A NEW TAKE ON TESTING

Evaluating Design Systems in Response to the Recent Natural Disaster in Nepal

JAZMINE BROWN
A NEW TAKE ON TESTING:
Evaluating Design Systems in Response to the Recent Natural Disaster in Nepal

By

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A thesis submitted in partial satisfaction of the requirements for the Honors in Architecture and Community Design in the Department of Art + Architecture in the College of Arts & Sciences of the University of San Francisco

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On April 15, 2015, intense seismic activity wracked the central region of Nepal. This natural destruction continued for over two months, destroying homes, monuments and infrastructure. The following monsoon season added to the destruction and struggle of the people. According to the United States Agency for International Development (USAID) Fact Sheet #24, 289,037 houses were damaged by the earthquake, 605,176 houses were destroyed, 8,891 people lost their lives, and 58,700 people have sought shelter in displacement sites. This intense destruction and the resulting displacement and death have inspired many individuals and organizations to evaluate the safety of the design systems in this region. Like many others, I hope to improve the safety and preparedness of the people so that such devastation is avoided in the future.

I began by researching the areas in Nepal that experienced the most damage in the earthquake. The capital, Kathmandu, was surrounded by many locations with intense seismic activity. There are three topographical zones in Nepal: the Himalayas, the Middle Hills, and the Terai (Figure 1).

While the Himalayan and Terai regions also experienced their own troubles with this natural disaster, many of the epicenters and much of the high intensity seems to have occurred in the Middle Hills regions of Nepal. The middle hills cover about 65% of the total land area of Nepal and about 45% the population of the country inhabits this region. (“Geography”)

Much of the devastation of this area can be linked to the structural design of the construction in this region. I believe there is much that can be done to improve the current conditions and prevent further seismic damage.
BACKGROUND
The April 2015 Earthquake in Nepal

It appears that the traditional housing in the hills is ill-prepared for intense seismic activity. According to Professor Bruce Owens of Wheaton College, Massachusetts, “Perhaps the most urgent work in reconstruction is in village housing in the hills, as these are traditionally quite fragile structures.”

Although I did not focus on one specific site for this project, I considered the idiosyncrasies and challenges specific to the Middle Hills region. This includes considering challenges such as limited access to contemporary building materials due to restricted transportation.
Figure 2: Destruction caused by the 2015 Earthquake
In this thesis project I analyze the destruction of the 2015 earthquake in Nepal, specifically in the structural and architectural collapse. I have focused my research on the areas with greatest documented destruction and vulnerability, specifically Kathmandu and the settlements in the Middle Hills. The introduction of a new lateral testing mechanism can provided much needed information on the seismic strengths of vernacular construction methods.
After taking the time (one semester timeline) and space (limited storage for two half-scale walls) constraints into mind I have decided to focus on creating 1.5"=1’ scale demonstration models and clear instructions on how to design and test half-scale wall specimens on a device called the Lateral Testing Mechanism (LTM), which I have helped to develop and construct.

The clarity I hope to bring to the LTM testing process will allow future research and testing of the seismic strength and reliability of available structural systems with the impact of natural disasters in mind. The resulting findings would help the people of the Kathmandu Valley to find materials and building techniques that will best suit the reconstruction and development of their built environment. Future use and results found using this device could benefit not just the people of Nepal, but other communities where common construction practices remain untested. A better understanding of the seismic strength of available structural systems could prevent such violent destruction in future natural disasters.

**Phase 1** Research

Determine Wall Construction Methods
Create Simple Construction Manuals (Drawing & Narrative)

**Phase 2** Create & Test Models

Make Models at 1/8"=1’ scale
Test Models

**Phase 3** Conclusions

Determine Quality of Results; Draw Conclusions
Finalize Conclusions & Prepare Final Deliverables
Figure 3: Recovery Efforts after the Earthquake
Figure 4: The Kasthamandapa before and after the 2015 earthquake

Figure 5: Bamboo transitional shelter in Nepal
I have begun by researching the building types and structural systems available in the Middle Hills. There are three main materials that stood out to me: Wood, Bamboo, and Stone.

