CIRCULAR DESIGN ATLAS

EARTHQUAKE RESISTANT MOUNTAIN SCHOOLS

Architect(s):
Smart Shelter Foundation

Year:
2007-2012

Location:
Kaski District, Nepal

More info:
https://www.smartshelterfoundation.org

Scales:
Buildings

Resources:
Inorganic
Secondary

Design Approaches:
Design for Standardization

R-Strategies:
Refuse
Rethink
Reduce
Refurbish
Remanufacture
Repurpose

Aspects:
Management
Resource Flows
Economy

TU Delft
BK Bouwkunde

Credits | Design: Smart Shelter Foundation | Photo: © Smart Shelter Foundation

The earthquake-resistant mountain schools in Nepal are a series of projects realized in the Kaski district by the Dutch NGO Smart Shelter Foundation (SSF). The project aims to provide schooling opportunities for mountain villages in places where the existing schools were destroyed by seismic activity.

Two main construction methods are used for the walls of the schools, which are either made with rubble or with concrete blocks. The projects are realized in collaboration with local communities, and local construction workers are trained to execute the building process. Many materials used in construction are sourced from the local forests, mountains, and rivers or repurposed from school buildings destroyed in previous earthquakes. In this way, the negative environmental impact on the area is kept at a minimum. When designing the mountain schools, SSF focused on safety and durability, as the main aim was for them to withstand the many strong earthquakes that take place in Nepal. Moreover, it was important for the construction process to be easily understood by the locals.

Layers of Change and Lifecycle Duration

In some areas of Kaski District the soil is naturally fertile. Fertile soil is advantageous for building sites as it provides a stable foundation for construction. Nonetheless, the use of heavy machinery and equipment can lead to soil compaction, which negatively affects the site's soil quality.

A well-applied and properly maintained cement plaster can last from 20 to 50 years or more. However, the local climate plays a significant role in its duration. In areas with harsh weather conditions the plaster may deteriorate more quickly. In Nepal the high average annual rainfall and temperatures can lead to a great amount of wear. However, the schools' design includes overhangs which help mitigate these effects.

The load-bearing capacity of a rubble stone structure affects its lifespan because walls that support significant structural loads or are subject to ground movement may require more frequent maintenance and may have a shorter lifespan. The walls however do not have such a havy load and the mountain schools have proven to be earthquake resistant after the earthquake of 2015. The expected lifespan of a hollow concrete block structure is estimated to be around 50-100 years. Seismic activity can work against the lifespan of the buildings' concrete structure. In regions prone to earthquakes, like Nepal, the design and construction must ensure their resilience during seismic events. The mountain schools, reinforced with horizontal conrete beams and vertical rebars, have proven to be earthquake resistant.

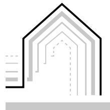
The schools are cross-ventilated between the ceiling and the roof. Cross ventilation helps to maintain good indoor air quality by removing stale air and pollutants and bringing in fresh, outdoor air. It regulates indoor temperatures, reducing the need for mechanical cooling systems. However, because there is no insulation, rooms heat up in summer and cool down in winter. The architect states that in winter the children bring an extra blanket and in summer everyone sits outside.

The window frames are made out of hardwood. Hardwood is naturally durable and resistant to wear and tear, but the window frames are exposed to rain and humidity, so apart from roof overnhangs regular maintenance and proper sealing are crucial to prevent issues like rot.

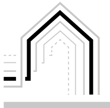
The school tables are made out of wood, which can easily be repaired when damaged. However, they present a significant fire load for the school buildings.

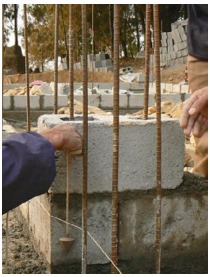
Site
Eternal

Skin
± 20 years

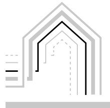


Structure
30-300 years

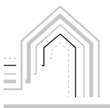




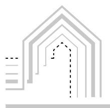
Services
7-15 years



Space plan
3-30 years



Stuff
Various



Credits | Design: Smart Shelter Foundation | Photo: © Smart Shelter Foundation

Carbon Footprint of Materials

Rubble stone or, as in the Construction Material Pyramid, reused brick, is lowest on the pyramid of the mineral/natural stones and with a thickness of 355.6 mm has an impact of 1,5 kg CO2 eq per m2

There is 19 mm of plaster applied outside and 13 mm on the inside of the rubble stone walls. This leaves a footprint of 12.0 kg CO2 eq.

The two reinforced concrete beams together have a total height of 15.24 cm and a footprint of 12,4 kg CO2 eq. The 4 steel rods, each with a diameter of 10 mm constitue 14,1 kg CO2 eq which makes a total footprint of 40,0 kg CO2 eq.

