D-LAB: SCHOOLS

Marbu Village School Design

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Introduction

On April 25th 2015, a 7.8 magnitude earthquake shook Nepal. Less than a month later the country experienced another earthquake, this one with a magnitude of 7.3. The two consecutive earthquakes devastated families and communities across the country and now the people of Nepal must work to rebuild their infrastructure. It is a great task, but also a great opportunity. There is a chance to bring new design consideration and construction techniques into the vernacular of Nepalese architecture to ensure a more stable and healthy future for the country.

In the months after the earthquakes, Nepal received significant funds to aid in rebuilding destroyed infrastructure. The Shree Kalika Secondary School, located in Marbu village, is but one example. Schools are a top priority when it comes to rebuilding. Not only are they vital for their role in educating the younger generation, but they also act as a central gathering point for the community to come together. Rebuilding schools with seismic resilience in mind helps education return to normal and ensures the safety of children in the case of future earthquakes, a top priority for families. Furthermore, focusing efforts on schools allows for access to the greater community so that everyone can participate and learn from the construction process and implement similar techniques into the rebuilding of their own homes and other buildings.

MIT's D-Lab is teaming up with local partners to develop a suitable design for the school in Marbu. Through this report, we present a design for a simple school building. It features a modular classroom structure with a plan that is tailored to the resources and restrictions of the region, yet also flexible enough to be easily replicated and modified. Leading up to this design, we sought to understand the physical and social context within which our building must function. All of our design decisions are based on thorough research and technical simulations, yet we have always kept the people who must occupy the building at the heart of the project.

Understanding the Thermal Context

Based on the geographic and economic limitations faced in Marbu, our design includes no mechanical heating and cooling systems, but instead employs passive strategies. To effectively use passive heating and cooling systems, a comprehensive understanding of the local climate is required. Unfortunately, no weather data is available from Marbu, so a weather file from the Katmandu International Airport was used. We analyzed the data using Climate Consultant, an application that helps architects understand the subtle attributes of climate and its impact on built form. Katmandu's geographically proximity to Marbu makes it a sufficient choice for estimating the local climate.

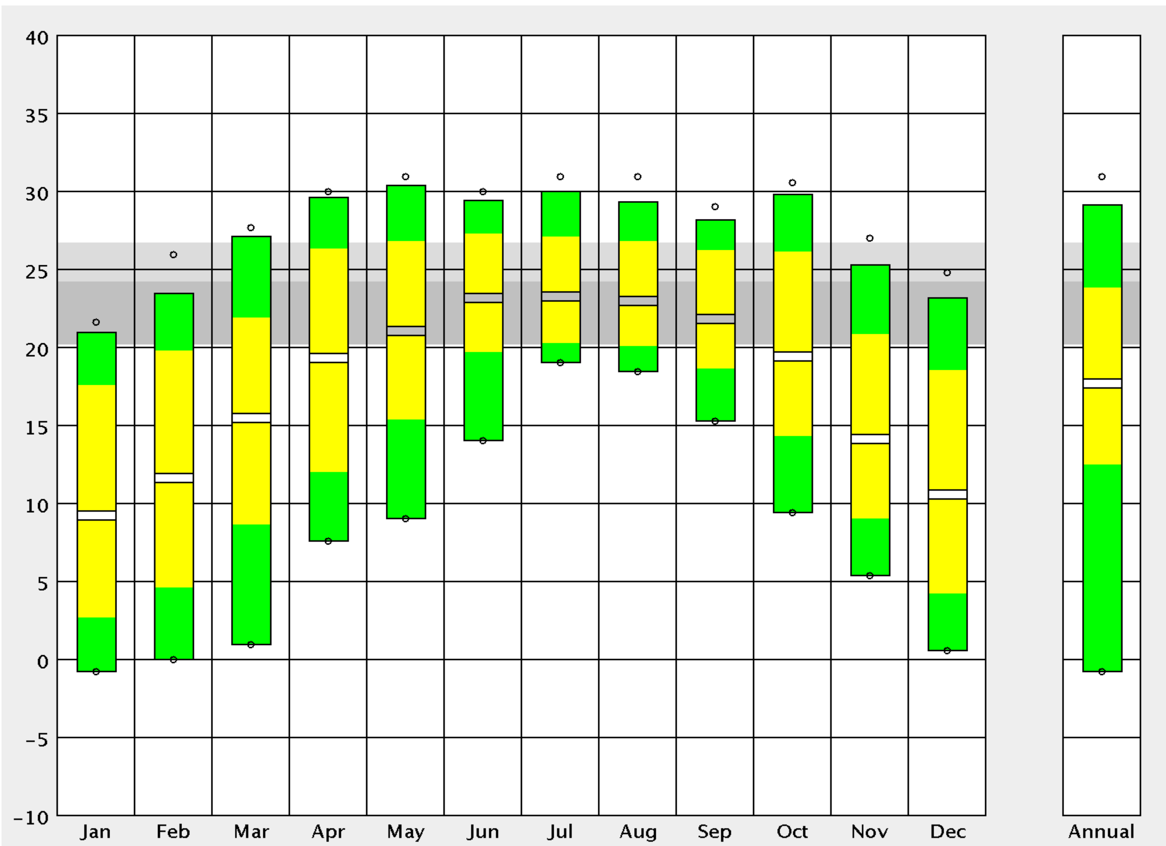

Figure 1 Average monthly temperatures (°C) in Katmandu. The grey region indicates thermal comfort, with the light grey zone accounting for the comfort of individuals used to warm climates.

Temperatures in Katmandu are cool in the winter with lows down to 0°C and warm in the summer with highs up to 30°C. Overall, however, the temperature is fairly temperate. As displayed in Figure 1, it usually falls within a comfortable zone, especially during summer months. During the winter, conditions are further from the comfort zone on average. Accordingly, our first priority was to mitigate cold temperatures during the winter months.

Thermal Model

To test the thermal properties of our proposed materials, the team created a simple model. Since the near-freezing winter temperatures in Marbu were identified as a major concern, the team focused on testing insulation's ability to increase the internal temperature.

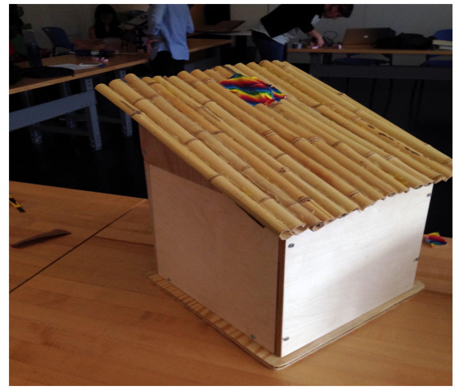

Figure 2 Thermal Model for testing

The original model incorporated a shed roof made of bamboo, with shredded paper to simulate natural insulation, supported by a lightweight cardboard structure under the roof. The walls were built of plywood. The outer surface was a dual-level waterproof roof constructed by splitting sticks of bamboo lengthwise and interlocking the pieces: a lower level was laid of bamboo cupping upwards, and a second level was laid cupping downwards (Figure 3). We used four sensors to gauge the success of our model: measuring the outside roof temperature, inside roof temperature, outside air temperature, and inside air temperature.

Figure 3 Schematic of interlocking bamboo roof design

Thermal Model Results

In the first week of testing, the differences between the outside air temperature and inside air temperature were minimal, and always less than 5°C. On average, as seen in Figure 4, the recorded inside temperature was 0.14°C warmer than the outside temperature. This small difference does little to protect students from harsh winter conditions, and even when body heat helps warm the space students will be cold. For the second iteration, we wanted to increase the effectiveness of insulation to mediate internal temperatures.

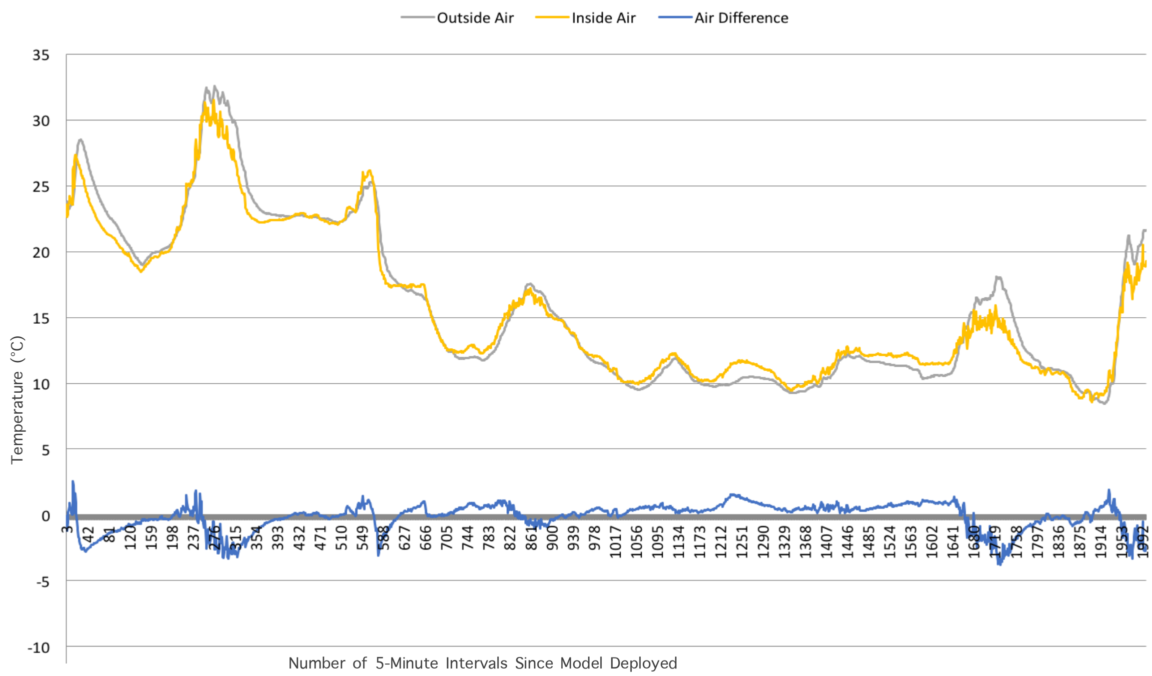

Figure 4 Week 1 Air Temperature Measurements. Temperature difference calculated as Outside Air Temperature minus Inside Air Temperature.

Figure 5 Modification to testing model for week 2. Rigid foam added as insulated lining.

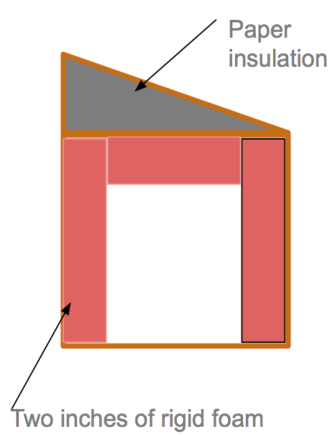

Figure 6 Insulation schematic

Thermal Model Redesign and Results

In light of preliminary results, the teamed added additional insulation, before the second week of testing. Two inches of rigid foam padded all interior surfaces, except the floor (Figures 5 and 6).

After increasing the level of insulation, the inside temperature was noticeably higher than the outside temperature (Figure 7). A temporal delay was also observed because increased insulation slowed the effects of external temperature changes on internal temperatures.

