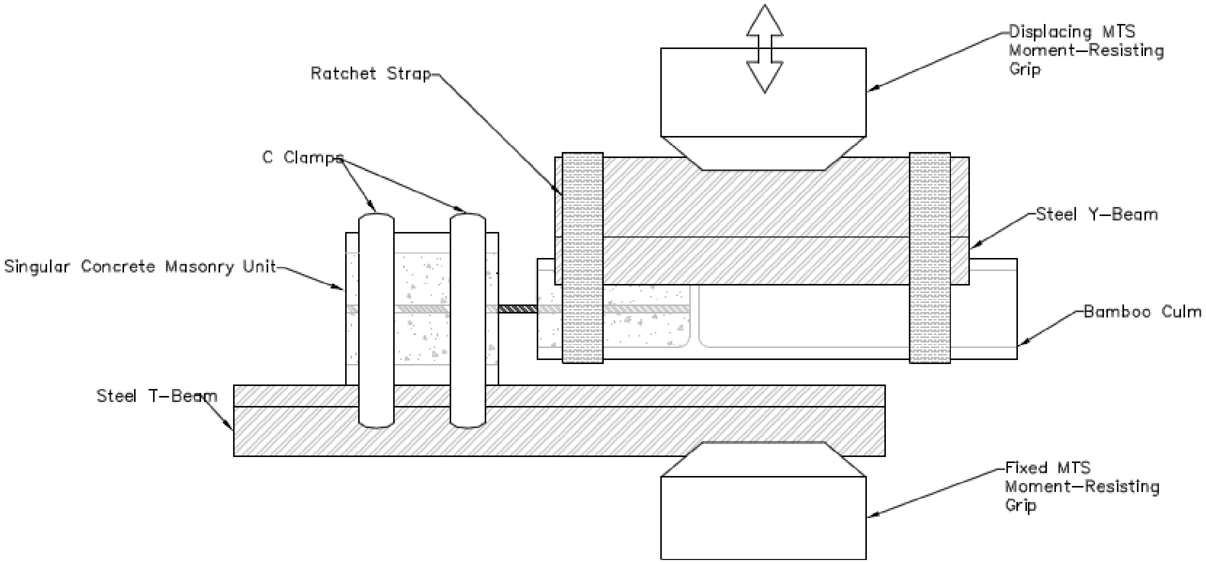

Figure 9: AutoCAD Representation of MTS Testing Apparatus and Unit Specimen

The upper MTS grip was fixed, while the lower MTS grip was displaced vertically according to a program from the Consortium of Universities for Research in Earthquake Engineering (CUREE). This cyclical vertical displacement would mimic lateral displacement that would occur in a ductile hinge mechanism within a structure under seismic loading. Force applied by the MTS machine was measured and plotted against the displacement.

Results

The values for the maximum forces generated in the ductile hinge mechanisms of the isolated unit specimens can be seen in Table 3.

Table 3: Measured lateral forces for isolated unit specimens

	Rebar Dowel Size	**Rebar Dowel Length (in.)**	**Maximum Lateral Force (lbs)**
Isolated Unit Specimen 1	No. 4	3”	1942
Isolated Unit Specimen 2	No. 4	3”	1983
Isolated Unit Specimen 3	No. 3	3”	494
Isolated Unit Specimen 4	No. 3	3”	544