Kathmandu means ‘city of wood,’ and much of the city is built using this material. It is even said that the Kasthamandapa, a Hindu temple, was built using the wood of a single Sal tree (Shorea Robusta). Until the last century, trees like the Sal and Sisau trees were abundant all around the Middle hills of the Kathmandu Valley. Unfortunately, Sal is now mainly found in the Terai region. Lumber systems often have a high seismic strength due to the high tensile strength of lumber, but are still vulnerable to failure. In the Kasthamandapa, the longer wooden posts or beams appeared to fail, mainly towards their middles. Failure in these wooden structures also appeared at their ground connections as the wooden elements lifted out of their supports. Still, the shorter wooden elements seemed to survive. (Nakachi)

High seismic strength is also found in many structures built with bamboo. Bamboo has been used in some Nepali construction, especially temporary housing after the earthquake. Unfortunately, it currently has poor acceptance in the region due to its association with the poor. There are many species of bamboo growing in the eastern, central, and western zones of Nepal. Keshab Shrestha explains that there are large-statured bamboos and small-statured bamboos. Large statured bamboos are mainly found in the Terai and Middle hills while small statured bamboos are mainly found in the high mountains or Himalayan region. It was hard to find examples of structural failure in the bamboo construction of Nepal. This may mean that there was little to no failure of bamboo structures. It could also mean that there was simply no documentation of the failure experienced.

Conversely, Rubble stone construction in Nepal has proven to be a dangerous yet popular practice. According to the World Housing Encyclopedia (WHE), “this is a typical rural housing construction [type] in the hills and mountains throughout Nepal. It is a traditional construction practice followed for over 200 years.” There are multiple examples of safety issues related to rubble stone construction in the 2015 earthquake alone. The WHE explains, “these buildings are basically loose-fitting, load-bearing structures constructed of uncoursed rubble stone walls in mud mortar, with timber floors and roofs. They are expected to be extremely vulnerable to the effects of earthquakes due to their lack of structural integrity.” For this reason, work has been done to improve the safety of this construction type. Many approaches to this seismic reinforcement have been presented.
Ultimately I chose to focus on rubble stone masonry construction for my wall specimens. It is a commonly used construction type in the Middle Hills region of Nepal as stone can be collected from old, damaged, or collapsed structures for reuse in new buildings, especially after natural disasters. Due to this practice, the exact material properties of the stone are hard to determine.

Rubble stone structures are typically constructed using mud mortar. This material is traditionally made using a mixture of soil, water, and straw. Clay additives are usually not included in the soil component, but can be added if the soil is found to be lacking sufficient clay. The Kathmandu Valley was once a lake from the Pliocene to Pleistocene age. This has resulted in an accumulation of what are called quaternary fluvio-lacustrine sediments in the Kathmandu basin. (Piya, 21) This mix of sediments consists of silt, sand, gravel and clay. The clay in this soil is described as a “thick black lacustrine clay unit locally known as the Kalimati Clay,” which is “rich in organic matter, diatoms, plant fossils and natural gases” (Gurung, 504). The presence of clay in this soil is beneficial for the mud mortar’s plasticity under moist condition and cohesion. Still, one should be careful to monitor the proportion of clay since an increase in the clay fraction is linked to a decrease in compressive strength, according to studies conducted by Walker and Stace, which were carried out on cement-soil mortar, cement mortars and cement-lime mortars (Rashmi, 27). Lime or cement are often added to mud mortar to make what is called stabilized soil. Soils with a clay content less than 30% can be stabilized using cement, while soils with a clay content more than 30% can be stabilized using lime (Rashmi, 27). It appears that in this region, the high clay content in the soil would favor lime as a stabilizing ingredient. (Piya, 28)