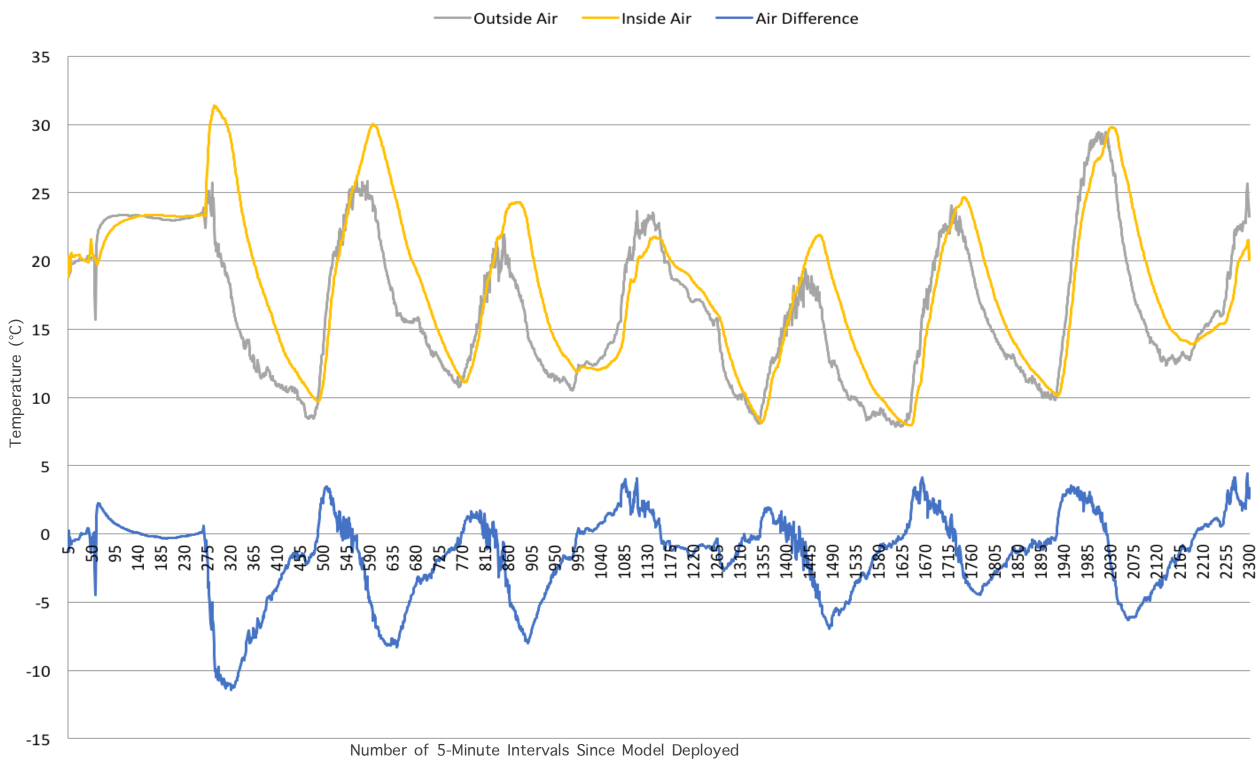

Figure 7 Week 2 Air Temperature Measurements. Temperature difference calculated as Outside Air Temperature minus Inside Air Temperature**.**

During this second week, the temperature difference was as large as 10°C. This is partially due to the higher levels of solar radiation during the second week, as seen in Figure 8. The additional energy from the sun produced more heat that could be stored in the structure. However, the additional insulation capitalized on the added heat, further increasing the temperature difference. This effect will be more pronounced when children act as heat sources within the school. Recognizing the important thermal affects of insulation, further tests and simulations were conducted to find the optimal level of insulation.

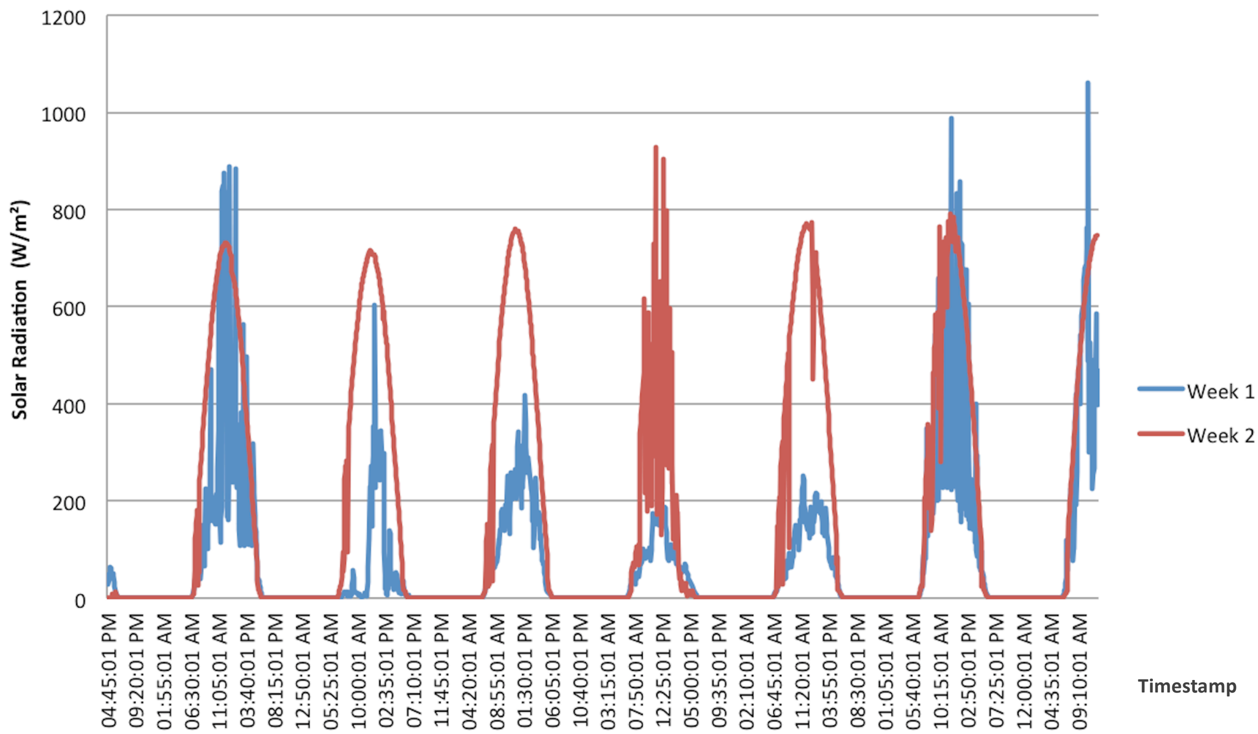

Figure 8 Solar Radiation During Week 1 and Week 2. Readings began on a Monday afternoon and were completed on the next Monday.

Energy Study and Simulation for Original Design

Using our initial design concept, we used Archsim to come up with a preliminary scaffolding for our thermally-oriented design goals. Archsim is a program that utilizes EnergyPlus simulations to test thermal conditions within simple architectural models. It is a tool that is best used for early design exploration to identify broad plans such as basic building shape, window to wall ratio, and construction materials that have the greatest potential for building performance and comfort.

Our initial form had a 7m x 16m block with a pitched roof divided into two classrooms with openings for windows on the north and south sides, as seen in Figure 9. Our goal through these simulations was to focus on materiality in a thermal context and not yet to improve on the design shape.

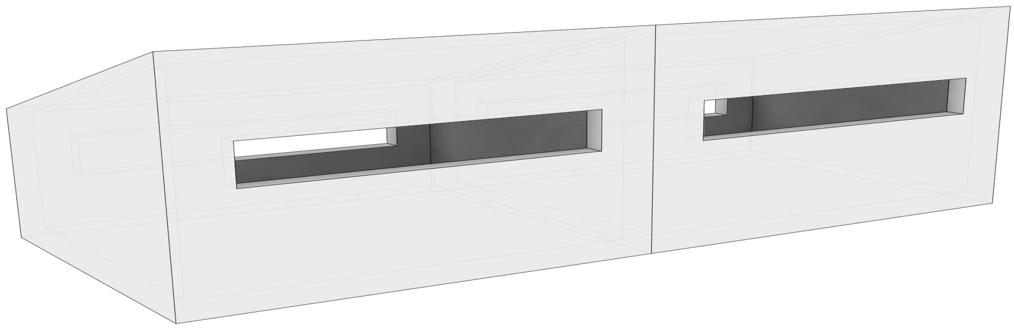

Figure 9 Simulation model for Archsim tests. Large windows are simplified to represent the general window-to-wall ratio and heights. The windows are facing north and south and remain constant for these simulations.

We began by analyzing the effects of different insulation quantities in our school by varying our effective R-values on the roof, floor, and walls. The R-value is a measure of thermal resistance for a particular material: the ratio of the temperature difference across an insulator and the heat transfer per unit area per unit time under uniform conditions (R $[m^2 \cdot K/W] = \Delta T/\dot{Q}_A$). Put more simply, it is a measure of the thermal resistance, or insulating properties, of a certain material construction.

Through simulations, we noticed that increasing insulation was extremely helpful for keeping the internal temperatures moderate, but only up to a certain point as additional increases to already high R-values made a minimal difference. For example, as shown in Figures 10 and 11, for the first two weeks of January, keeping all other factors constant, when the R-values for the walls increased from 2 to 3.5, there is a notable difference in indoor air temperatures, but when the R is changed from 3.5 to 5, as shown in Figures 11 and 12, barely any difference registers. Similar results were also found when looking at the roof.

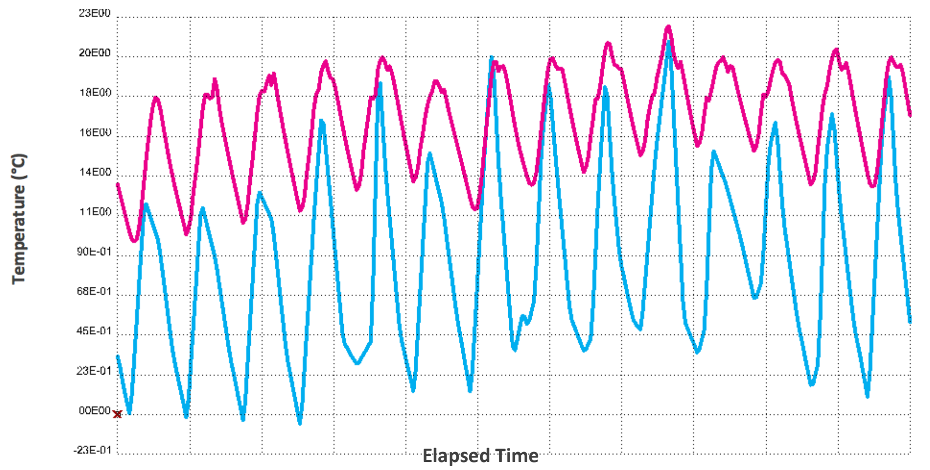

Figure 10 Temperature with R-2 Walls. Jan 1-14. Blue line: Site Outdoor Air Drybulb Temperature. Red Line: Zone Operative Temperature.

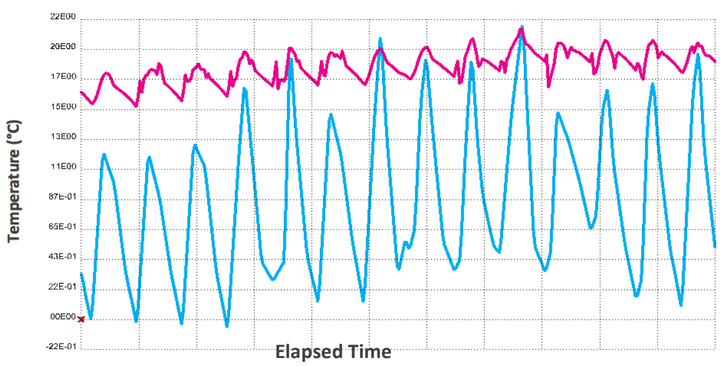

Figure 11 Temperature with R-3.5 Walls. Jan 1-14. Blue line: Site Outdoor Air Drybulb Temperature. Red line: Zone Operative Temperature.

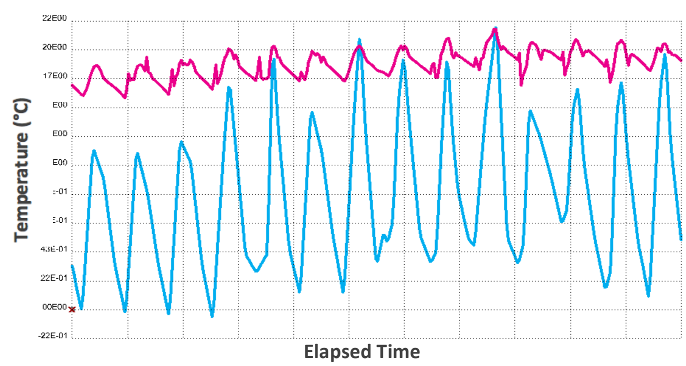

Figure 12 Temperature with R-5 walls. Jan 1-14. Blue line: Site Outdoor Air Drybulb Temperature. Red line: Zone Operative Temperature.

We also found that the properties of the floor made a very significant difference when it comes to heat loss in the winter. When comparing a "slab-on-grade" floor to the very basic "default construction," there was a 5°C difference in temperature. A slab-on-grade floor uses a concrete lab that rests directly on the natural grade, making it a technique that lends itself easily to most types of terrain (with the exception of heavily sloped sites). It adds thermal mass within the building, which has the ability to absorb and store heat, greatly helping to regulate interior temperatures. Furthermore, it reduces risk of problems due to humidity and water infiltration[1]. Without this kind of solid foundation, our simulations often found it was colder inside the school in the winter than outside the school, even during the warmest parts of the day. This is likely due to conduction when the ground is cold and is difficult to reheat, especially because it has limited exposure to radiant heat.