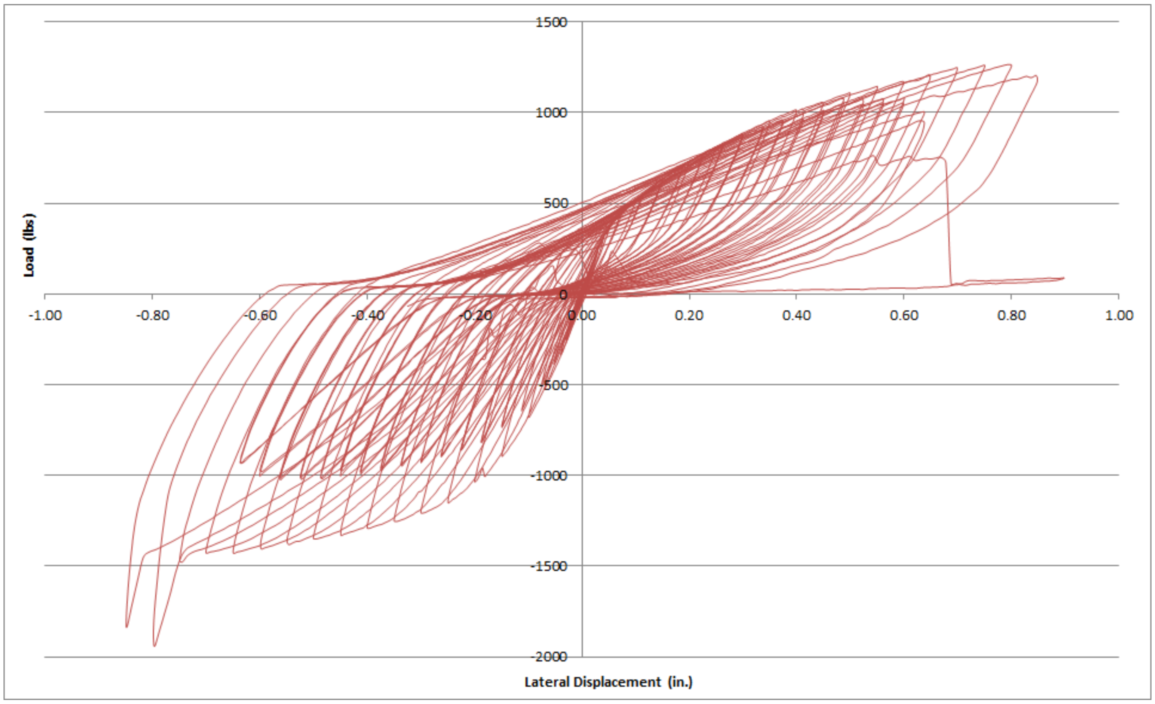

Figure 10: Load vs. displacement plot for Isolated Unit Specimen 1

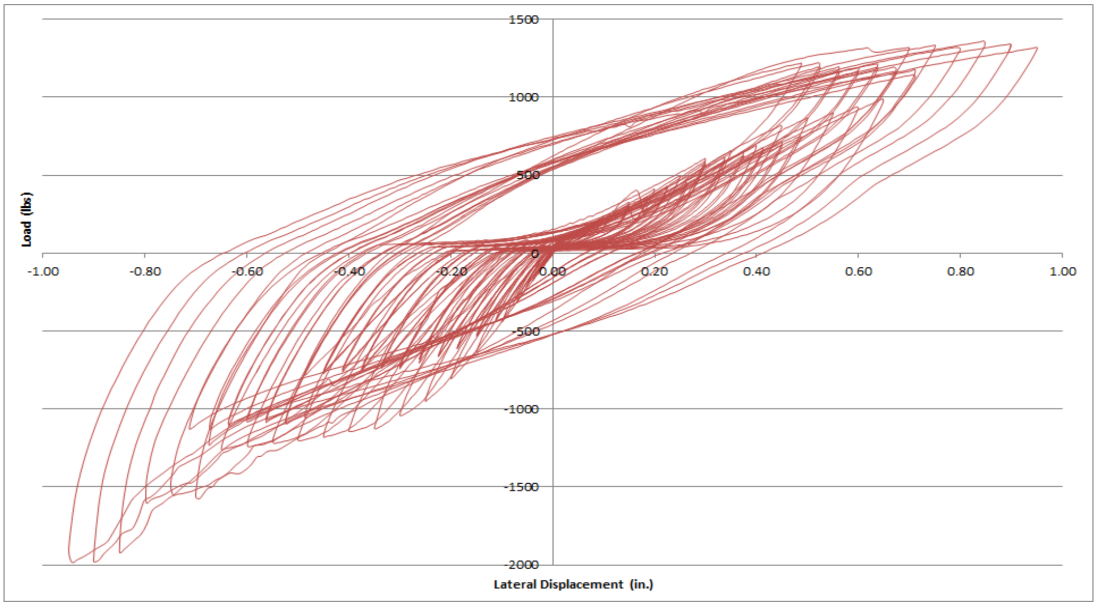

Figure 11: Load vs. displacement plot for Isolated Unit Specimen 2

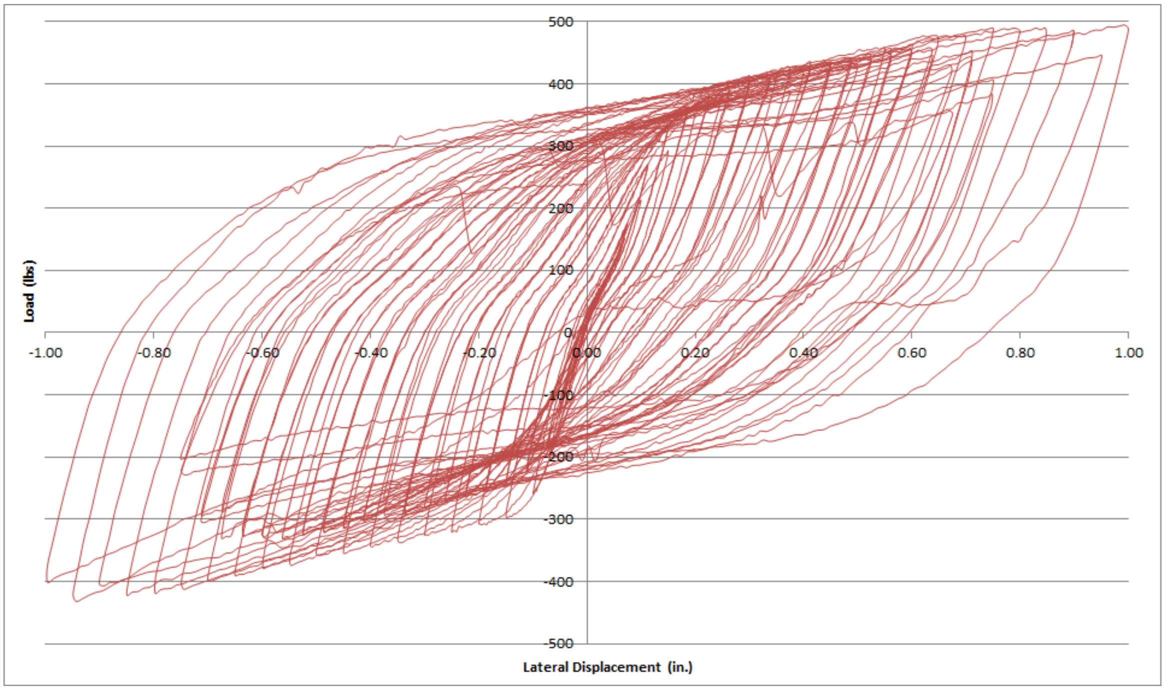

Figure 12: Load vs. displacement plot for Isolated Unit Specimen 3

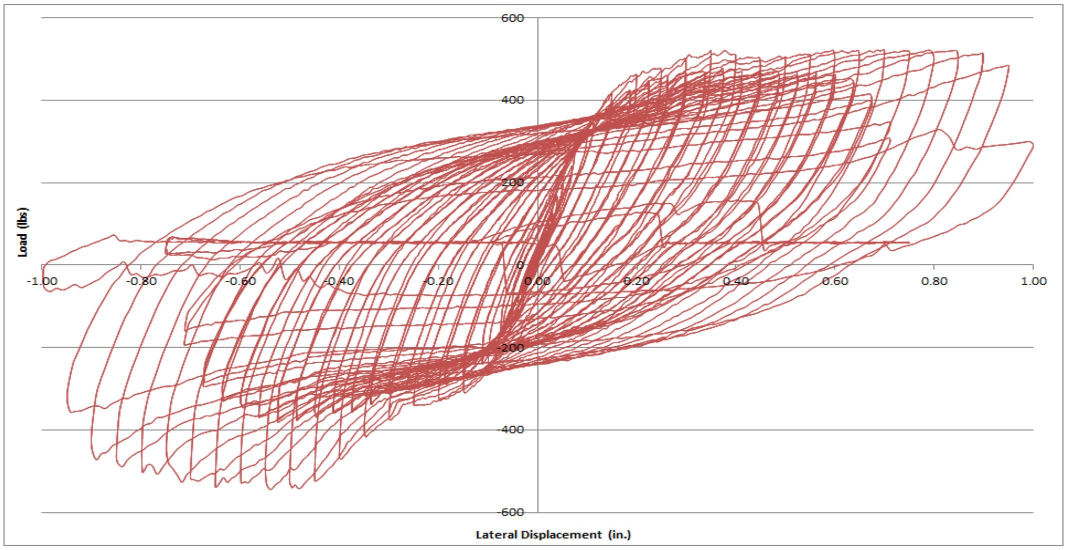

Figure 13: Load vs. displacement plot for Isolated Unit Specimen 4

Modes of Failure

For Isolated Unit Specimens 1-3, there was no obvious mode of failure although the maximum load in each cycle did either begin to decline with subsequent cycles, or showed a plateau. This most likely indicates that the rebar dowels were experiencing flexural fatigue and would have failed similarly to Isolated Unit Specimen 4, which ruptured due to flexural fatigue.

Figure 14: Isolated Unit Specimen 4 after testing demonstrating rebar dowel rupture

As can be seen in Figure 14, for Isolated Unit Specimen 4, the No. 3 rebar dowel failed after several loading cycles. The effects of flexural fatigue and rupture failure can be seen in Figure 13, where there is a significant decrease in the maximum strengths of each cycle as the displacements approach 1” and -1”.

Conclusions from Test Results

As seen in the load vs. displacement curves, the load generally increased as the displacement increased due to strain hardening. However, each graph demonstrates a plateau with respect to the maximum strength reached.

The values for relative stiffness for the isolated unit specimens were determined and plotted in Figures 27, 28, 29, 30 in Appendix C. The data points represent the relative stiffness values, calculated as the ratio of the change in force to the change in displacement for the linear portion of each displacement cycle. Figures 27, 28, and 29, which represent Isolated Unit Specimens 1, 3, and 4 respectively, show obvious degradation in relative stiffness with succeeding displacement cycles. This could be due to spalling in the grout ends, leading to an increase in the effective length of the rebar dowel. For Isolated Unit

Specimen 2 and Figure 28, there is not an obvious trend of decreasing relative stiffness. This may be due to slip in the testing apparatus. As the test occurred, the ratchet tie down straps became loose and were tightened during the test. This could have led to increases in the relative stiffness values measures.

The ductility factors for the Isolated Unit Specimens could be estimated based on the data gathered. Due to constraints in the MTS machine and the testing rig, specimens 1, 2 and 3 could not be tested until failure with the CUREE displacement history. Therefore, the values obtained for maximum displacement will represent that of displacement at failure in calculating the ductility factor, μ. The ductility factor is determined by dividing the displacement at failure by the yield displacement. These values are displayed in Tables 4 and 5.

Table 4: Ductility Factors and Displacements in Positive Direction

	Yield Displacement (in.)	Max Displacement (in.)	Ductility Factor, μ
Isolated Unit Specimen 1	0.0576	0.951	16.51041667
Isolated Unit Specimen 2	0.0586	0.951	16.22866894
Isolated Unit Specimen 3	0.139	0.951	6.841726619
Isolated Unit Specimen 4	0.113	0.951	8.415929204

Table 5: Ductility Factors and Displacements in Negative Direction

	Yield Displacement (in.)	Max Displacement (in.)	Ductility Factor, μ
Isolated Unit Specimen 1	-0.0656	-0.849	12.94207317
Isolated Unit Specimen 2	-0.0586	-0.951	16.22866894
Isolated Unit Specimen 3	-0.14	-0.951	6.792857143
Isolated Unit Specimen 4	-0.114	-0.951	8.342105263

Since the values for the maximum displacement were used for specimens 1 through 3, it may be assumed that the calculated ductility factors are lesser than the actual since it is probable that the specimen would have experienced greater displacements before failure.

Full-Scale Wall Specimen

Introduction and Purpose

A full-scale wall was constructed to further assess the viability of the ductile hinge mechanism as an effective structural component for resisting seismic loads. In addition to this, the Full-Scale Wall Specimen would provide information regarding the behavior of the ductile hinge mechanism within the context of the full scale wall.