Overall, the use of rubble stone construction can be very unsafe due to the improper placement of reinforcement. Even with stronger mud mortar mixes the seismic strength of a masonry system in this area can be low. The two wall construction approaches I have chosen attempt to solve this issue. By testing models based on the structural systems presented by Randolph Langenbach and Martijn Schildkamp, one can come to better understand the seismic strength and safety of each. Positive results will hopefully boost the credibility of these construction systems, which are already in use in the Kathmandu Valley.
Figure 6: Partially collapsed rubble stone structure

Figure 7: Kathmandu Valley, Himalayas in the distance
Randolph Langenbach has been described as a “historical conservationist, photographer, architect, author, and athlete.” (Spector, 19) He has conducted considerable research and led many international projects on earthquakes and their interaction with traditional construction. Currently he has focused his work on those devastated by the August 2015 Nepal earthquake. Much of his work has been devoted to preserving traditional or vernacular construction styles and techniques while ensuring seismic stability.

Of his conservation efforts he has said, “I firmly believe that the protection and remembering of the lessons of history and culture are an essential ingredient to the health of a society—and can contribute to the quality of life of everyone on the planet” (Spector 22). This is evident in his application of gabion bands to traditional rubble stone construction in Nepal. He has conducted rigorous study into the construction process in Nepal so as to better understand how to prevent structural collapse under seismic loads. He has proposed and constructed a design that he believes can aid in preventing structural collapse. Langenbach’s “Gabion Bands” Report discusses how he believes a rural stone dwelling could be constructed or rebuilt in the absence of imported materials or quality timber. It is his hope that this construction technique can be evaluated and eventually introduced as a safer system. Langenbach writes: This is a proposal for the use of a particular construction technology, rather than the architectural or engineering design of a specific structure. The concept is guided by the need in Nepal—as well as in many other countries subject to earthquakes—to improve the safety of owner-built, non-engineered construction of rubble stone masonry structures laid with mud mortar. The 2015 earthquakes in Nepal demonstrated both the particular vulnerability of this kind of construction and its widespread use within the damage district, such that entire villages were sometimes flattened by the tremors. It is also common in rural areas throughout the rest of the country. (“Stone Masonry”, 1) The below figures are examples of the designs and real-life applications of his gabion band technique.
Martijn Schildkamp is the founder and Executive Director of the Smart Shelter Foundation. According to the Smart Shelter website, “Martijn is an architect and building engineer from The Netherlands, with a passion for alternative materials and experimental construction.” He founded Smart Shelter Foundation in 2005 to with the goal “to create safe and protective constructions, which respond to the direct needs of the poorest. [He believes] that safe and affordable housing should be available to everyone” (“About Us”). Martijn has focused on developing low-tech earthquake resistant principles.

Key to the work of the Smart Shelter Foundation is the concept of active community participation and ownership. This will lead to a sense of responsibility for the users of the construction, as well as a greater guarantee that proper maintenance is sustained. Also involved is the use of “low-cost & low-tech materials and techniques, while respecting the local needs, customs, habits, influences and the environment” (“About Us”). Martijn and his team have developed multiple manuals which place importance on correct building technique and material instead of new or untested practices. The simplicity of the manuals is important to the easy spread of knowledge and seismically safe construction.

The figures below are examples of the designs and real-life applications of the Smart Shelter seismically safe construction.
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Figure 14: Wall Construction Annotated Drawing

- **wooden trusses 4" x 5"**
  - firmly tied to top beam with galvanized steel wire

- **continuous top beam rcc 1 : 2 : 4 (3/4")**
  - 4" x 14" with 2 rods 10 mm and stirrups 7 mm tor steel every 6"
  - with proper hooks 3"

- **continuous lintel of rcc 1 : 2 : 4 (3/4")**
  - 4" x 14" with 3 rods 12 mm and stirrups 7 mm tor steel every 6"
  - with proper hooks 3"

- **wall of mountain stones in cement mortar 1 : 6**
  - (if possible re-used)

- **in between stitch of rcc 1 : 2 : 4 (3/4")**
  - 3" x 14" with 2 rods 10 mm and stirrups 7 mm tor steel every 6"
  - with proper hooks 3"