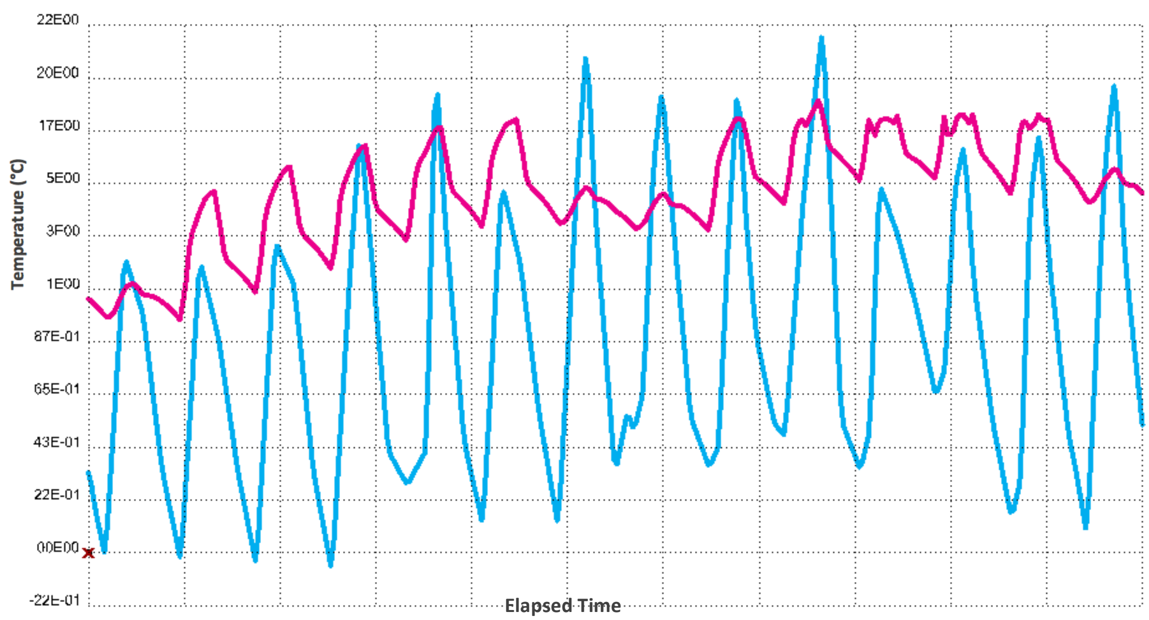

Figure 13 Temperature with Slab Floor. Jan 1-14. Blue line: Site Outdoor Air Drybulb Temperature. Red line: Zone Operative Temperature.

After numerous iterations, we formulated a building goal that utilized a roof and walls with an expected R-value of about 3.5 $m^2 \cdot K/W$. This could be achieved by making a thatch roof, using dried vegetation that is gathered, bundled, and secured to insulate the roof. Due to the thousands of air pockets that exist between and within the stems of vegetation, thatch is a very effective insulator and 15 cm should be sufficient to achieve our desired R-3.5[2].

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[1] *Ecohome*. N.p., n.d. Web. 17 Dec. 2015. < http://www.ecohome.net/guide/slab-grade-technical-guide>

[2] *McGhee & Co Roof Thatching*. N.p., n.d. Web. <http://www.thatching.com/thatching.html>.

For these simulations, we focused more on warming the school up in the winter rather than cooling it down in the summer. When we shifted our gaze to examine the summer months (looking at the first two weeks in July as a sample), our simulations show that the maximum temperatures in our school are comparable to that of outside temperatures, making it important to utilize other forms of passive cooling: for example, have windows that are able to open and create a breeze, and have shading to minimize solar radiation in the summer. We focused on these concepts in further testing and simulations.

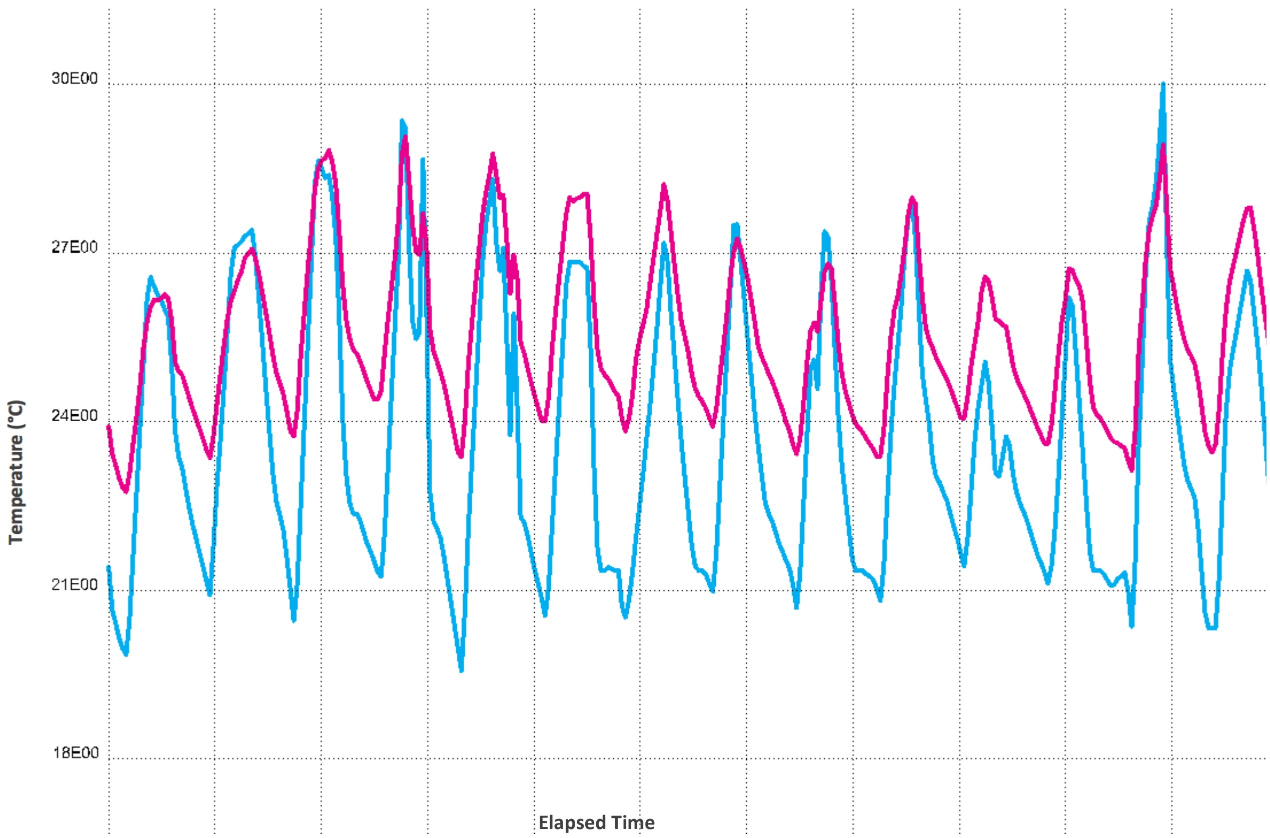


Figure 14 Summer Temperatures with R-3.5 Roof and R-3.4 Walls. July 1-14. Slab-on-grade floor. Blue line: Site Outdoor Air Drybulb Temperature. Red line: Zone Operative Temperature.

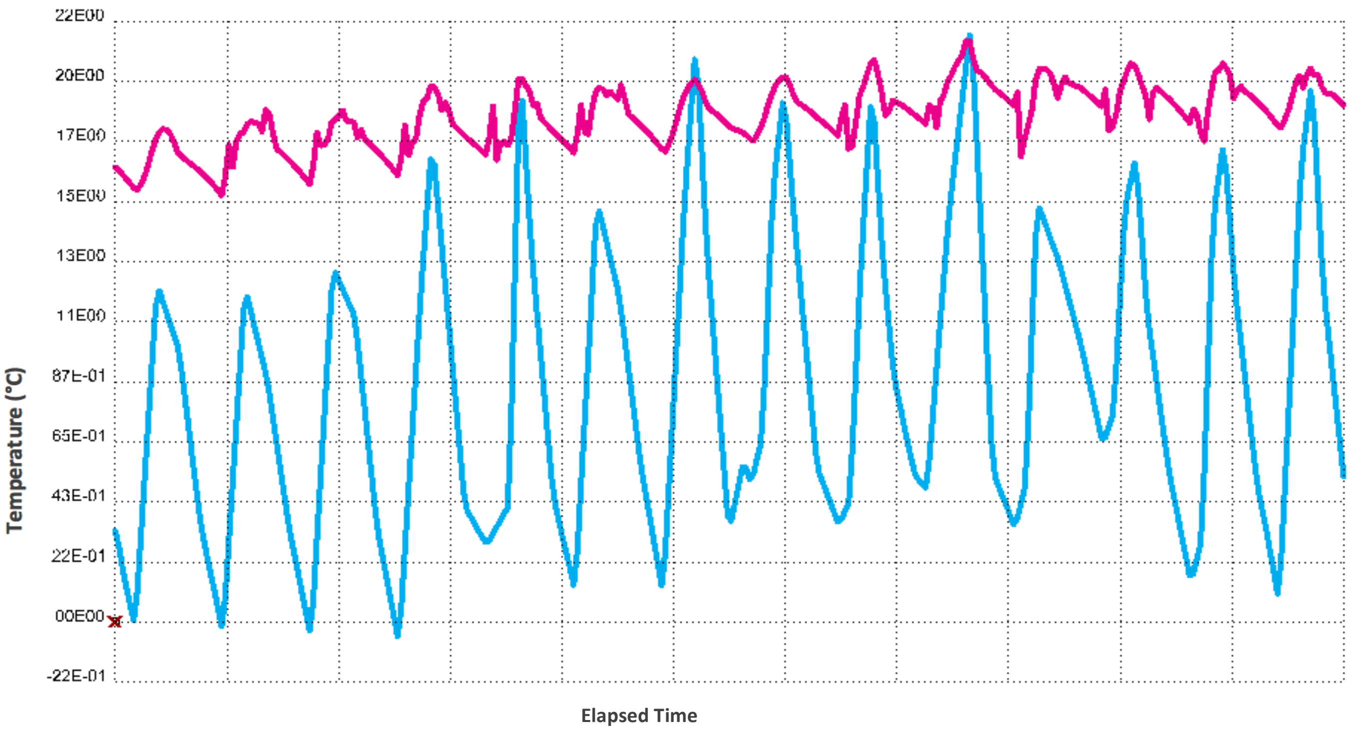


Figure 15 Winter Temperatures with R-3.5 Roof and R-3.5 Walls. January 1-14. Slab on grade floor. Blue line: Site Outdoor Air Drybulb Temperature. Red line: Zone Operative Temperature.

Wind and Ventilation Calculations

While insulation is needed to keep students warm in the winter, the school must also remain cool during summer months. Without mechanical cooling, ventilation acts as the primary cooling mechanism. Analysis of the Katmandu weather file using Climate Consultant revealed wind speeds averaging between 2 and 12 m/s, or about 2-6 on the Beaufort scale: between a "gentle breeze" and "strong breeze, as seen in Figure 16. The wind speeds fluctuate frequently and have no overall dominating direction Using this data, we explored how wind can be utilized for passive cooling in the warmer months.

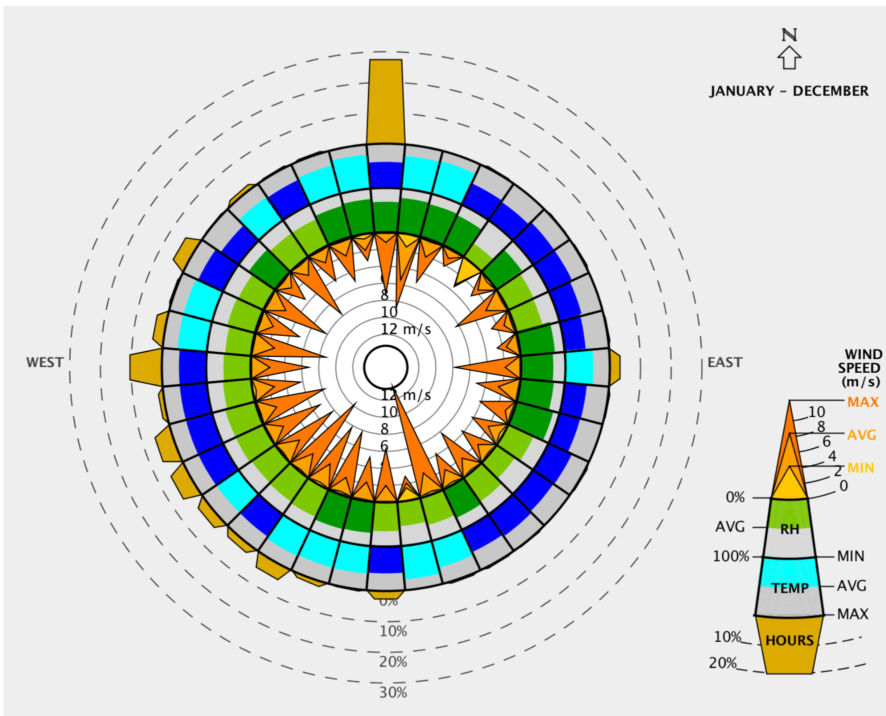


Figure 16 Windrose generated in Climate Consultant for Kathmandu

Ventilation Calculations

Ventilation both helps cool a space and circulate air. ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) standards indicate the amount of airflow needed to prevent stagnancies. Assuming 40 students in a classroom that is 8m x 7m, airflow of 0.23 m^3/s is required for a secondary school environment. To benefit from the cooling properties of ventilation, greater airflow is needed. The $q = \varrho C_p \dot{V} \Delta T$ equation was used to calculate the airflow needed to create a 2 kelvin difference in external and internal temperatures. The resulting 1.8 m^3/s is significantly larger than 0.23 m^3/s required by ASHRAE. This indicates that there must be area for greater airflow, if we expect the airflow to help cool the room.