There were three main components of the Full-Scale Wall Specimen:

1. The CMU plinth wall
2. The bamboo frame including connections
3. The ductile hinge mechanism

This senior design project sought to assess the viability and behavior of the ductile hinge mechanism. For this reason, the CMU plinth wall and the bamboo frame were over-designed with discretion in order to assure that system failure resulted from yielding in the rebar dowel of the ductile hinge mechanism rather than in any other component. Overdesign with discretion implies that the CMU plinth wall and bamboo frame were designed with a high factor of safety to account for uncertainty in forces generated in the ductile hinge mechanism. At the same time, discretion was demonstrated in that the materials and construction techniques used were relatively feasible with respect to economic and geographical constraints.

CMU Plinth Wall

According to the Ecological Building Network, the CMU Plinth wall serves to raise the bamboo frame and the ductile hinge mechanism from the ground and moisture. The CMU plinth wall is a standard CMU wall consisting of mortared CMU blocks, a shear cap, and a continuous concrete footing. Reinforced grout columns occur at all vertical nodes that contain a ductile hinge mechanism. This provides that the rebar member constituting the rebar dowel may run into the grout column and be lapped with rebar reinforcement, which is anchored to the concrete strip footing. The CMU plinth wall and its components can be seen in Figure 15 below.

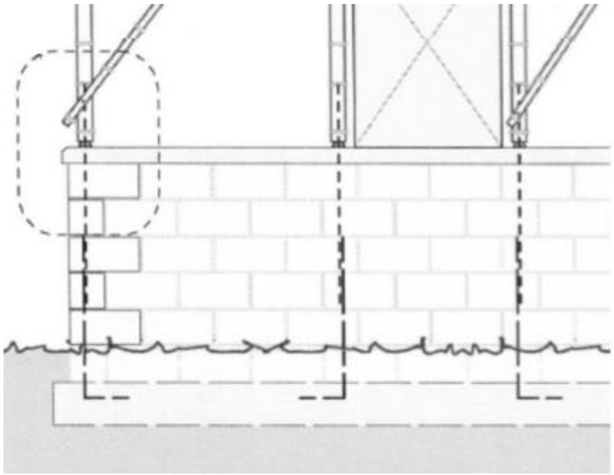

Figure 15: Diagram showing CMU plinth wall with Shear Cap and Strip Footing

Design Philosophy and Demand for the CMU Plinth Wall

In order to achieve favorable system behavior under seismic loading, and to assure system failure in the ductile hinge mechanism, the CMU plinth wall must provide adequate rigidity to the ductile hinge mechanism. This implies that the wall must be able to resist lateral forces generated in the ductile hinge mechanism. Under lateral loads transferred by the ductile hinge mechanism, a possible mode of failure in the CMU plinth wall could be tensile rupture in the mortar between CMU blocks. Additionally tensile rupture could also occur in the CMU blocks themselves. To prevent against this potential mode of failure, several measures were taken. Firstly, the concept of the shear key was conceived. Secondly, the shear cap was reinforced with a No. 4 steel rebar stirrup in tension. Thirdly, mortar mixes for the shear key grout cap, and the grout columns were deliberately over-designed for high strength.

The Shear Key Grout Cap

To prevent against tensile rupture in the CMU plinth wall, a high-strength grout cap was proposed by the Ecological Building Network. To further develop this idea, the high-strength cap was developed into a shear key grout cap, which can be seen in Figure 17. The shear key grout cap was designed to resist lateral load and prevent shear failure between the uppermost run of the CMU plinth wall and the high-strength cap resulting from poor cohesion between these elements. The shear key grout cap would consist of a single pour of mortar, which penetrates into each node of the uppermost CMU block run.

It was decided by judgement that the “teeth” of the shear key grout cap should penetrate into the uppermost run of CMU plinth wall for a minimum penetration depth of 3”. The shear key was over-built in this project because the original design only consisted of a cap sitting on top of the CMU wall but added shear strength was desired to prevent failure in this section.

The height thickness of the shear key grout cap from the top of the CMU plinth wall was 2” in order to provide sufficient concrete cover for cast-in-place for rebar stirrup reinforcement.

For the Full-Scale Wall Specimen the shear key grout cap provided lateral strength proportional to its total area in shear. The area in shear was equal to total area of the teeth of the shear key. This area was equal to total nodal area of the upper face of CMU wall. The Full-Scale Wall Specimen consisted of sixteen equivalent 8 x 8 x 16 CMU blocks. The uppermost CMU block row consisted of eight nodes, each with an area of 37 in^2. Therefore, the total area in shear was 296 in^2. The shear strength of the shear key was calculated using Equation (8) and was found to be 16,030 lbs.

$$V_c = 2\sqrt{f_c'}A_s \tag{8}$$

Where:

V_c = shear strength of the shear key grout cap (lbs)

f_c' = measured compressive strength (psi)

A_s = total area of shear key teeth (in^2)

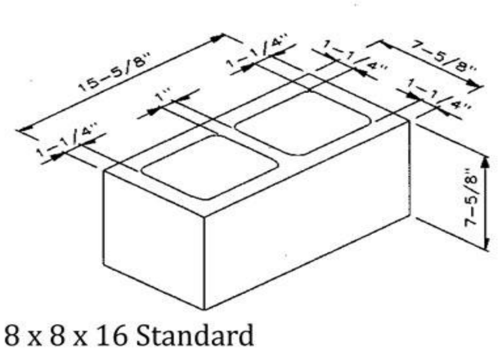

Figure 16: Dimensions of standard CMU block used in Full-Scale Wall Specimen[6]

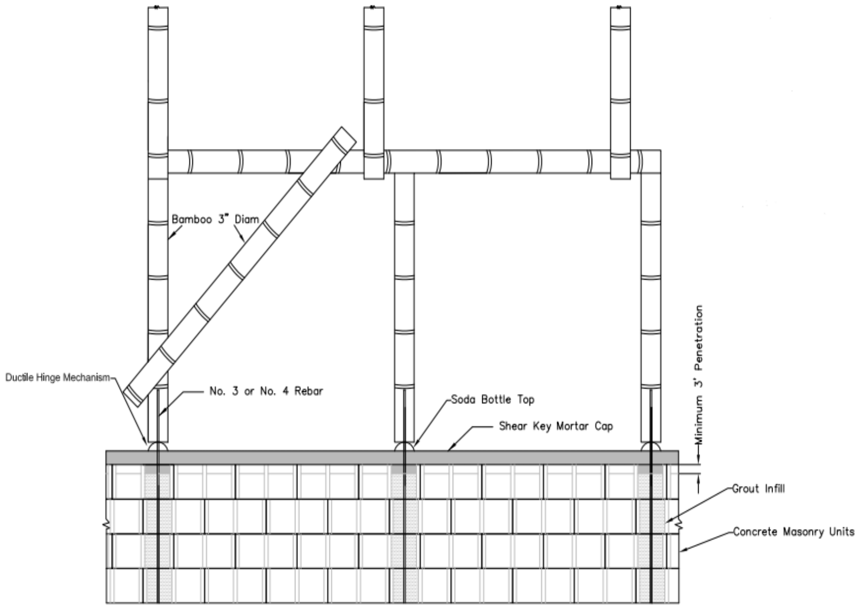

Figure 17: Diagram of bamboo braced frame and CMU plinth structure

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[6] Image from http://southwestblock.net/wp-content/uploads/2013/04/000880000-8x8x16-standard-.jpg

Reinforcement of the Shear Key Grout Cap

Lateral tension reinforcement was provided in the shear key grout cap from a No. 4 steel rebar stirrup. It was decided that lateral reinforcement be provided by a stirrup rather than a rebar tie anchored into the grout columns. This was done to prevent the addition of loads and forces due to the anchored ends of the rebar tie.