- **sill stitch of rcc 1 : 2 : 4 (3/4")**
  - 3" x 14" with 2 rods 10 mm and stirrups 7 mm tor steel every 6"
  - with proper hooks 3"

- **continuous tie beam of rcc 1 : 2 : 4 (3/4")**
  - 6" x 16" with 4 rods 12 mm and stirrups 7 mm tor steel every 6"
  - with proper hooks 3"

- **footing of mountain stones (re-use)**
  - 2'9" deep in cement mortar
  - 3" of pcc 1 : 3 : 6 (3/4")
  - on layer of compacted stone soling 6"

- **bottom of lintel = 7'-0"**
When I began my research for seismic testing devices I focused on ease of access to materials and simplicity of use so as to make it usable for a rural community. I was excited to discover testing systems which were being used in South American universities such as the University of El Salvador and the Catholic University of Peru. Figure 15 displays one example of these testing devices sometimes referred to as a “mesa inclinable” or tilting platform. This technology seems to be very successful in testing lateral loads, and has inspired my smaller scale version, called the Lateral Testing Mechanism (LTM).

The Lateral Testing Mechanism is used to test the lateral strength of half-scale wall specimens. Specimens are built on a wooden base which can be tilted up by raising one edge with a cable pulley system. The lateral force \( F \) experienced by the specimen is a fraction of the specimen’s total weight \( W \), increasing with tilt as \( F = W \sin \theta \), with \( \theta \) measured as the angle of the platform from the horizontal. The resulting data will provide a qualitative understanding of how a wall system may respond to seismic forces compared to another system tested in the same manner. This will hopefully further current knowledge about the performance of the two rubble stone construction systems I will be testing.

I had planned to follow the original LTM design and mount the winch to the ground. This would have prevented the LTM from being a transportable device, limiting its use. With the direction of Professor Mark Aschheim of the Santa Clara University Civil Engineering Department, I was able to develop a “self-reacting” system. This was accomplished by bolting the winch to the assembly at the center of a horizontal member. I calculated that the dead load of the table and wall specimen would likely be 2,402.5 pounds. So to be safe I made sure that all the components of the system could withstand a one ton (2,000lb) load. I have now designed and constructed a new LTM design.
It’s important to note that specimens tested on the LTM would still be subjected to friction forces, resisting the downward gravitational pull. In this case, the lateral force experienced would be calculated using the equation $F = W \sin\theta - f$, with $f$ representing the friction force experienced by the specimen. Since both specimens will be experiencing friction forces, it does not need to be considered in final calculations.

I have also designed a method for attaching the wall specimens to the testing platforms. As indicated in Figure 18, the thin concrete “foundation” of the specimens will have threaded rods placed into it before curing. These rods will be positioned through corresponding holes in the platform so that the wall specimen can be securely fastened while under the lateral load. Once the foundation is placed, the wall will then be built upon it. It can also allow for movability of the wall specimens if the construction methods are lighter.
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Figure 18: My Lateral Testing Mechanism Design