Based on a desired airflow of 1.8 m^3/s, a wind speed of 1 m/s, and wind perpendicular to the surface with windows, the following equation, $\dot{V} = C_d A_{eff} V \sqrt{C_{w1} - C_{w2}}$ was used to calculate an effective area of 3.16 m^2. If the windows on both sides of the building had equal area, and only cross ventilation was considered, this required 4.5m^2 per side.

Alternatively, we considered using buoyancy flow to ventilate our school. A clerestory window can create airflow in the absence of wind. When it is hot, a clerestory can help exhaust hot air and facilitate the entering of a breeze through the lower openings. Using the equation $\dot{V} = C_d A_{eff} V \sqrt{\frac{2gh\Delta T}{T}}$, an effective area of 5.53 m^2 was calculated to support purely buoyancy driven flow. The window area required, given the minimal height between windows in a single-story building, did not justify using buoyancy flow. The hard-to-access operable windows would probably cause leaks in the winter. We determined clerestory windows were not needed for a circulatory purpose. Our design relies solely on ventilation flow.

In response to the calculations above, we designed a school such that each classroom has four operable 1m^2 windows on one side and three 1m^2 windows and a 2m^2 door on the other. These windows are glassless and instead consist of wooden shutters to be opened and closed as desired. When all windows and doors are open, this provides a 3.12 m^2 effective area, which is very close in value to that needed to lower temperature by 2K using ventilation flow. Because each classroom has significant window area and as later explained no East-West facing windows for programming purposes, we've decided against creating a window between classrooms for airflow.

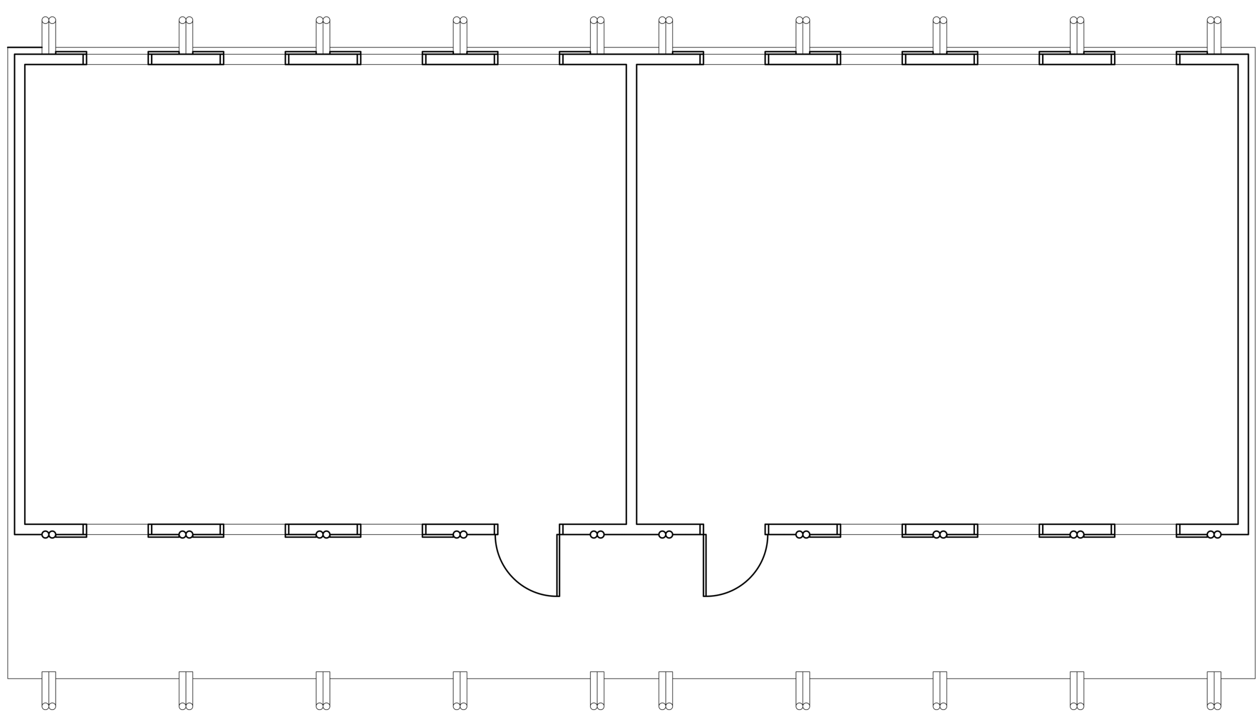


Figure 17 School floor plan. Windows are 1 m^2 and doors are 2 m^2.

CoolVent Ventilation Analysis

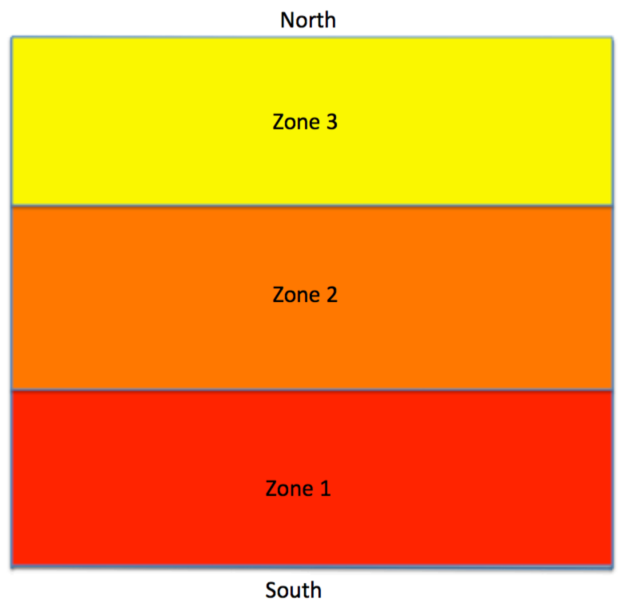


Figure 18 Classroom zones for CoolVent analysis.

Using the basic dimensions of our design, we used CoolVent, a natural ventilation simulation tool, to analyze the temperatures in different zones (detailed in Figure 18) of the classroom during July, the warmest month when school is in session. Figure 19 shows the temperature of the different zones using settings ignoring both solar heat gain and heat gain through the side walls. In this simulation, the inside temperatures drastically increase at 8 a.m. when we programmed students to enter the building. After 5 p.m. when students were programmed to leave, the internal temperatures drop to match that observed outside. These results indicate even with open windows we are unable to cool students to a comfortable temperature as defined by CoolVent parameters. With an external temperature over 24°C for much of the day, it is inevitable that students feel warm, and short of introducing an air conditioning unit or installing fans, there is little we can do to lower temperatures using only wind power. We also ran a simulation that ignored heat gain through the

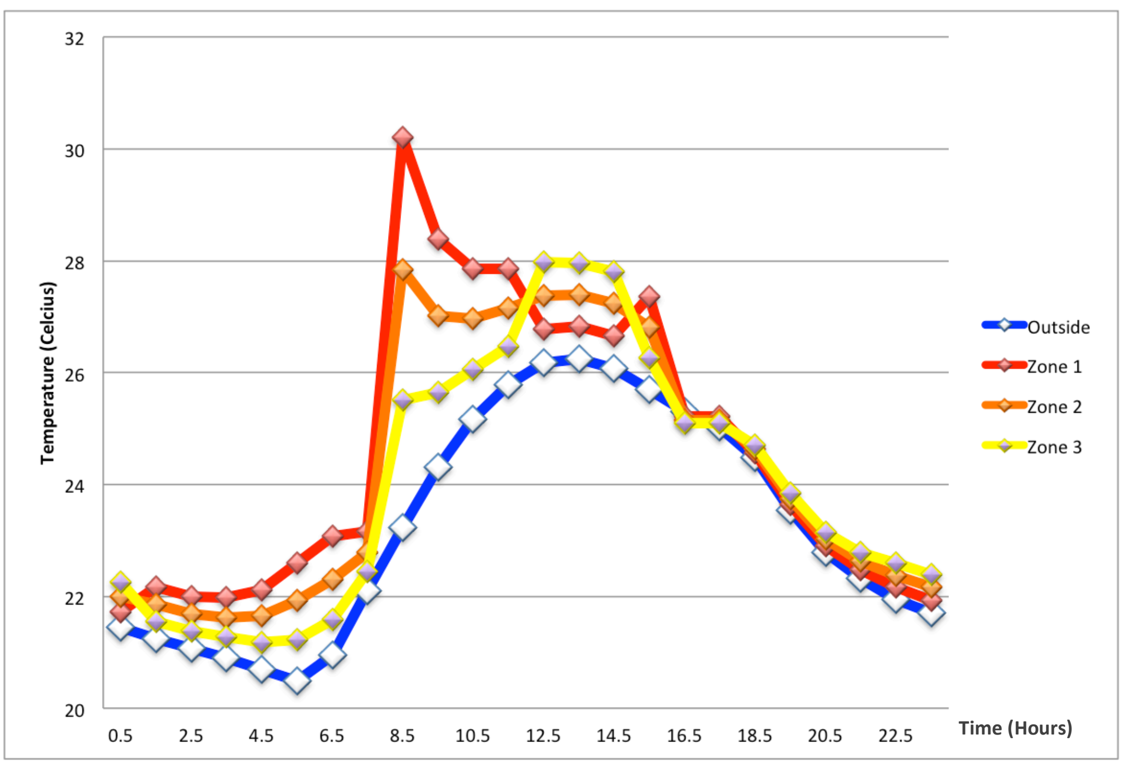


Figure 19 Temperature Throughout a July Day Ignoring Solar Heat Transfer.

side walls but considered the solar heat gain in order to identify whether or not solar heat gain drastically changed internal temperatures. As seen in Figure 20, during daylight hours, the internal temperatures are all slightly higher than those observed when ignoring solar heat gain. This indicates that solar energy entering through the windows is contributing to warming the classroom. In our design, a roof overhang helps shade the windows to block solar energy. Shutters also help mitigate the temperature increase due to solar heat gain.

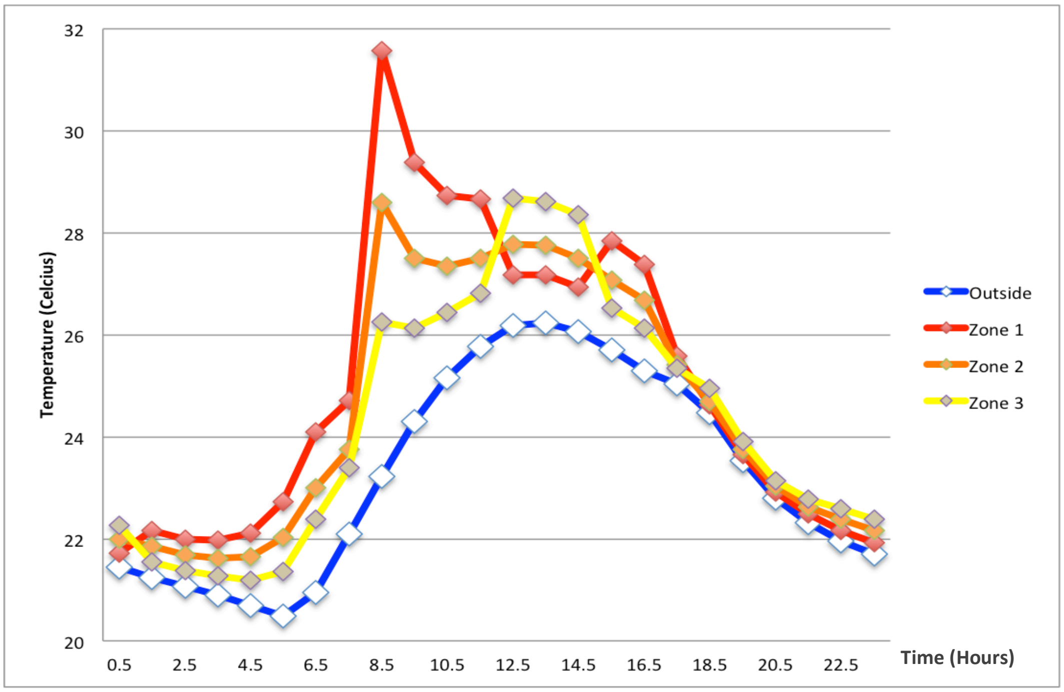


Figure 20: Temperature Throughout a July Day Considering Solar Heat Transfer.

<u>Detailed Ventilation Simulation with scStream</u>

CoolVent's analysis of a specific design is limited, so we also used scStream thermo-fluid software to perform a more detailed simulation of computational fluid dynamics. Analyzing the ventilation flow though the design was important to ensure that air reaches students in all corners of the classroom. We examined three wind directions: front-facing (North), back-facing (South), and side-facing (East).