The rebar stirrup was designed in accordance with ACI standards and treated as a crosstie stirrup with seismic hooks at both ends. Per ACI 318-11, the crosstie stirrup had hook lengths of no less than $6d_b$ and a bend not less than 135 degrees. The nominal tensile yield strength of the shear key grout cap due to the rebar reinforcement was over-designed at per Equation 9.

$$F_{nt} = A_{ts} f_y \tag{9}$$

Where:

F_{nt} = nominal tensile strength of the rebar reinforcement

A_{ts} = cross sectional area of tensile reinforcement

f_y = specified yield strength of the tensile reinforcement

The No. 4 rebar lateral reinforcement was cast-in-place in the vertical center of center of the shear key grout cap. ACI 318-11, requires for concrete cover of No. 4 rebar reinforcement to be no less than ¾”. Therefore, the rebar was placed in the center of 3” upper portion of the shear key grout cap. This provided ¾“ of concrete cover with respect to the surface of the shear key grout cap.

Grout Mix Designs

The CMU plinth wall utilized three different grout mixes corresponding to:

1. The shear key grout cap
2. The ductile hinge mechanism
3. The grout column below the ductile hinge mechanism

The grout mixes were designed in accordance with ASTM C-476 and also according to rough slump requirements, which were dictated by constructability concerns. Compressive strengths were determined through compression testing of 2”x 2”x 2” cubes.

Mix design ratios and measured values for compressive strength of grout cube samples can be seen in Table 6 below.

Table 6: Ratio of ingredients and measured compressive srengths of mortar mixes

	Ratio of ingredients (water : cement : fine aggregate) (ft^3)	**Measured 7-day Compressive Strength (psi)**
Shear Key Grout Cap	0.24 : 0.20 : 1.0	734
Ductile Hinge Mechanism	0.24 : 0.20 : 1.0	734
Grout Column Below Ductile Hinge Mechanism	0.30 : 0.25 : 2.25	82
CMU Mortar Mix	1 : 16 (Water : Mortar Mix)	1011

Mortar Mix

For practical reasons, Quikrete Mortar Mix (No. 1102) was used to construct the mortar joints between CMU blocks. This was done for the sake of simplicity. Also, the mix is both well-studied and reproducible. Furthermore, the mortar joints do not play a significant role in preventing tensile rupture in the CMU plinth wall.

Creating a Surrogate for the Continuous Concrete Strip Footing

In order to test the Full-Scale Wall Specimen, it was necessary to affix the CMU plinth wall to the testing machine. In order to do this, and for logistical reasons relating to the transportation of the Full-Scale Wall Specimen, the continuous concrete strip footing was excluded from the specimen. A steel wide-flange beam as seen in Figure 18 served as a surrogate for the continuous concrete strip footing.

Figure 18: Steel Wide-Flange Beam Used as Strip Footing Surrogate

In order to represent the anchored reinforcement in the continuous concrete strip footing per the Ecological Building Network's design, steel threaded rod of 1" diameter was bolted onto the upper flange of the steel beam. In accordance with ACI 318-11, the threaded rod was lapped with the steel rebar that ran the full length of the CMU wall and into the node of the bamboo culm. The lap length was determined in this fashion to mimic the continuous concrete strip footing as in the design. From calculations, the expected loads during testing would create negligible pull-out forces in the system so this part of the design was considered adequate for this specific application.

Bamboo Frame

The geometry of the bamboo frame was designed in accordance with the desired height of the structure and the number of bays that may occur in a structure. Using SAP200, the theoretical lateral deflection in the frame was determined. The bamboo frame was modeled as a truss with pinned supports as seen in Figure 19.

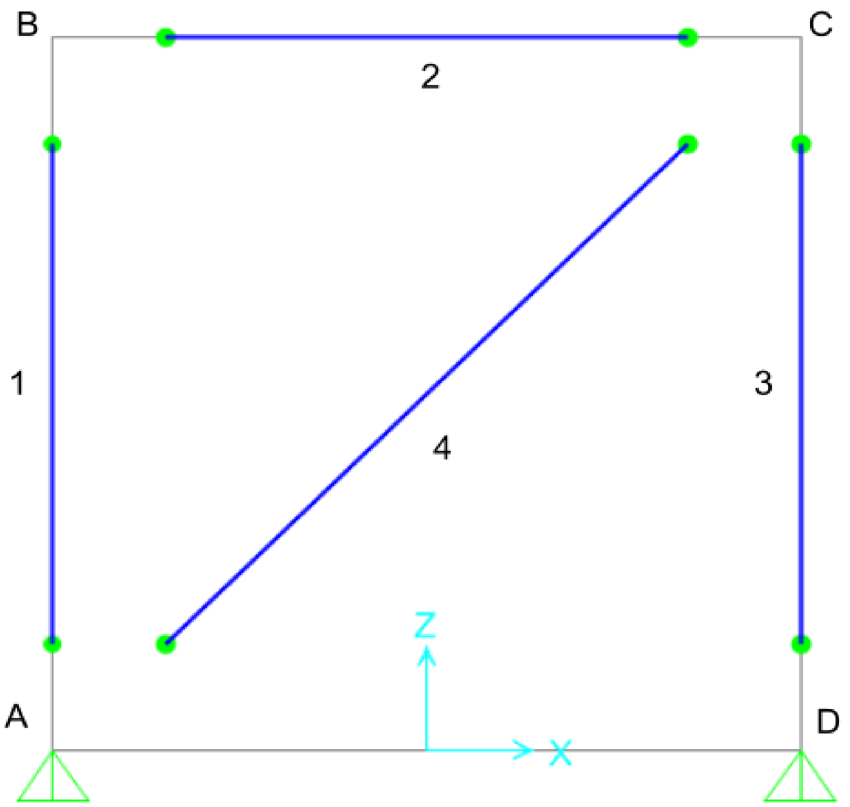

Figure 19: SAP2000 Model of Bamboo Frame Indicating Direction Conventions, Member Labels and Joint Labels

The modulus of elasticity of the bamboo was taken as $2*10^6$ psi for Guadua Angustifolia, according to a previous senior design project. The bamboo culms were modeled as hollow circular sections with outer diameter of 3.875" and wall thickness of 0.375". The lateral deflection was found to be negligible with respect to the lateral loads generated in the ductile hinge mechanism.

Despite this, it was recognized that the lateral deflection at the horizontal bamboo member would be due primarily to slip in the connections between bamboo members in the frame. The connections will be discussed in detail in the next section.

Bamboo Frame Connections

The connections between the bamboo members in the frame were designed according to AISC Manual, recommendations from previous senior design projects, and INBAR specifications. The yield strength of the strap connections, which can be seen in Figure 20, was calculated based on the maximum strengths experienced by the No. 3 Isolated Unit Specimens. Therefore, the nominal strength of the connections was designed as greater than 544.28 lbs.

16 gauge steel straps were used in the bamboo frame connections. The cross sectional area of the steel straps was measured as 0.097 in^2. Through a previous senior design project, which utilized this product from the same manufacturer, the average yield strength of the straps was determined to be 59,200 psi. Multiplying the cross sectional area of the steel straps by the yield strength gave the nominal tensile strength of the steel straps, which was 5742.4 lbs.

The straps were connected to the bamboo culms by self-tapping screws, which were subjected to shear. The nominal cross-sectional area of each screw was 0.0176 in^2 with shear strength taken as 90000 psi for Grade 8 steel screws. Multiplying the cross-sectional area of each screw with the shear strength gave the nominal strength of each bolt, which was 1584 lbs per bolt. It was decided that failure in the connections should limited to yielding in the straps rather than shear in the self-tapping screws. Accordingly, the straps were designed as can be seen in Figure 20 below, which indicates the use of four staggered screws for each connection between the steel strap and the bamboo culm. This provided that the nominal shear strength of the bolts, at 6336 lbs was greater than the yield strength of the steel straps. The bolts were staggered to prevent against block shear rupture in the straps.

Figure 20: Bamboo frame connection

The ends of the bamboo culms framing into other culms were fish-mouthed in order to decrease slip in the connections. Also, per INBAR provision, screw holes were drilled at a minimum distance of about 1.5” or three finger-lengths from the most extreme in-tact node. This provision prevents against block shear failure in the bamboo culm.