Figure 19: Completed LTM, Front

Figure 20: Completed LTM, Back
### Figure 21: Completed LTM, Inclinometer

### Figure 22: Completed LTM, Pulley

### Figure 23: List of Materials for LTM Completion

<table>
<thead>
<tr>
<th>Item #</th>
<th>Manufacturer</th>
<th>Product Name</th>
<th>Description</th>
<th>Load Capacity</th>
<th>Price (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>66142</td>
<td>Not indicated</td>
<td>3” Aluminum Sheave Block with Hook</td>
<td>1/2” max. cable diameter</td>
<td>2,000 lb</td>
<td>9.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Diameter: 5/8”, Width 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5/6”, Length 7 3/4”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>361-412</td>
<td>Dayton Parts</td>
<td>Square U-Bolt</td>
<td>5/8” bolt holes, 2 5/6” apart</td>
<td>2,000 lb</td>
<td>17.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Steel Plate for U-Bolt Attachment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5798</td>
<td>Haul Master</td>
<td>Worm Gear Hand Winch</td>
<td>Mountable, 25’x 3/16” cable</td>
<td>2,000 lb</td>
<td>27.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>To connect winch to 2x6 and frame</td>
<td></td>
<td></td>
</tr>
<tr>
<td>95998</td>
<td>Harbor Freight</td>
<td>7”+ long 3/8” Nut and Bolt</td>
<td>Magnetic, so can be used for other projects</td>
<td>10.00</td>
<td>10.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>For mounting winch</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>TOTAL:</strong> 138.46</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
As discussed before, I have decided to focus on wall specimens based on rubble stone construction. The lateral testing mechanism is designed to test half-scale wall specimens. This will be demonstrated by my construction of the 1.5” = 1’ scale models, which I will construct based on the works of Randolph Langenbach and Martijn Schildkamp. Figures 25 and 26 display my designs of these wall systems. The two walls will be 4.5” long, 6” tall, and 1” to 1.125” wide. By creating these systems, one can directly compare the qualitative results of the LTM testing.

As discussed above, these wall specimens will be 1/8 of a regular wall. So, I will be using mud mortar to bind the courses that are about 0.2” tall. Because it’s meant to mimic the rubble stone used by builders in Nepal’s Middle Hills, there are few limits on the shape of the stones, except for the wall width of 1” to 1.125”. This means that through-stones would be the largest, at 0.19” tall by 1” to 1.125” wide, with an undetermined length.

I have developed a list of materials that would be needed to construct two half-scale wall specimens. (Figure 24) Although I will be designing my models as 1.5”-1’ scale, this is a helpful visualization of how one might go about designing future wall specimens.

### WALL #1 (LANGENBACH)

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Dimensions</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tilting Platform</td>
<td>Palate, Metal strip, winch attachment</td>
<td>40&quot;x48&quot;x5&quot; = 3'4&quot;x4'</td>
<td>1</td>
</tr>
<tr>
<td>Base Course</td>
<td>Concrete</td>
<td>6&quot;x9&quot;x3'</td>
<td>1</td>
</tr>
<tr>
<td>Rubble Stone</td>
<td>Slate</td>
<td>1.5-1.75&quot; tall, up to 9&quot; long</td>
<td>1</td>
</tr>
<tr>
<td>Gabion Band</td>
<td>Wire mesh roll</td>
<td>Minimum 1.5'x30' (1&quot; squares)</td>
<td>1</td>
</tr>
<tr>
<td>Mud Mortar</td>
<td>Sand + Clay + Water (+ Lime if stabilized)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### WALL #2 (SCHILDKAMP)

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Dimensions</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tilting Platform</td>
<td>Palate, Metal strip, winch attachment</td>
<td>40&quot;x48&quot;x5&quot; = 3'4&quot;x4'</td>
<td>1</td>
</tr>
<tr>
<td>Base &amp; Bond beams</td>
<td>Concrete</td>
<td>2&quot;x8&quot;x3', 1.5&quot;x8&quot;x3', 3&quot;x8&quot;x3'</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Small foundation</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Reinforcement</td>
<td>Rebars (use a threaded rod)</td>
<td>0.197 in (5mm)</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>About #2 Rebars (1/4&quot;)</td>
<td>0.236 in (6mm)</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Stirrups</td>
<td>0.138 in (3.5mm)</td>
<td>80</td>
</tr>
<tr>
<td>Rubble Stone</td>
<td>Slate</td>
<td>1.5-1.75&quot; tall, up to 8&quot; long</td>
<td>-</td>
</tr>
<tr>
<td>Mud Mortar</td>
<td>Sand + Clay + Water (+ Lime if stabilized)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 24: Hypothetical Wall Specimen Materials List
Figure 24: Sketches of Wall Design

- HALF-SCALE
- FOUNDATION = CMU?

OVERALL:

3'-3.5' = 4.5' (up to 6')

MORE LIKE 8-9''

OR LESS TO FIT ON PALATE??