Our simulations showed that with both front-facing and back-facing wind, the airflow through the building is qualitatively sufficient, meaning all regions of the classroom are ventilated (Figures 21 and 22). At its peak within the building, wind velocity is 1.8m/s, which does not cause disruptions such as wind-blown papers. With side-facing wind, however, we were concerned that there were too many opportunities for dead space with no air flows, as seen in Figure 23, on the right.

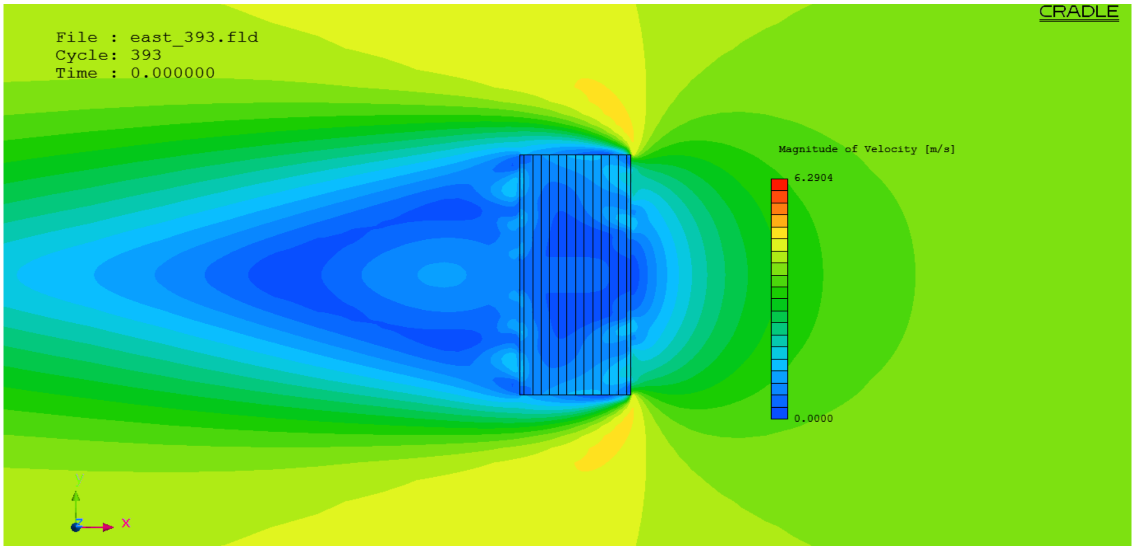


Figure 21 Plan view of design, with front-facing wind. Cradle scStream simulation, where colors indicate magnitude of wind velocity. Wind flow through the building is evident.

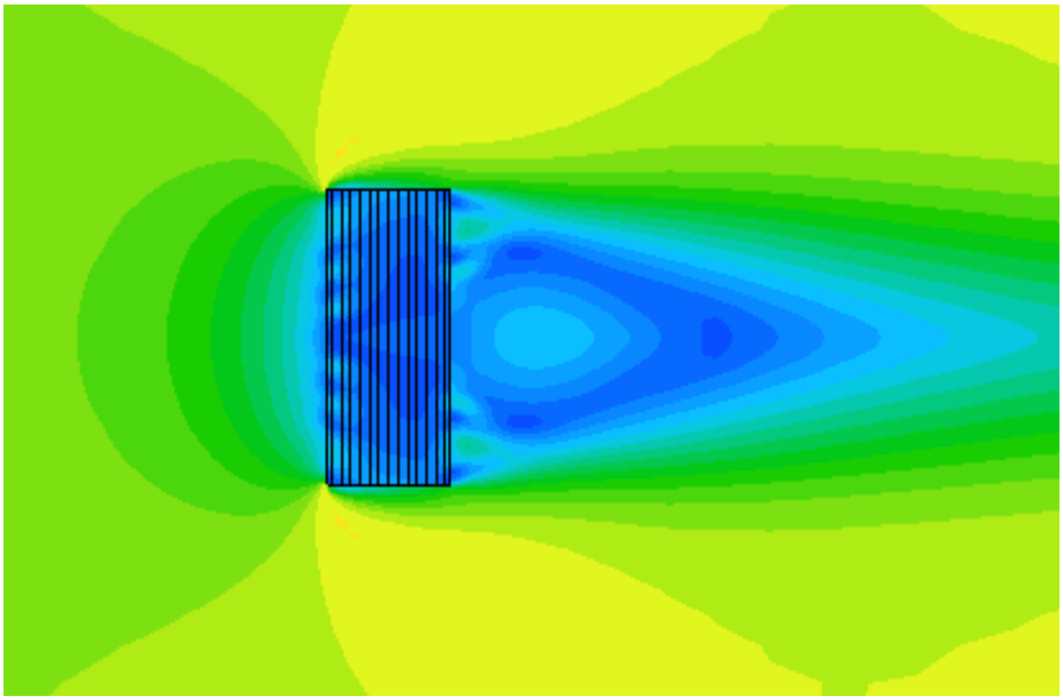


Figure 22 Plan view of design, with back-facing wind. Colors again indicate magnitude of wind velocity. Wind flow through building is evident.

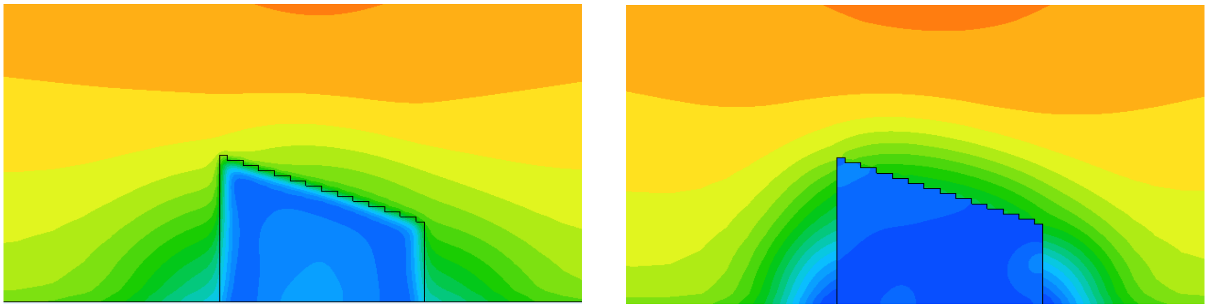


Figure 23: Elevation of design, with side facing wind. Colors again indicate magnitude of wind velocity. There is some wind flow within the building**.**

In an attempt to remedy the issue, we realized the simple shutters, which we had already included to block the sun, could also be oriented to direct more wind into the school. We conducted another simulation of side-facing wind with shutters included on the model. This appeared to improve wind flow when wind was coming from the side. Furthermore, the shutters would be able to reduce unwanted wind when too cold.

Figure 24 Basic shutter design

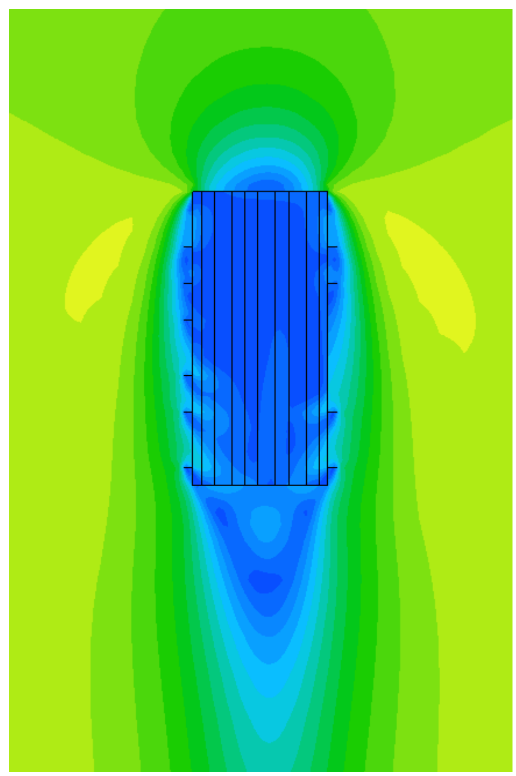


Figure 25 Simulation of design with shutters.

Structural Considerations

Seismic Concerns and Precedents

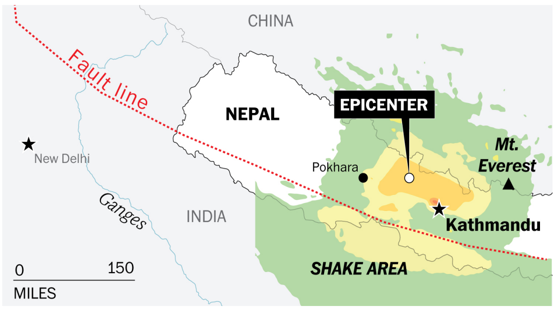


Figure 26 Nepal's proximity to fault lines

With Marbu's location near a major fault line, and the occurrence of recent earthquakes, seismic stability is of pressing concern. In order to make the most informed design decisions, we examined precedents of construction in other seismic zones.

In Pakistan, houses are constructed using locally sourced materials, primarily adobe bricks and stone[3]. These houses are reinforced with a cross-braced structure, which are then filled with stones and adobe bricks. The cross bracing helps to alleviate seismic force by directing it downward. This type of construction is demonstrated in Figure 27. In addition to their seismic advantage, these buildings are easily constructed in remote areas with local materials. Where timber is used in Pakistan, we propose the use of bamboo that is native to Nepal. This mitigates deforestation and transportation concerns.

Figure 27 Close up of cross bracing structure as used in a Pakistani house.

The insides of these houses are spackled with clay or mud, and then painted to achieve a standard looking interior. We envision something similar for our school.

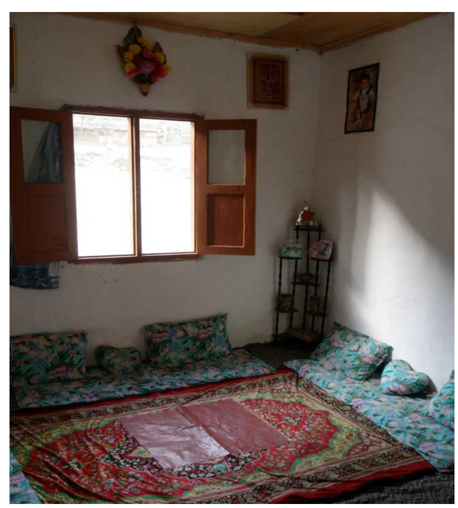


Figure 28 Left: Construction of Pakistani house in remote, mountainous region, similar to Nepal. Right: The interior of such a house.

[3] Cross, Robin. "Haiti Buildings - Earthquake Zone Design - E-architect." Earchitect. 29 Mar. 2010. Web. 15 Dec. 2015. <http://www.e-architect.co.uk/haiti/haiti-buildings>.

Another precedent that excited us was the use of bamboo for roof support that is relatively independent from the walls. A bamboo truss and support provides the lateral strength and flexibility for seismic areas. This kind of construction can be seen in Eleen Jamil's Millennium School Project in Figures 29, 30, and 31, which uses interlocking bamboo beams to create strong, resilient structures[4].

Figure 29 Exterior view of project, showing the outward leaning support columns relatively independent from the classroom structure.

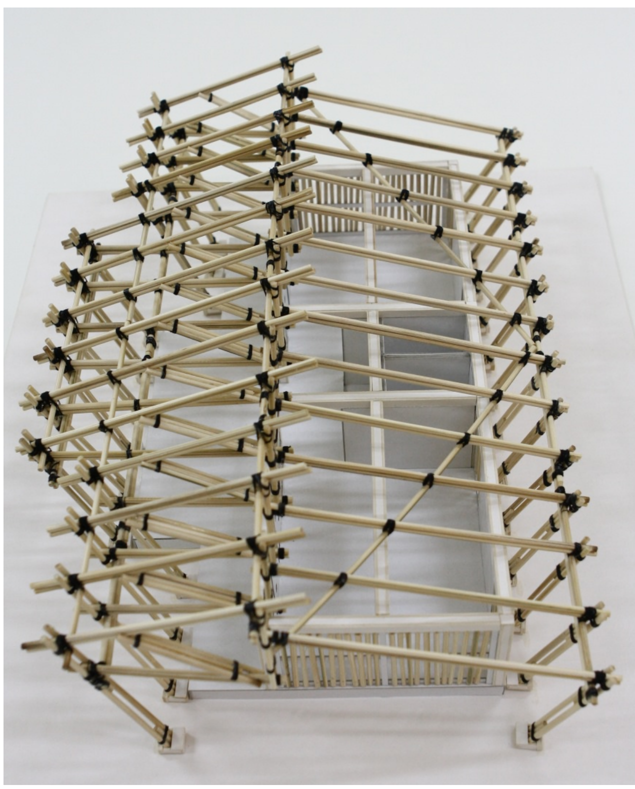


Figure 30 Scale model demonstrating structural network of bamboo trussing and supporting columns in the Millennium School Project.