Theory and Predicted Behavior

It is important to note that in the constructed Full-Scale Wall Specimen, there was only one ductile hinge mechanism as indicated in the red box in Figure 21. Connection D as indicated in Figure 19, was not considered as a ductile hinge mechanism in this specimen since, due to the frame geometry, would not experience the fixed, guided end conditions, which characterizes a ductile hinge mechanism. For this reason, the system yield strength was calculated similarly to that of the isolated unit specimens. Load resisted by the rebar dowel in Connection D was considered to be negligible since non-moment resisting Connection C provided that the rebar dowel in Connection D would only experience minute rotational end deflection of no more than 9.5 degrees for the maximum lateral deflection of 10”. Therefore, the theoretical system yield strength was identical to that of the No. 3 Isolated Unit Specimen at 160.89 lbs.

Test Apparatus

The Full-Scale Wall Specimen was tested in an apparatus as seen in Figure 21. The apparatus consisted of Santa Clara University's seismic simulator machine. The Full-Scale Wall Specimen was affixed to the machine at it’s base with bolted 1” threaded steel rod. The horizontal bamboo member was affixed at both ends to the laterally displacing horizontal beam of the seismic simulator machine with ball jointed steel fixtures.

Figure 21: Full-Scale Wall Specimen in seismic simulator machine with ductile hinge mechanism boxed in red

Testing of the Full Scale Wall Specimen: Test Run 1

The testing of the Full-Scale Wall Specimen occurred in two parts. Firstly, the specimen was tested as-built in the aforementioned test apparatus seen in Figure 21. A pneumatic actuator displaced the horizontal beam connected to the horizontal bamboo member laterally according to a CUREE displacement history that can be seen in Figure 25 in Appendix A. The load vs. displacement curve can be seen in Figure 22. As the test progressed, the load increased steadily with increased deflection until around 2” of deflection in either direction. As can be seen in Figure 22, the maximum load for each cycle showed incremental degradation. In addition to this, the load, displacement curve for positive deflection as can be seen in the positive quadrant, showed increasing slopes, for each cycle. This was due to significant slip in the connections for the diagonal bamboo member and also due to splitting, which occurred in the grouted bamboo culm of the ductile hinge mechanism. At this point the test was halted in order to perform modifications to the specimen and to the displacement history.

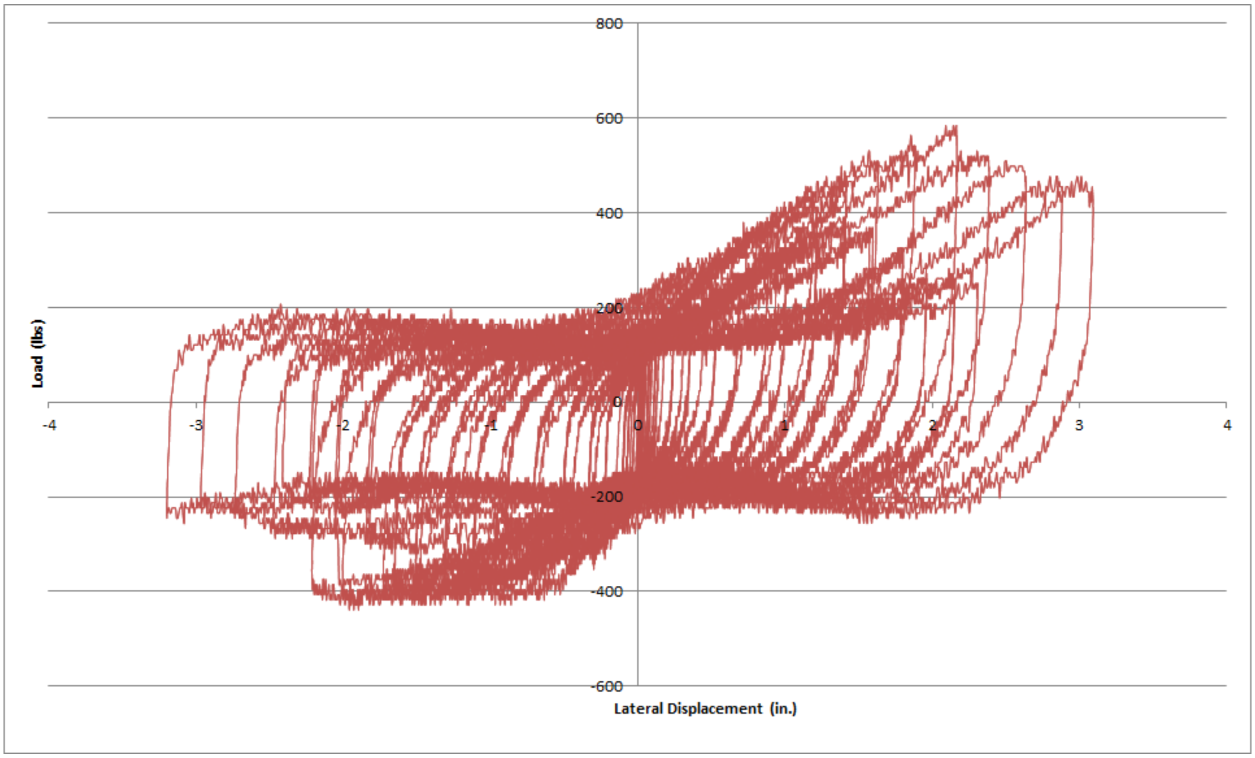

Figure 22: Load vs. displacement curve for Full-Scale Wall Specimen Test Run 1

Testing of the Full Scale Wall Specimen: Test Run 2

Following Test Run 1, it was decided that the minor failures in the frame be repaired and strengthened in order to promote deflection in the rebar dowel within the ductile hinge mechanism. In order to accomplish this, modifications were made as can be seen in Figure 23 below. Firstly, the grouted bamboo culm that had experienced splitting was wrapped tightly with steel wire. Then two more strap connections were added to the diagonal member in order to prevent slip in the frame. In addition to this, the CUREE displacement history was adjusted to increase displacement. The adjusted displacement history for Test Run 2 can be seen in Figure 26 of Appendix B.

Figure 23: Full-Scale Wall Specimen after frame connection modifications

The load vs. displacement curve for Test Run 2 can be seen in Figure 24. In contrast to the load vs. displacement curve for Test Run 1, the curves are more closely representative of the ideal ductile hinge mechanism. This shows that the significant yielding, which occurred in Test Run 1, was due primarily to slip in the frame. As evidenced in Figure 22 and Figure 24, Test Run 2 demonstrated greater load values than Test Run 1 for similar displacements.

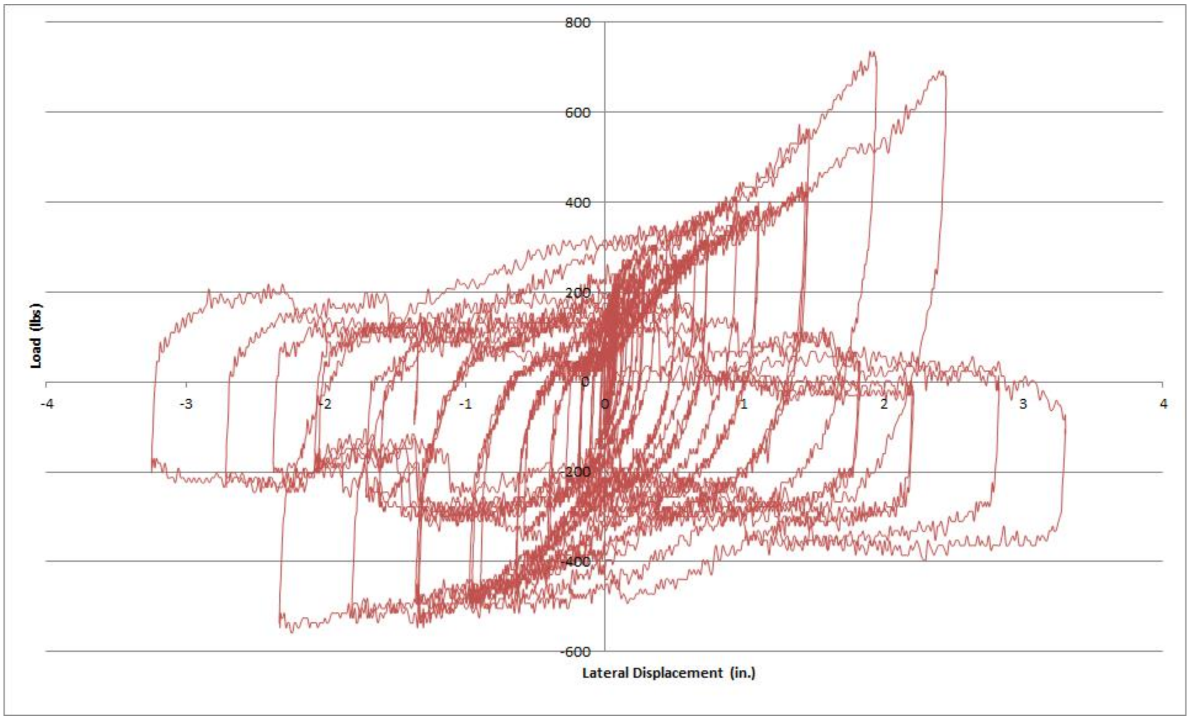

Figure 24: Load vs. displacement curve for Full-Scale Wall Specimen Test Run 2

Mode of Failure

Similarly to Isolated Unit Specimen 4, the Full-Scale Wall Specimen failed in rupture due to flexural fatigue in the rebar dowel of the ductile hinge mechanism. This result occurred after several displacement cycles. The maximum load resisted by the specimen was 735 lbs, which occurred at 1.89” in the positive direction. The maximum displacement at failure was 2.44”.