NEED:

- CONCRETE "foundation"?
- "Rubble Stone" @ HALF THE SIZE - LOW SPHERICITY
- 'GABION' BANDS (HALF THE SIZE -> WIRE MESH)
- CLAY MORTAR (4 LIME?) (CEMENT?)

2 Palates w/ 1) METAL STRIP, 2) Winch Attachment
(40 x 48'')

3) Reinforcement?
4) ABILITY TO CONNECT TO WALL "FOUNDATIONS"
Figure 25: Randolph Langenbach Wall Design
Figure 26: Martijn Schildkamp Wall Design

- Rubble Stone
- Concrete Foundation
- Reinforced Concrete Bands

Dimensions:
- Total height: 6" (152.4 mm)
- Width: 4.5" (114.3 mm)
- Foundation depth: 1.125" (28.6 mm)
- Additional layers:
  - 0.25" (6.4 mm)
  - 1.19" (29.7 mm)
  - 0.19" (4.8 mm)
  - 1.75" (44.5 mm)
  - 0.19" (4.8 mm)
  - 1.29" (32.7 mm)
  - 0.375" (9.5 mm)
  - 0.75" (19.0 mm)

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Below are the models I have designed based on my wall specimens I proposed above. Each model is at 1.5”-1” scale. I used these to demonstrate how the Lateral Testing Mechanism and wall specimens would interact as a whole. After constructing the LTM and two wall specimens, I tested them to compare both rubble stone systems.
Figure 31: Mud Mortar

Figure 32: Form, First Iteration

Figure 33: Forms, Second & Third Iterations
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Figure 34: Beginning Concrete Mix

Figure 35: Final Concrete Mix

Figure 36: First Iteration Foundation Attachments

Figure 37: Final Iteration Foundation Attachments

Threaded Rods
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Figure 38: Third Iteration of Concrete

Figure 39: Wire used as Reinforcement in Concrete Elements

Wire “Rebar”

Figure 40: Reinforcement in Concrete
Figure 41: Example of Failure in First two Iterations

Figure 42: Final Concrete Elements

Figure 43: Langenbach Wall Materials

Figure 44: Wall Construction – Through Stone

Gold Quarts Stone
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TESTING

Round 1 Procedure

A ruler was used to measure the length the horizontal and vertical components of the testing platform to calculate $e$, or the angle of each incremental change.
Figure 59: Schildkamp Wall Specimen Testing

Figure 60: Schildkamp Wall Specimen Testing

Figure 61: Schildkamp Wall Specimen Testing
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Figure 61: Schildkamp Wall Specimen Failure

Figure 62: Schildkamp Wall Specimen Failure

Figure 63: Schildkamp Wall Specimen Failure
TESTING

Round 1 Procedure

For this round of testing I decided to also build and test a control. Although not vital to my comparative approach, it will provide more insight into how an unreinforced wall system would fail at this scale.
Figure 71: Schildkamp Wall Specimen Testing

Figure 72: Schildkamp Wall Specimen Testing

Figure 73: Schildkamp Wall Specimen Failure

Figure 74: Schildkamp Wall Specimen Failure
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Figure 78: Control Wall Specimen Testing