Figure 31 Construction detail from project, demonstrating how multiple smaller bamboo pieces can be combined for a stronger continuous beam, and how such beams can be elegantly and soundly joined.

[4] "Millennium School Bamboo Project ." *Design Other 90*. Smithsonian CooperHewitt National Design Museum, 05 Oct. 2011. Web. 16 Dec. 2015. <http://www.designother90.org/solution/millennium-school-bamboo-project/>.

Materials Testing

The design we have chosen works well with adobe or rammed earth bricks. There are several positive aspects of using rammed earth or earth bricks for the school construction. Local soil requires lower transportation costs for imported materials, thus potentially lowering the overall cost of the construction. Additionally, fabricating the bricks on site creates jobs for local Nepalese workers, which could help raise morale in communities devastated by the earthquake.

We performed experiments to test the crush strength of rammed earth bricks, specifically those mixed with small quantities of cement. Cement has additional bonding properties that allow the brick to withstand greater force before failure.

The bricks tested and selected were composed of 5% cement by volume of dry material. Although we have not conducted local soil tests, we used a standardized mix to approximate common soil in Nepal. This mix was two parts sand, one part gravel, and one part clay, each per volume. The final brick mix is detailed in Table 1. Cement was added to the previously determined approximate soil mixture. Water was then added until a cement-like consistency was reached, ensuring that the bricks would dry in time for testing.

Brick strength was tested one week after brick creation using a crush strength-testing machine. Bricks were centered within the testing plate, and load was applied to the surface of the bricks until failure occurred. The load at failure was measured in pounds, and then the surface area of the bricks was used to calculate the psi of breaking point. Detailed results for each brick tested are provided in Table 2, and the average failure stress was 354 psi (2.4 Mpa, rounding down to 2Mpa for our calculations). Applying a conservative safety factor of 10, the cement stabilized earth brick could safely support 0.2 Mpa of stress.

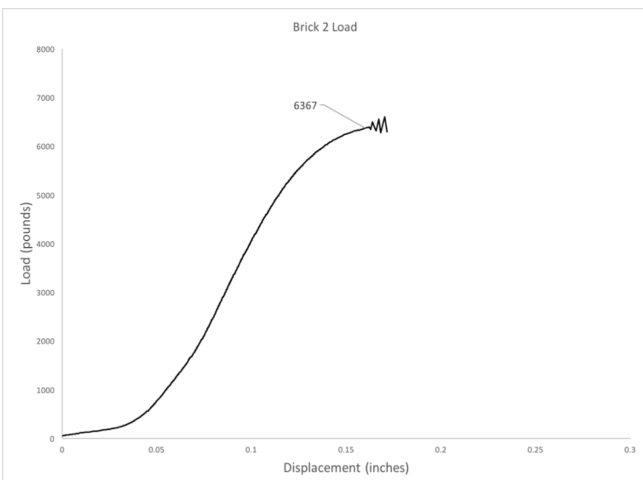
Table 1: Composition of Bricks

Materials	Amount	Percent By Volume
Soil (1 Clay: 2 Sand: 1 Gravel)	8.01 quarts	87%
Cement	0.43 quarts	5%
Water	**0.75 quarts**	**8%**

Table 2: Brick Measurements and Stress at Failure

Brick	Mass (g)	Surface Area (in2)	Max Load (lbs)	Max Stress (psi)	Failure Mass (Mpa)
1	1854.2	18.43	6055	328	2.26
2	1837.6	18.3	6367	347	2.39
3	**1921.5**	**19.03**	**7379**	**388**	**2.68**

Stress was calculated by dividing the maximum load by the surface area. The third brick failed at a larger stress value. It is possible that this is because it was denser than the other two bricks, possibly due to a higher water content.



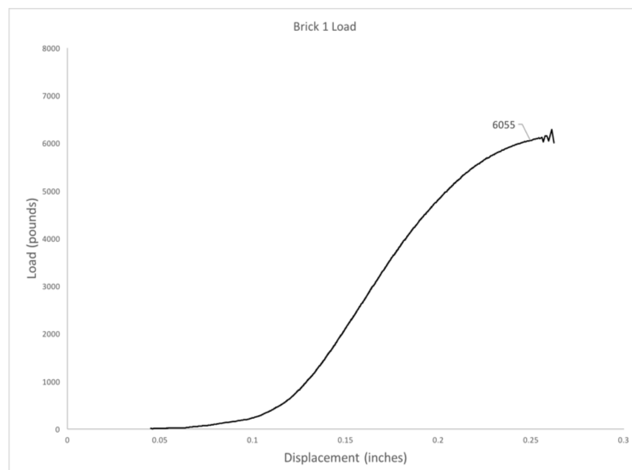


Figure 32 Displacement vs. Load for Bricks 1 and 2, which failed at 6367 lbs and 6055 lbs respectively.

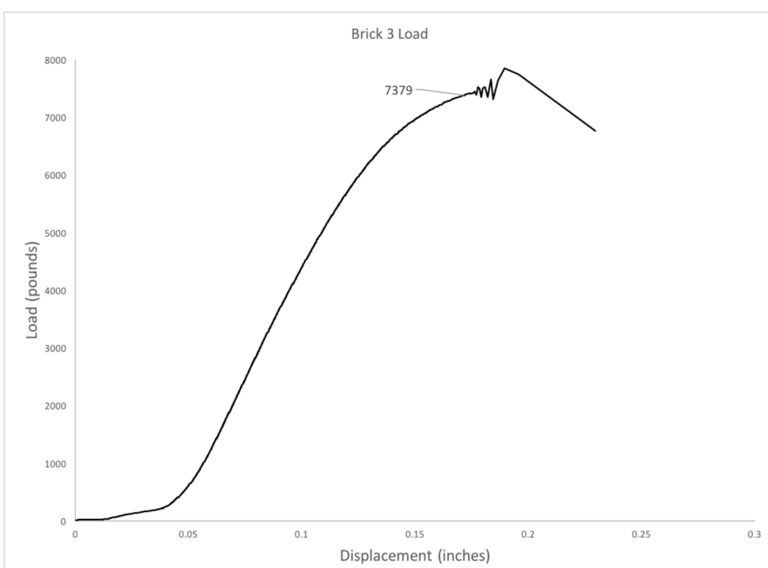


Figure 33 Displacement vs. Load for Brick 3, which failed at 7379 lbs. This brick failed most visibly and dramatically. Additionally, this brick was heavier and denser than the other two, which we attributed to higher water content, and which possibly contributed to its additional strength

Our Structural Design

Each classroom in this design is 7m x 9m, and together the two together cover a floor area of 129m^2. Our roof is designed to cover a significantly larger area to provide shading and rain coverage outside as well, and for our calculations covers a total floor area of around 200m^2, extending beyond the classrooms to provide exterior shelter form the elements. We calculated a total roof size of 206m^2. Our roof is constructed out of bamboo and thatch, using the bamboo for structure and exterior weather protection and thatch on the underside for insulation. This roof would weigh an estimated 42.5kg/m^2 (8.5kg/m^2 for the thatch and 34 kg/m^2 for the bamboo), which gives a total roof weight of 8755 kg.

For our school design, we decided to mount the roof relatively independently from the walls by creating a system of independent columns and trusses. Our design has ten sets of supporting columns and trusses, so we divided this roof up into ten tributary areas, each weighing 875.5 kg on average. This weight provides a downward force of 8,580N to be held by each truss.

As the precedents above suggest, we plan for the weight-bearing columns under the truss system to be made of bamboo. Bamboo is inexpensive, strong, flexible, abundant, and sustainable material. As seen in Figure 29, this would mean two sets of outwardly leaning bamboo beams, and two sets of vertical beams integrated into the front and back façades of the building.

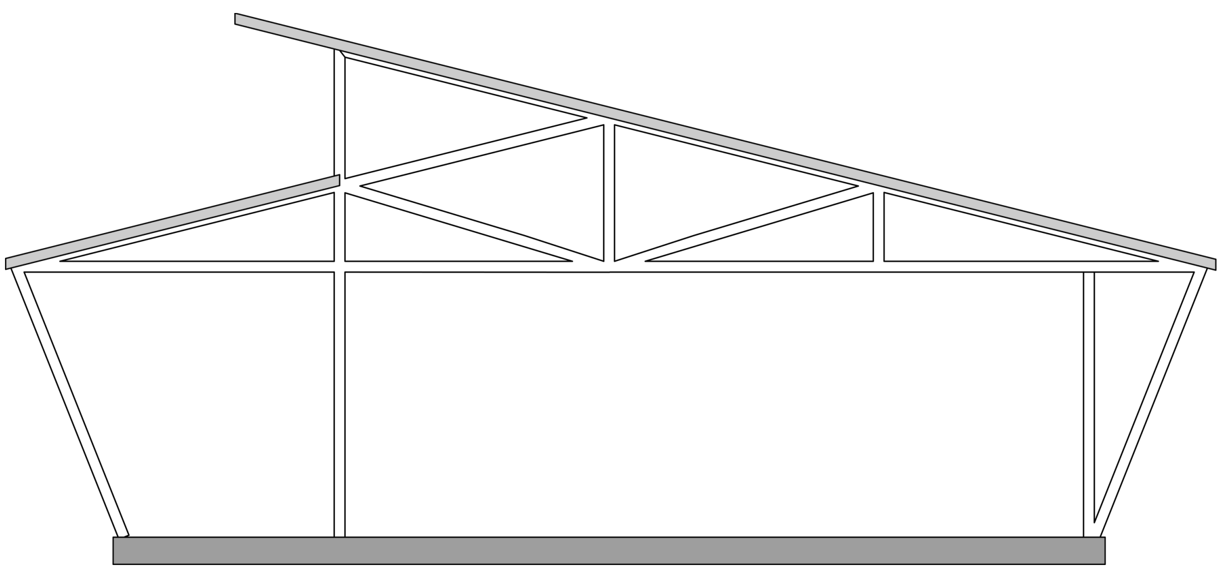


Figure 34 Side view of bamboo truss system.

Alternatively, these weight-bearing vertical members could be made of two sets of earthen brick columns. Earthen bricks have a failure stress of 2 MPa, (and allowable stress of 0.2 MPa), so an area of 0.0045m^2 total would be the bare minimum to support our load. With our safety factor of 10, we want that area to be .045m^2. We would have each load-bearing column be about 0.15m x 0.15m (with an area of .0225m^2 each). As our composition of 5% cement had a minimum tested MPa of 2.26 (psi of 328), we would deem this composition appropriate for our desired results.

With a roof that is integrated, yet independently supported, the walls now only have to support their self-weight. We plan to use a system of bamboo wooden cross beams, as mentioned previously and diagramed in Figures 29 and 30. These kinds of timber masonry structures have been used in seismic zones throughout the world with significant success[5]. Cross-bracing units have been shown to be relatively independent of fill material, and have high ductility, which can experience significant deformation and dissipate energy from seismic forces. Implementing this system in our school should help brace the walls against the kind of lateral forces that result from earthquakes. We also plan to use a reinforcing ring beam around the top of the wall at 3m high, under our clerestory windows and truss system, as seen in Figure 30.

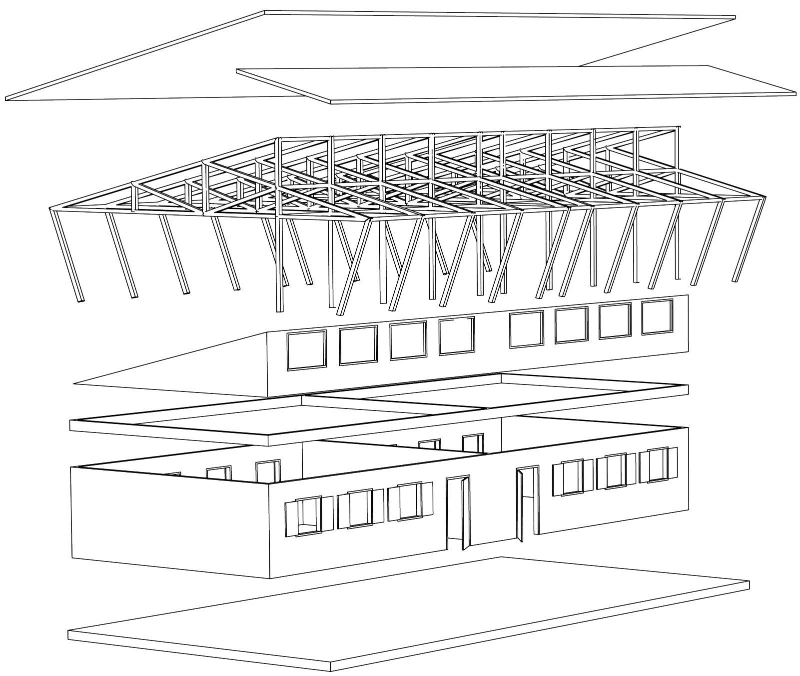


Figure 35 Exploded Isometric diagram of elements of school design. Bottom to top: concrete slab foundation, primary walls (integrated cross beam support), reinforcing ring beam, clerestory window and upper walls, bamboo trusses, roof (thatch and bamboo).