Conclusions from Test Results

As can be seen in Table 7, the ductility factor for the Full-Scale Wall Specimen was calculated at 130\6. This was determined with the initial yield displacement taken from the results of Test Run 1. The maximum displacement was taken from the point of failure, which occurred in Test Run 2. This value for the ductility factor is much greater than that of isolated unit specimen 3 and 4 despite having similar ductile hinge mechanisms with 3" No. 3 rebar dowels. This is due to a maximum displacement which was larger than that of the isolated unit specimens. Isolated Unit Specimen 4 failed similarly to the Full-Scale Wall Specimen. However, it had a maximum displacement of 0.951". Despite this, both the Full-Scale wall specimen and Isolated Unit Specimen 4 failed after a similar number of displacement cycles. The Full-Scale Wall Specimen failed after 160 cycles and Isolated Unit Specimen 4 failed after 158 cycles. The discrepancy between the values for maximum displacement could be attributed to slip in the bamboo frame or within connections in the test apparatus.

Table 7: Ductility factor and displacements for Full-Scale Wall Specimen

	Yield Displacement (in.)	**Max Displacement (in.)**	**Ductility Factor, μ**
Full Scale Wall Specimen	0.0187	2.442	136

Summary and Conclusion

Further Research Needed and Recommendations

In order to bring the CMU and bamboo braced frame structure closer to realization, much research still needs to be conducted. In order to build off of data obtained through this senior design project, it would be significant to increase design efficiency and to refine over-designed elements in order to decrease material costs.

The first suggestion to limit the overall costs of constructing these wall units is to optimize the mix design of the grout and high strength cap. This project wanted to prevent spalling in the concrete so a high strength mix was selected. Tests need to be conducted in order to find the exact strength of concrete that is needed for the wall unit to perform as expected.

In relation to concrete, another alternative to the CMU blocks would be to used crushed, recycled concrete. The blocks that we used were bought directly from Home Depot, which isn't the cheapest or most sustainable source of material. In addition, the use of these blocks is not practical since they would have to be shipped to Haiti from America, which would inherently have associated costs. There should be plenty of concrete rubble that has potential to be used in the construction of these wall units and that would help to decrease the overall cost and the environmental impact from construction.

The next area of research should be into the strap design. For this project, the straps were intentionally over designed because the ductile hinge mechanism was the specific area of focus. To prevent any slipping in the system, the connections were made with 16 gauge steel straps and Grade 40 steel self-tapping screws of 0.15" diameter. We expected these to hold but there was still substantial slipping in the connections during testing. To correct for this, extra straps were added after the initial series of tests as seen in Figure 23. These new strap configurations provided strength in two directions, which helped the performance of the wall under the cyclic loading. We fastened a strap vertically but the load was transferred through our diagonal member. The straps should be fastened in-line with the actual direction of the member load in order to effectively utilize the steel straps and decrease the total cost of construction.

Some recommendations for testing the unit specimens after finding the optimal mix design would be to test them to greater deflections than in this project. In our test specimens, we saw that the ultimate mode of failure was fatigue in the steel rebar due to the programmed cyclic loading of the MTS machine. Our recommendation would be to increase the deflections in the test specimens because we had only fatigue failure while testing these but the full wall test frame experienced failure due to deflection.

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All Equations Generated With:

http://www.codecogs.com/latex/eqneditor.php

Appendix A: Displacement Histories

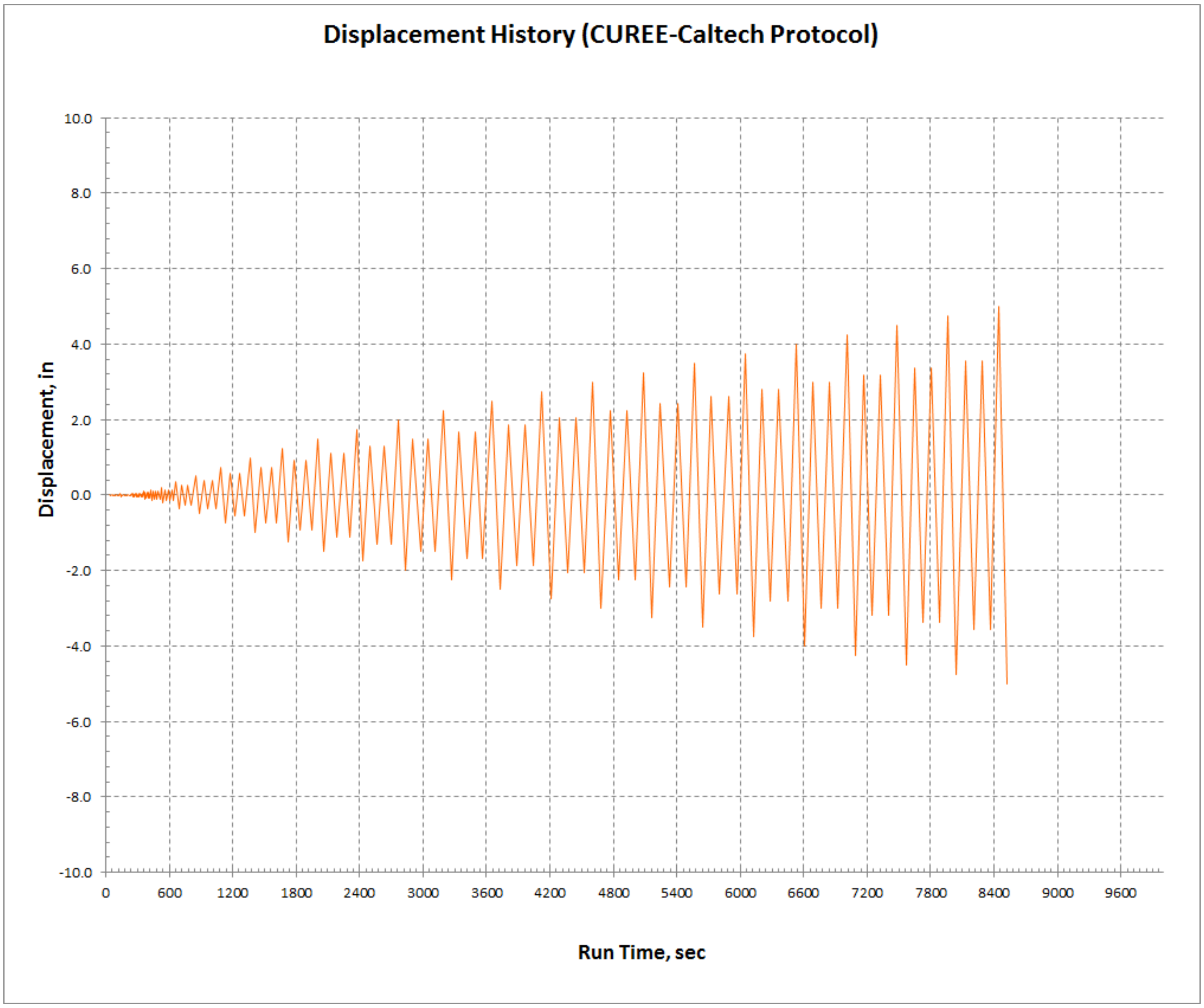

Figure 25: Displacement History for Full-Scale Wall Specimen Test Run 1

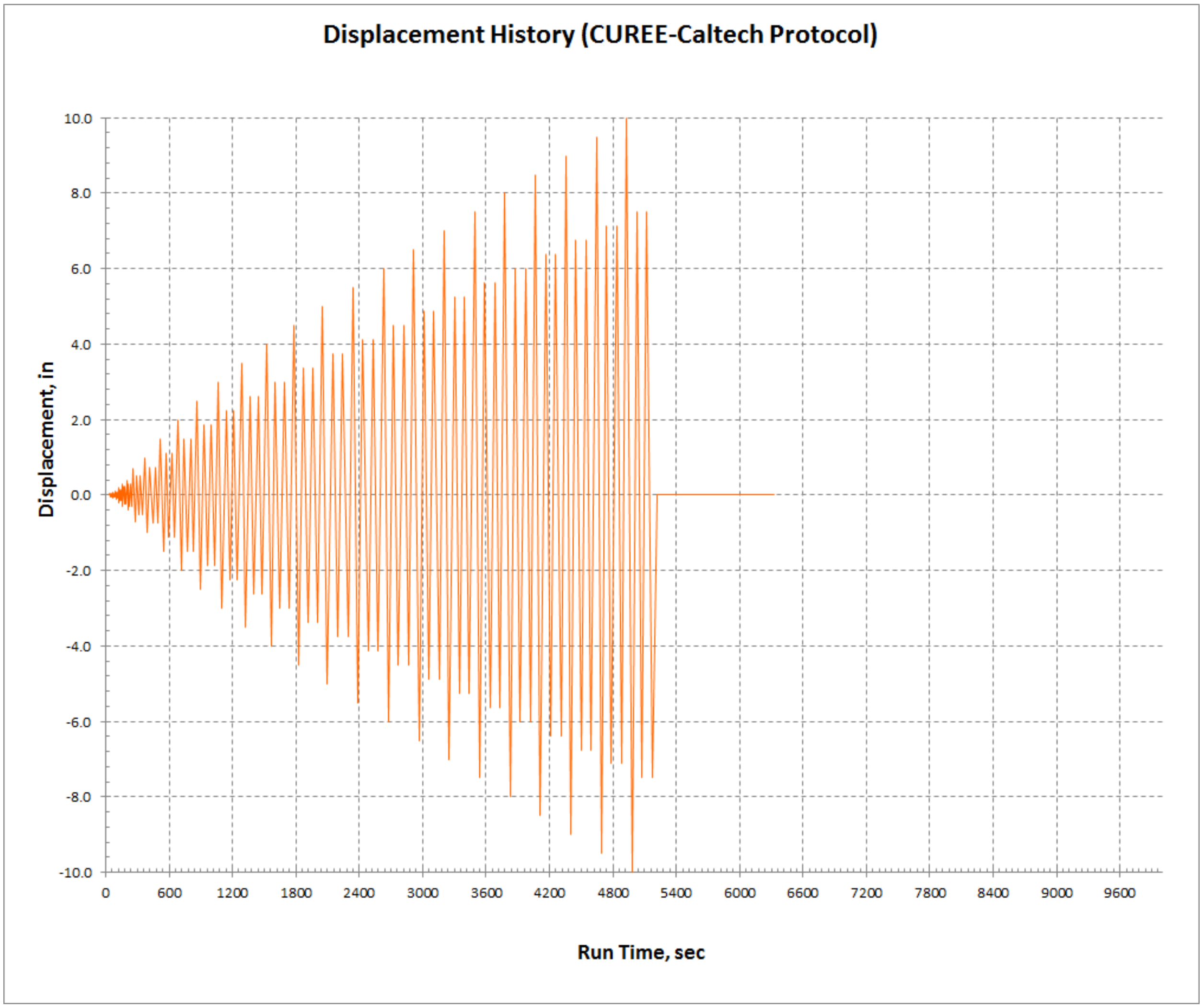

Figure 26: Displacement History for Full-Scale Wall Specimen Test Run 2

Appendix B: Construction Methods

Isolated Unit Specimens

Materials:

- 8” x 8” x 8” CMU block
- Bamboo with node
- Grout (Portland Cement, Fine Aggregate, Water)
- Steel Rebar

Construction Procedure:

1. Presoak CMU block in water for approximately 30 minutes
2. Cut bamboo node to approximately 1 foot length
3. Cut Rebar to length
    a. Consider depth of CMU block, 3” dowel spacing and length of bamboo node
4. Mix grout in concrete mixer following specified ratios for desired strength
5. Pour grout into bamboo, filling the node to the top
6. Place rebar in the center of the grout-filled bamboo end
    a. Ensure homogenous compaction by rodding all areas within the node and especially those directly in contact with the rebar
7. Let this end of the Isolated Unit Specimen cure for about 24 hours
    a. Clamps may be used to keep rebar perfectly straight and in the center of the bamboo node
8. After the bamboo ends have had 24 hours to cure, Presoak CMU block in water for approximately 30 minutes
9. Mix grout following the same mix design criteria as the first day
10. Place CMU block on plastic and apply petroleum jelly around all inside and outside edges
    a. This application prevents any water from escaping the grout mix and reducing strength
11. Pour grout into CMU block
12. Place bamboo end with exposed rebar into the center of the CMU block
    a. Ensure homogenous compaction by rodding all areas within the node and especially those directly in contact with the rebar
13. Support bamboo end using clamps and let cure for the desired amount of time before testing

CMU Plinth Wall

Materials:

- (14) 8” x 8” x 16” CMU blocks
- (4) 8” x 8” x 8” CMU blocks
- Quickrete™ Mortar Mix
- Water
- Metal Chicken Wire

Construction Procedure:

1. Wet all outer surfaces of CMU blocks
2. Mix mortar using specified ratios from Directions List on the bag
3. Apply a 1” Mortar foundation along the entire proposed length of the wall
4. Place corner CMU block onto foundation using a 8” x 8” x 16” CMU block
5. Apply mortar to the two corner edges of the next CMU block and firmly press it against the face of the corner block ensuring that they are level in both the horizontal and vertical directions
    a. Continue this step until the entire first row of CMU blocks are placed
6. For the next row, apply mortar to the top faces of the bottom row and place the smaller 8” x 8” x 8” block on top of the corner block
    a. Repeat Step 5 until the end of the next row is assembled
7. Apply mortar to the top faces of the second row
    a. Repeat step 5 until the end of the next row is assembled
8. Apply ½” of mortar to the top faces of the CMU blocks in the third row
9. Cut Metal Chicken Wire to fit the length of (3) 8” x 8” x 16” CMU blocks and place it in the middle of the top row
10. Apply and additional ½” of mortar on top of the Chicken Wire where it comes into contact with the top faces of the CMU blocks in the third row
11. Place final row of CMU blocks following step 5
12. Scrape all excess mortar from the outside surfaces of the wall and seal all creases using a mortar styling tool

Bamboo Frame and Connections

Materials:

- (2) 56” long pieces of bamboo
- (1) 68” long piece of bamboo
- (1) 60” long piece of bamboo
- (7) 16 Gauge - 24” Length by 1.5” Width Steel Straps
- (2) 55” long pieces of Steel Rebar
- (40) 0.15” Diameter Grade 8 Steel Screws
- Large aggregate
- No. 4 rebar for Shear Cap Reinforcement

Construction Methods:

1. Mix grout for column using a concrete mixer and the specified ratios of ingredients for desired strength
2. Pour grout into the two end columns of the CMU wall until it reaches the top of the third row of CMU blocks
    a. Ensure homogenous compaction by rodding in layers
3. Fill the top row of CMU blocks with large aggregate on top of the Chicken Wire to about half the height
4. Mix the grout for the High Strength Shear Grout Cap following the ratios for desired strength
5. Fill the top node of the two CMU corner ends with High Strength Grout
6. Pour High Strength Grout on top of the large aggregate until it reaches the top of the node
7. Take one of the 56” long pieces of bamboo and punch a 55” long pieces of steel rebar through its length
    a. Repeat for the other piece of bamboo and rebar
8. Fill the last open node of the bamboo with the High Strength Grout
    a. Seal the end with duct tape so that the grout does not fall out of the node but allow an opening the exact size of the rebar
9. Place the bamboo over the end column in the CMU wall and pull the rebar thru the bamboo and into the CMU wall until it reaches the bottom, creating a column
    a. Work quickly in this step so that setting does not occur in the end node before pulling the rebar through
    b. This method was chosen because of height restrictions in the lab during construction
    c. Clamps are helpful to ensure that the bamboo stays in place and does not move while the grout is curing
10. Repeat Steps 8 and 9 for the other bamboo, rebar and CMU end