Figure 79: Control Wall Specimen Testing

Figure 80: Control Wall Specimen Failure

Figure 81: Control Wall Specimen Failure
<table>
<thead>
<tr>
<th></th>
<th>Langenbach</th>
<th>Schilkamp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (W)</td>
<td>1.84lb (1 lb)</td>
<td>1.88lb (1 lb)</td>
</tr>
<tr>
<td>Height 1 (X1)</td>
<td>13.5oz</td>
<td>14.0 oz</td>
</tr>
<tr>
<td>Angle 1 (θ1)</td>
<td>0.5&quot;</td>
<td>0.5&quot;</td>
</tr>
<tr>
<td>Height 2 (X2)</td>
<td>6.34°</td>
<td>6.34°</td>
</tr>
<tr>
<td>Angle 2 (θ2)</td>
<td>1&quot;</td>
<td>1&quot;</td>
</tr>
<tr>
<td>Height 3 (X3)</td>
<td>14.03°</td>
<td>14.03°</td>
</tr>
<tr>
<td>Angle 3 (θ3)</td>
<td>1.5&quot;</td>
<td>1.5&quot;</td>
</tr>
<tr>
<td>Height 4 (X4)</td>
<td>20.56°</td>
<td>20.56°</td>
</tr>
<tr>
<td>Angle 4 (θ4)</td>
<td>2&quot;</td>
<td>2&quot;</td>
</tr>
<tr>
<td>Height 5 (X5)</td>
<td>25.57°</td>
<td>25.57°</td>
</tr>
<tr>
<td>Angle 5 (θ5)</td>
<td>2.5&quot;</td>
<td>2.5&quot;</td>
</tr>
<tr>
<td>Height 6 (X6)</td>
<td>32°</td>
<td>32°</td>
</tr>
<tr>
<td>Angle 6 (θ6)</td>
<td>3&quot;</td>
<td>3&quot;</td>
</tr>
<tr>
<td>Height 7 (X7)</td>
<td>36.87°</td>
<td>36.87°</td>
</tr>
<tr>
<td>Angle 7 (θ7)</td>
<td>3.5&quot;</td>
<td>3.5&quot;</td>
</tr>
<tr>
<td>Height 8 (X8)</td>
<td>41.19°</td>
<td>41.19°</td>
</tr>
<tr>
<td>Angle 8 (θ8)</td>
<td>4&quot;</td>
<td>4&quot;</td>
</tr>
<tr>
<td>Height 9 (X9)</td>
<td>45°</td>
<td>45°</td>
</tr>
<tr>
<td>Angle 9 (θ9)</td>
<td>-</td>
<td>4.5&quot;</td>
</tr>
<tr>
<td>Height At Failure (XMAX)</td>
<td>-</td>
<td>48.37°</td>
</tr>
<tr>
<td>Angle at Failure (θMAX)</td>
<td>4&quot;</td>
<td>4.5&quot;</td>
</tr>
<tr>
<td>Force at Failure (F = Wsinθ)</td>
<td>1.30</td>
<td>1.41</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Langenbach</th>
<th>Schilkamp</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (W)</td>
<td>2.20lb</td>
<td>1.95lb</td>
<td>2.8lb</td>
</tr>
<tr>
<td>Height At Failure (XMAX)</td>
<td>4&quot;</td>
<td>3.5&quot;</td>
<td>4.5&quot;</td>
</tr>
<tr>
<td>Angle at Failure (θMAX)</td>
<td>45°</td>
<td>41.19°</td>
<td>48.37°</td>
</tr>
<tr>
<td>Force at Failure (F = Wsinθ)</td>
<td>1.56</td>
<td>1.28</td>
<td>2.09</td>
</tr>
</tbody>
</table>

Figure 82: Testing Round 1 & 2 Results
CONCLUSIONS

Testing Observations

After testing my wall specimens, I’m able to make multiple observations regarding the concrete mixing, mud mortar, and metal components of my miniature models.

To begin, I had difficulty finding the right mix that would both simulate a full scale mix and sustain an increasing lateral load without crumbling. I made my forms out of cardboard and chipboard, painting the inside with acrylic paint (black) and then spraying it with Pam cooking spray to prevent the concrete from adhering to the forms. It’s important to note that the Schildkamp design appears to use concrete elements poured in place. This would have been extremely difficult at such a small scale, but is likely to have improved the bond between stone and concrete if utilized. I then developed three iterations of concrete, each with different mix ratios. I used sand to simulate both the coarse and fine aggregates. After two mixes that crumbled under low force (crushed in my hand), I decided to make my concrete elements with a mix of cement and water. They were reinforced with wire pieces to simulate the real-life reinforcement. Since the wall specimens’ joints were being tested, not the stone and concrete elements, I believe my final concrete pieces fulfilled their purpose in my testing.