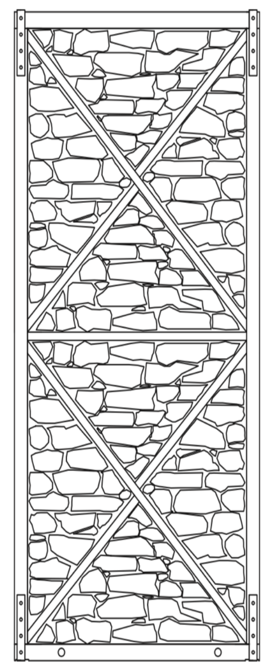


Figure 36 Example of cross beam design in a masonry timber structure

Standard bricks are about 10cm thick and we believe that would be sufficient for the thickness of our walls, not including the thickness of insulation. Our walls would be around 3m high at the lowest point and 4.5m high at the highest point.

Our bricks weighed about 1.8 kg each and took a minimum load of over 2720 kg to crush—the equivalent of stacking 1500 bricks on top of each other to crush the bottom brick. With a maximum height of 4.7 meters, if we were using bricks of approximately the same size and shape as we tested in lab, then we would conservatively never need to stack more than 67, which would apply about 122 kg of pressure on the bottom brick. This gives us more than enough confidence that our walls will stand up under their own weight.

[5] Vieux-Champagne, F., Y. Sieffert, S. Grange, A. Polastri, A. Ceccotti, and L. Daudeville. "Experimental Analysis of Seismic Resistance of Timber-framed Structures with Stones and Earth Infill." Engineering Structures 69 (2014): 102-15. Web.

Designing for Education

Educational Background

Through the design process the team recognized that the structure should not only provide thermal comfort and structural integrity, but it should also create an environment conducive to learning. A new school gives students in Marbu access to new exciting resources. To best tailor our design decisions to the students' educational needs, we conducted background research on the state of education in Nepal.

The current education system in Nepal was established by the Education Act, passed in 1971. As shown in Figure 38, students are expected to complete eight years of schooling, which encompasses all of primary education and lower secondary education. There is also optional pre-primary school in some parts of the country. At the end of the eighth grade, students choose to study at a higher secondary school where they will receive a traditional education, or they can attend a vocational school. Before schooling is considered complete, students need to pass a national exam, which results in the achievement of a School Leaving Certificate (SLC) or Vocational School Leaving Certificate (VSLC).[6] Students on the university path finish another two years of schooling before beginning their undergraduate education.

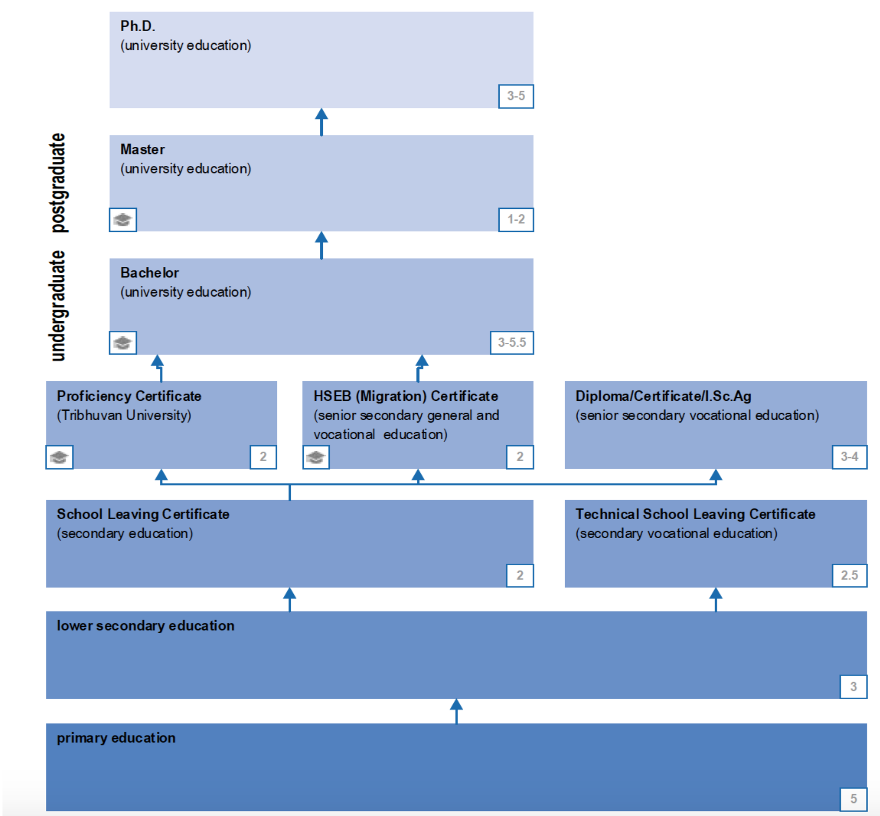


Figure 37 Structure of educational system in Nepal

6 Education System Nepal: The Nepalese Education System Described and Compared with the Dutch System. Den Haag: EP-Nuffic, 2015. PDF.

Information provided by Marbu local Jeewan Rimal exhibits slight contradiction with the structure officially supported the Nepalese government. In Marbu, it seems that some schools encompass multiple levels of education, likely because of the lack of teachers and resources available. Additionally, the school type distinctions differ from national standards.[7] This suggests that the system is not formally enforceable. In more isolated communities like Marbu, the desire to provide at least some kind of education with limited resources may led to deviations from suggested national standards. Lack of resources explains why Marbu only offers education up to grade 10 as opposed to the grade 12 suggested by the national government.

Policy considerations aside, our school design needs to be flexible enough to be relevant no matter how the educational system changes, and yet still be specific enough to serve adequate purpose. Based on this consideration, and based on precedents of schools that existed before the earthquakes, we will orient our design towards a system of duplex classroom blocks, which allows for separation of elementary and secondary school teaching. Addition of more standalone classroom blocks will provide flexibility if and when the school receives more funds and is able to better adhere to national guidelines.

Additionally, in Nepal, educational opportunities are not uniform between genders. Only 67% percent of females aged 6-10 attend school, while 78% of males in the same age group are currently working towards their school or vocational school leaving certificate.[8] There is also dramatic disparity among castes. 60-90% of children of higher castes receive an education, but fewer than 25% of children of lower castes do.[9] Globalization has already begun to break down the traditional caste system, and as Nepal moves towards a more modern future, this disparity is anticipated to decrease.

Those with disabilities, both mental and physical, comprise another underrepresented group in the Nepalese education system. The situation has become so bad that it has been identified by the Human Rights Watch organization. With crowded classrooms and teachers untrained in handling disabilities, many disabled students are discouraged from attending school, even though education is considered a universal right. As many as 329,000 disabled students of primary school age are not in school.[10] Most schools in Nepal are not designed for wheelchair accessibility, so students who struggle with steps maybe denied access to education. Very few specialized schools exist in Nepal; outside of urban areas they are all but nonexistent.

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7 Romal, Jeewan. Report for MIT 4.411J/EC713J Class, 27 September 2015.

[8] Moore, Colleen. "7 Facts About Education in Nepal." *The Borgen Project RSS2*. The Borgen Project, 10 July 2014. Web. 21 Oct. 2015. <http://borgenproject.org/ facts-about-education-in-nepal/>.

[9] *National Population and Housing Census 2011 (National Report)*. Vol. 01. Katmandu: Government of Nepal National Planning Commission Secretariat Central Bureau of Statistics, 2012. PDF.

[10] "Nepal: Separate and Unequal Education." *Human Rights Watch*. Human Rights Watch, 24 Aug. 2011. Web. 21 Oct. 2015. <https://www.hrw.org/news/2011/08/24 /nepal-separate-and-unequal-education>.

External Design Features

Figure 38 Exterior view of school design.

Based on the disparities in Nepalese education and our own understanding of childhood needs, we designed the outside of our school to be inviting to young students. As mentioned above, students with physical disabilities often struggle to reach the classroom. Though our school is located on an elevated apron to protect against heavy rains during the monsoon season, we also would advise installing a ramp for students who have difficulty moving up stairs. Hopefully, this small handicap accommodation will position the Shree Kalika Secondary School as a leader in accessible education.

The large roof overhang was another design decision targeted towards the student experience. Children enjoy the break from their classroom and the chance to play outdoors. During sunny days the large overhanging roof will create a shaded area for students who want to play outdoors, but not overheat. And during the rainy season, it will provide a dry exterior space for activities.

Internal Design Features

The team made similar considerations when designing the school interior. As mentioned previously, the structure is completely divided into a two-classroom block. The partitioning wall reaches from floor to ceiling to prevent sound intermixing. With between 20-40 students per class, the rooms will already easily become noisy Additional chatter will only further distract students.

The wall dividing the classrooms also creates space where teachers can hang teaching materials. Blackboards are already used in Nepalese classrooms, and posters and bulletin boards could be a useful addition to aid content retention. All require large expanses of flat open wall. Windows were placed only on the long North-South sides of the structure. The East-West classroom walls were left open to preserve wall space.

Figure 39 Interior view of school design

Additionally, the chairs and table in the classroom are not designed to be stationary. Therefore, they can be moved for class activities or community use of the space in the evening.

Daylighting

Once thermal comfort and seismic safety were addressed, daylighting became the next pressing concern. We conducted several tests of daylighting to better understand how much natural and supplemental lighting we would need to ensure that students are working in conditions with ample light to read and focus on tasks.

Daylight Autonomy

Using DIVA for Rhino, a daylighting and energy modeling program, we conducted a Daylight Autonomy evaluation on our model. The threshold for acceptably lit was set to 300 lux [lumen per square meter], a typical threshold for academic institutions, and for the purposes of this evaluation, occupants were not allowed to adjust. We evaluated our model with both shutters open and shutters closed. We found that with shutters open, daylight was almost sufficient, reaching autonomy 75.8% of the occupied hours (8am-6pm, Figure 40). With shutters closed, autonomy dropped to 36.4% (Figure 41). If shutters are to be closed for insulation during the winter, the clerestory window alone does not seem to provide enough light. Additional analysis was conducted to find values for luminance, described further below.

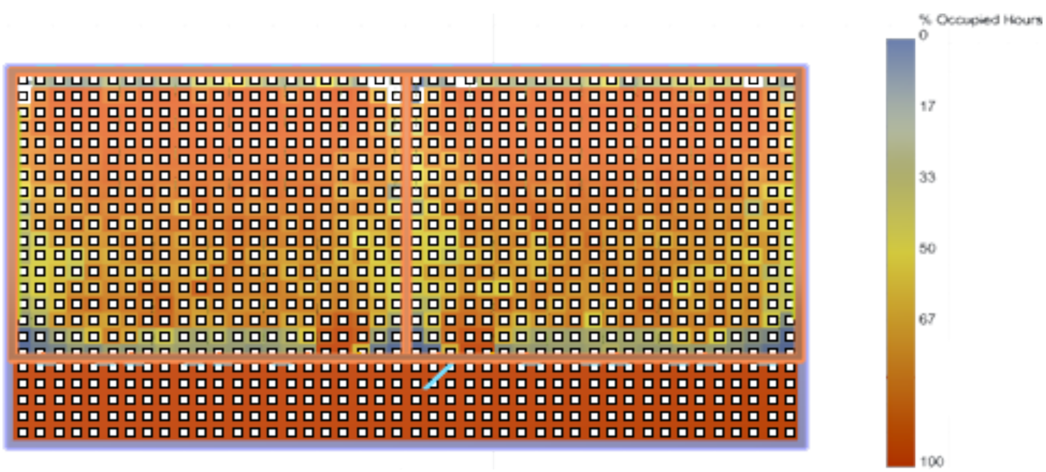

Figure 40 Annual Daylight Autonomy, shutters open, for threshold at 300 lux, without allowing occupants to adjust.

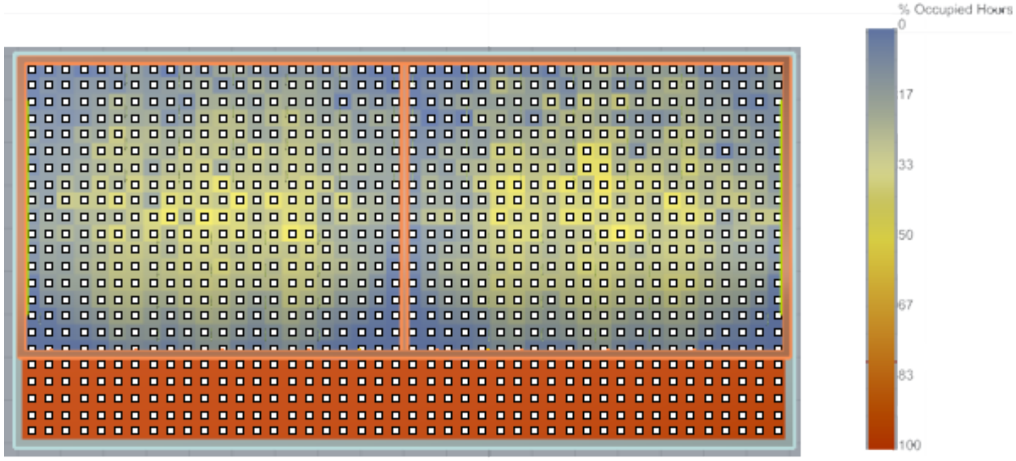

Figure 41 Annual Daylight Autonomy, shutters closed, threshold at 300 lux, without allowing occupants to adjust.