11. Using a concrete vibrator or the technique of rodding, ensure tight compaction around the rebar and the surrounding grout
12. After the two columns are level and clamped in place, apply a 1” layer of High Strength Grout on top of the CMU wall
13. Bend and Place the No. 4 rebar around the columns and exposed rebar for the shear cap
14. Apply an additional inch of High Strength Grout on top of the reinforcement and shape the edges to form a cap that is flush with the rest of the wall and measures exactly 2 inches in height
15. Place the 68” long piece of bamboo diagonally, starting 11” above the bottom of the bamboo culm and about 5” from the center of the opposite bamboo culm
16. Mark distances for each area of connection on the diagonal piece
17. Fishmouth the ends for these areas of connection using a circular saw to cut the bamboo to the desired angle
    a. Use a jigsaw to cut any extra pieces or angles needed for a smooth connection
18. Place the 16 gauge straps in the area for connection and mark the distances of the nodes and where the desired holes will be drilled
    a. Ensure that the drill sites are always between two closed nodes to prevent pull-out failure
    b. If necessary, combine two straps by overlapping them and drilling through both holes when fastening
19. Drill holes in the metal straps at the desired drill sites using the same diameter as the screws
20. Repeat Step 18 for all connection areas
21. With the drilled metal straps in place, pre-drill a small hole to help the self-tapping screws enter the bamboo
22. Starting with the 60” long piece of bamboo across the top, fasten all connections, ensuring a tight and secure fit to the bamboo
23. Using a mallet, flatten all straps that are not flush to the bamboo culms and try to tighten the screws in that area again to ensure a tight fit

Appendix C: Relative Stiffness Plots for Isolated Unit Specimens

Figure 27: Relative Stiffness vs. Number of Previous Cycles for Isolated Unit Specimen 1

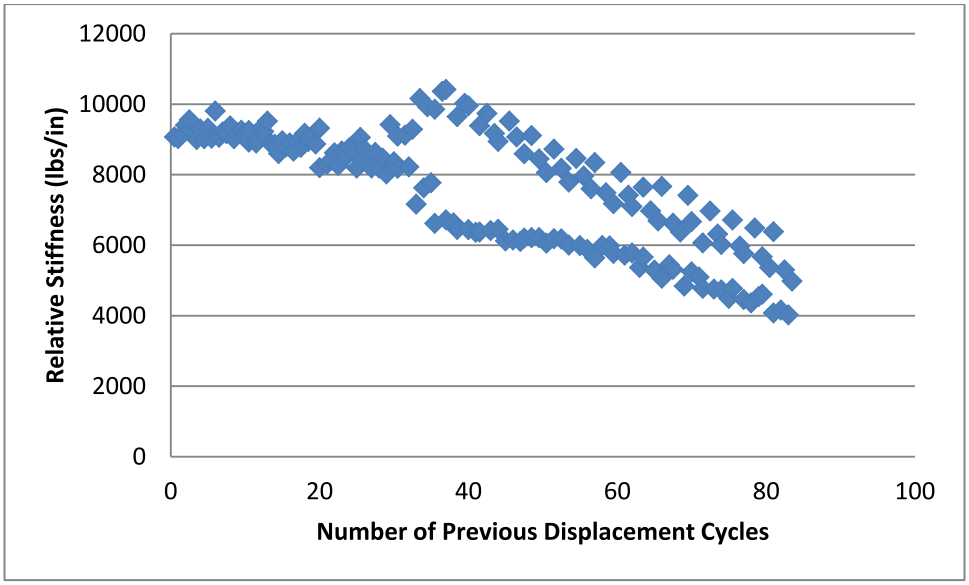

Figure 28: Relative Stiffness vs. Number of Previous Cycles for Isolated Unit Specimen 2

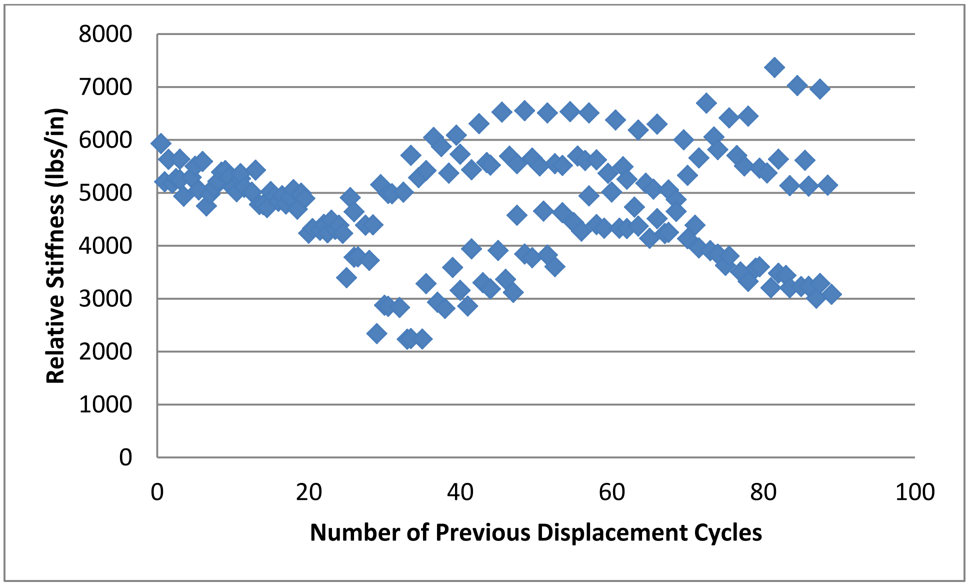

Figure 29: Relative Stiffness vs. Number of Previous Cycles for Isolated Unit Specimen 3

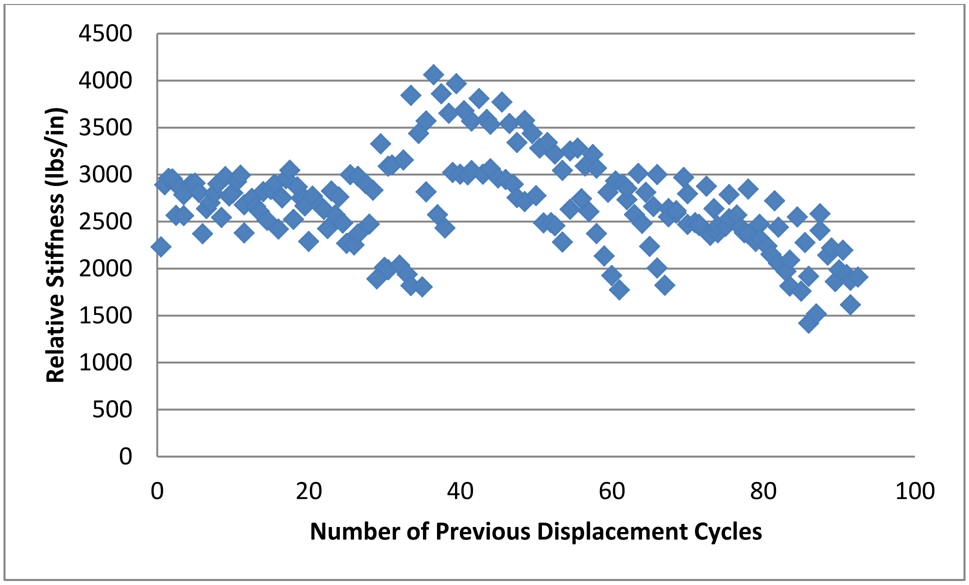

Figure 30: Relative Stiffness vs. Number of Previous Cycles for Isolated Unit Specimen 4