I used the mud mortar for two reasons. Firstly, it is a common element in Nepali vernacular design. Secondly, I needed to use a material that would allow significant failure at the scale which I made my smaller models. This is because this testing I conducted was meant to evaluate the joint failure of a wall system instead of failure in the individual elements. Lime or cement can be added in the larger half-scale models to strengthen the mortar, but for this scale of testing it was not necessary.

Although I had originally intended to include clay into my mortar mix, I was dissuaded to do so by my advisor. Martijn explained to me that there are many types of soil available and while the locals often knew how to find the best clay-rich soils, this wasn’t always the case. Instead, I chose to use the soil available in my area. When compared to the Nepal soil, it was probably much lower in clay content. This may mean that the mud mortar in Nepal is stronger and more reliable.
The size of full scale steel mesh used for gabion design has typically 1” to 4” openings. Scaled down to 1.5” = 1’ scale, they would be from 1/8” to 1/2” sized openings. In my models I used an expandable metal mesh with a diamond pattern and 1/16” to 1/2” openings. I believe this is a fairly accurate representation. Similarly, the wire I used to reinforce the concrete elements may have been a bit large and ill-shaped if they were meant to truly represent the rebars used in reinforced concrete. Still, both the mesh and wire appeared to work with the systems and accurately depict how a full scale wall may react to similar testing.

When testing, I increased the angle of the platform incrementally, lifting it ½” upward each time. Figure 82 gives a list of calculations for each of these increments until failure of the wall specimens. I used the equation $F = W \sin \theta$, which I referenced above, to understand what force was placed upon my wall specimens. Since my mini models lacked the inclinometer of the larger scale LTM, I measured the horizontal and vertical components of the testing platform to calculate $\theta$, or the angle of each incremental change. Figure 83 demonstrates this.

There were noticeable differences in the weights of the specimens during both rounds of testing. The control specimen, tested in round 2, was significantly heavier than the other specimens. The increased weight can be attributed to its being made entirely of stone and mud. Also the mortar hadn’t completely dried at the time of testing, and therefore had a high water content. This appeared to be very influential in the testing of the specimens as increased weight led to a higher force at failure. (Figure 82) I believe that this is because a heavier self weight can actually create a better connection between the materials. A life-sized wall also has the weight of a roof upon it. All this added weight is important to the structural system.

Failure appeared to occur mainly between the stone courses and added elements (gabion and concrete bands). This may also explain why the control was stronger, as it lacked these weaker bonds between elements. In a larger scale of construction, this type of failure may not occur.

Another important point was made by Randolph Langenbach about the absence of dynamic frequency. This is important to consider since as dynamic frequency increases, the masonry separates and a momentary frictionless surface develops.
However, it would be difficult to incorporate both lateral and dynamic loads into this one testing mechanism. By focusing on the lateral strength I’m able to isolate one basic aspect of seismic failure.

Through my creation of smaller scale models I was able to demonstrate how the LTM and wall specimens can be used for accurate testing. Even at a smaller scale, the results of my testing were intriguing and are likely to be beneficial to those proposing these designs. As can be seen in Figure 82, there was no clear winner in the test of stronger wall system. Still, it’s important to consider that Schildkamp’s design typically uses cement or lime mortar in construction of the walls. Since the concrete horizontal reinforcement elements appeared to separate from the stone during failure, it’s clear that mud mortar is probably not a safe replacement for traditional mortars.

The next steps in this research would be construction and testing of half-scale wall specimens so as to better understand the Lateral Testing Mechanism. Evaluation and improvement of this project will hopefully develop the Lateral Testing Mechanism into a highly valued asset in the field. I believe that my work with the LTM will provide a much easier field testing process for communities that may be lacking access to more “modern” materials. It can provide a qualitative and comparative understanding of the safety of construction types, especially vernacular or traditional building types. Current Nepal building codes highlight the importance of safe masonry construction, but will hopefully also evolve to accept new testing standards.

The University of San Francisco emphasizes our commitment to Social Justice. It is my hope that this research and future findings will come to help those most affected by major natural disaster, not just in Nepal but all over the world. Hopefully it can adapted to other earthquake-prone areas, especially in poorer countries or communities.
FIGURES


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