Daylight autonomy was also examined for a school oriented facing east instead of the original south, because we are unsure of the orientation of the school on the site and would like it to be flexible (Figure 42). With shutters open, this produced a remarkably similar result to the south facing orientation: 75.4% Daylight Autonomy, differing by less than half a percent. Since this orientation was similar with shutters open, we assumed that with shutters closed would also be similar.

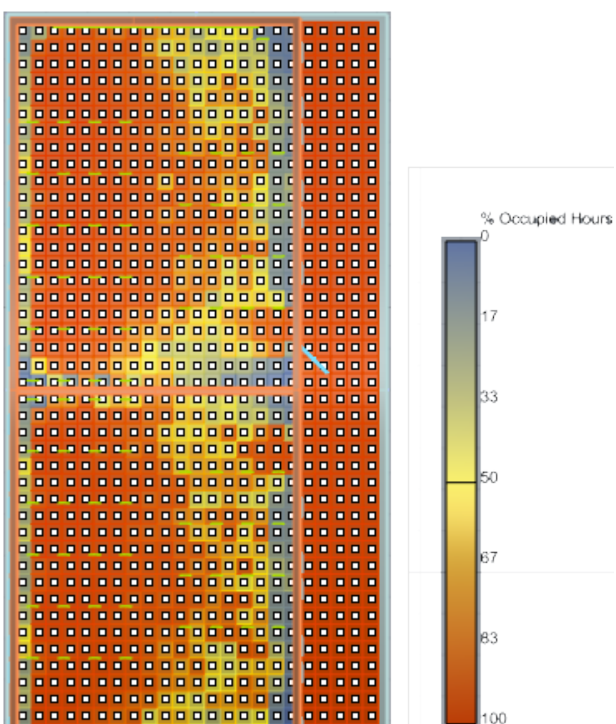

Figure 42 Annual Daylight Autonomy, shutters open, threshold at 300 lux, without allowing occupants to adjust. Building orientation: east.

Additional analysis included snapshot checks of luminance in the months of September and February, representative of late summer and winter. These checks were conducted with shutters open and shutters closed, all at 9am. Each of these snapshot simulations shows levels of luminance mostly above 150 lux, with certain areas falling around 100 lux (around the equivalent light as found on a dark overcast day). (Figure 43)

Figure 43 Top row: September 22nd, 9am, snapshot simulations with shutters open (left) and closed (right). Bottom row: February 22nd, 9am simulation, with shutters open (left) and closed (right)

Glare Analysis

Clearly, daylight is not entirely sufficient to illuminate the classroom during the day. On the other extreme, however, we needed to make sure that when daylight was present, the glare was not distracting. This is a classroom, after all, and with excessive glare learning becomes impossible. Snapshot glare analysis (Figure 44) of different views of the classroom showed low levels of glare, 6% and 39% Daylight Glare Probability.

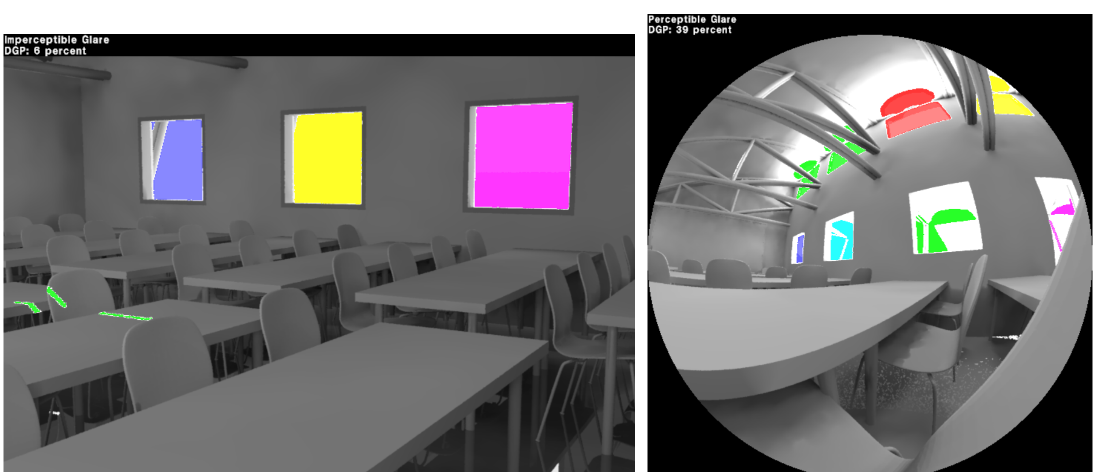

Figure 44 Snapshot Glare Analysis, perspective view (left) and fisheye view (right).

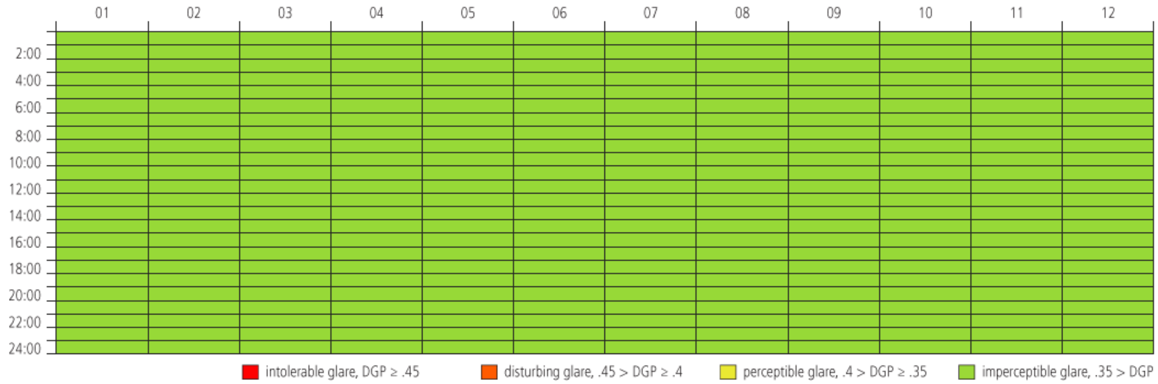

Figure 45 Annual Glare analysis, showing imperceptible glare for all hours of the day and all months of the year.

Annual Glare Analysis (Figure 45) showed similar results for the entire year. Every hour of every day seemed to have imperceptible glare, and we attributed this to the extended overhang of our roof. (Figure 46) illustrates the placement of the camera for the glare analysis.

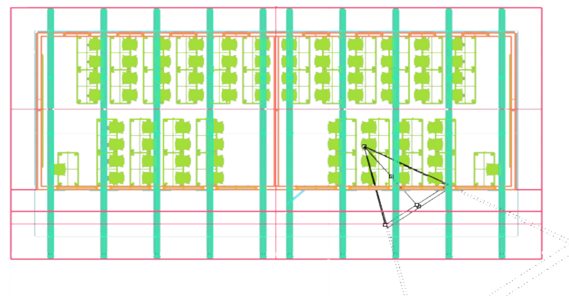

Figure 46 Plan view of school design, showing camera placement for glare analysis

With the inclusion of shutters into our design, we predict that glare will not be a problem.

Artificial Lighting

Artificial lighting could help supplement natural lighting during school hours, but we also wanted it to be present so the school can be used by members of the community at night. Our lighting design incorporates 24W Zumtobel Slot Lights that output 850 lm. Each light is 0.585m long. The lights are dimmable, and can be mounted as recessed, flush, or pendant lights. For the purposes of our analysis and lighting plan, we envisioned the lights hanging from the exposed trusses of our design. Based on rough estimates, we initially implemented 5 lights per classroom, centered along the length of the classroom (Figure 47, left). After initial tests, however, these lights were not sufficient to light the classroom at night. Luminance in the darkest working surfaces of the classroom fell as low as 9 lux, and even in the brightest surfaces didn't break 150 lux. We increased the number of lights to 15 per classroom (Figure 47, right), which exceeded the threshold of 150 lux on the working surface.

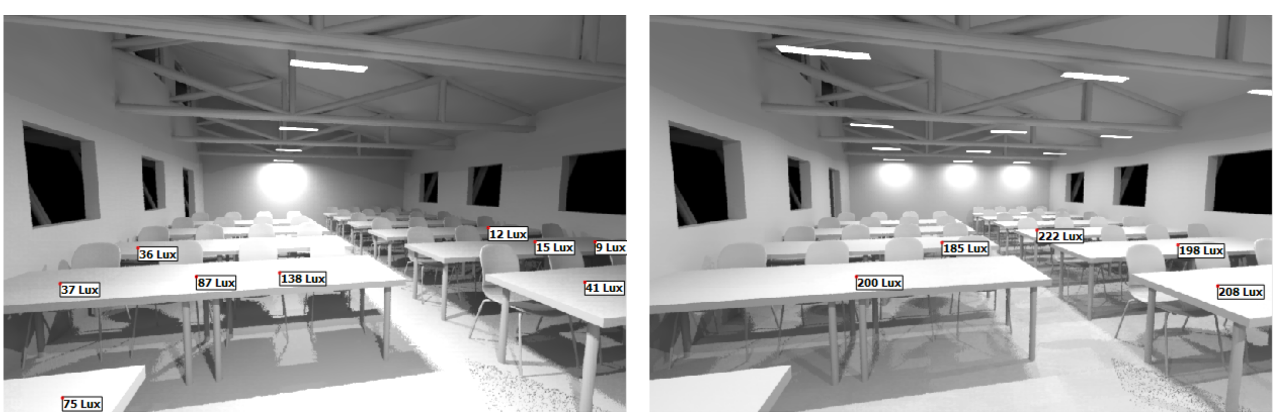

Figure 47 Lighting analysis for 5 lights per classroom (left) and 15 lights per classroom (right)

We evaluated the daylighting simulation again, including the 15 lights per classroom. Using manual controls, estimated power usage for the year is 495.5 kWh.

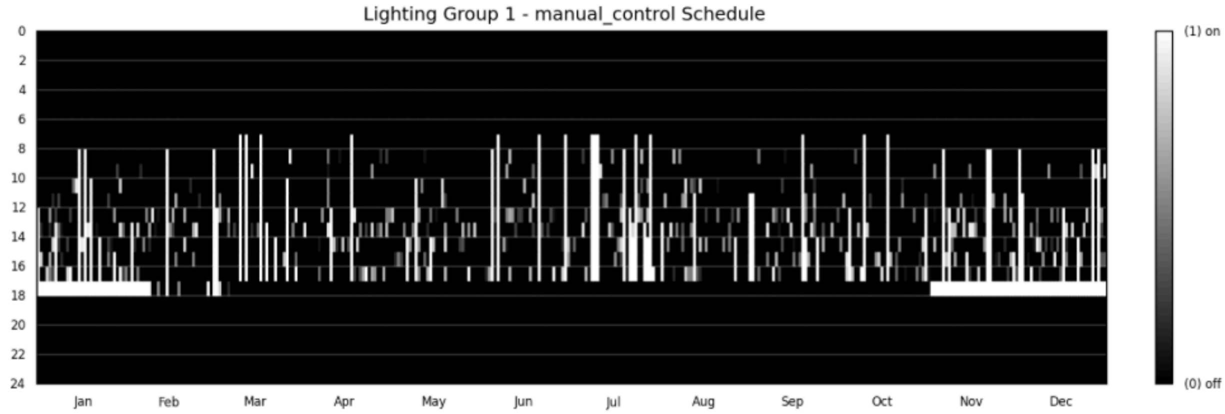

Figure 48 Lighting Control chart for simulated lighting usage.

Conclusion

Over the course of the semester, we have learned a great deal about the climatic, material, educational, and operational conditions of Nepal, and more specifically, of Marbu. This proposed design is culmination of all those lessons, drawing from numerous approaches to achieve structural stability and comfort. It is a rigorously researched and inspired design, but it presents just one solution to a challenge that has many potential solutions. It is also detailed, yet far from complete as work to further understand the local environment, needs, and situation would be necessary in order to create a more finalized proposal that will truly benefit the students and community of Marbu. We hope that the design recommendations from this proposal will be useful to the architects and community. We are excited for this project to advance beyond the confines of our class project and, moving forward, we can't wait to see where this project goes.