For the concrete school reinforced concrete is used for the calculation. Due to the lack of hollow concrete blocks in the material pyramid, they are substituted with reinforced concrete in the analysis. The calculation takes into account the actual thickness of the concrete in the blocks, which sums up to 97.5mm. This results into a footprint of 22,3 kg CO2 eq.

The plaster thickness is 13 mm on the outside and 12 mm on the inside of the hollow concrete block walls, leaves a footprint of 9,4 kg CO2 eq.

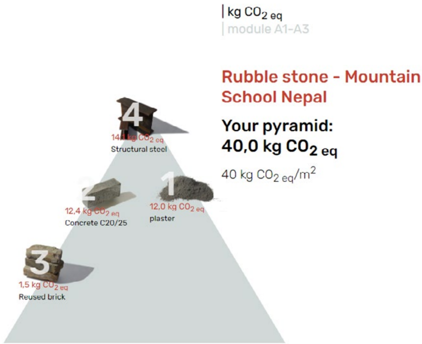
Lastly, the steel rods are considered. There are 6 rods per square meter and each with a diameter of 10 mm. This results in a total of 31,8 kg CO2 eq. This makes the total carbon footprint of the building 63,5 kg CO2 eq.

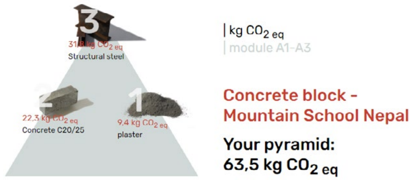
show result in pyramid ↑	reset calculation	Rubble stone - Mountain School Nepal		1 m^2			
	material	group	impact / m3	volume [m3]	area [m2]	thickness [mm]	result
1	plaster	mineralsk	375.1 kg CO2eq/m3	0,03 m3	1 m2	32 mm	12,0 kg $CO_{2\ eq}$
2	Concrete C20/25	mineralsk	229.0 kg CO2eq/m3	0,05 m3	0,1524 m2	355,6 mm	12,4 kg $CO_{2\ eq}$
3	Reused brick	mineralsk	4.9 kg CO2eq/m3	0,30 m3	0,8476 m2	355.6 mm	1,5 kg $CO_{2\ eq}$
4	Structural steel	metal	8831.2 kg CO2eq/m3	0,00 m3	0.04 m2	40 mm	14,1 kg $CO_{2\ eq}$
							40,0 kg $CO_{2\ eq}$

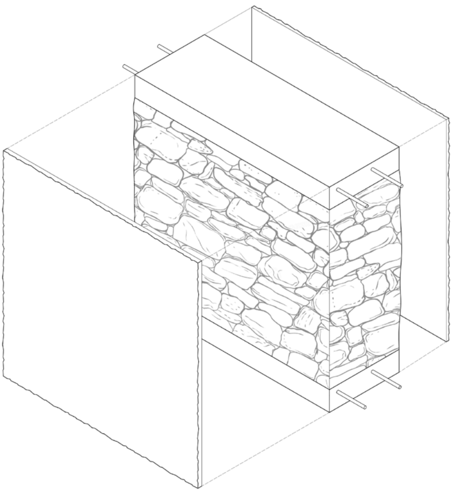
show result in pyramid ↑	reset calculation	Concrete block - Mountain school Nepal		1 m^2			
	material	group	impact / m3	volume [m3]	area [m2]	thickness [mm]	result
1	plaster	mineralsk	375 kg $CO_{2\ eq}$/m3	0,03 m3	1 m2	25 mm	9,4 kg $CO_{2\ eq}$
2	Concrete C20/25	mineralsk	229 kg $CO_{2\ eq}$/m3	0,10 m3	1 m2	97.5 mm	22,3 kg $CO_{2\ eq}$
3	Structural steel	metal	8830 kg $CO_{2\ eq}$/m3	0,00 m3	0.06 m2	60 mm	31,8 kg $CO_{2\ eq}$
							63,5 kg $CO_{2\ eq}$

Credits | Construction Material Pyramid and calculations: CINARK/The Royal Danish Academy

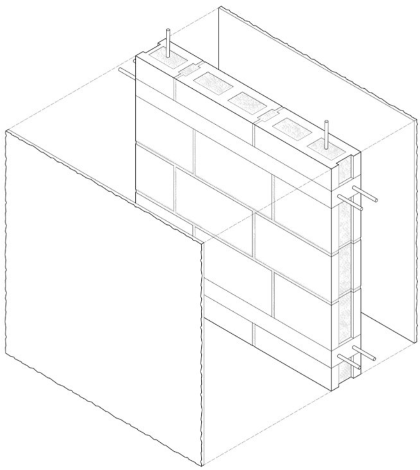
To compare the two: the concrete block school has a higher carbon footprint than the rubble stone one. However, we should look critically into some significant aspects that lead to the growth of the footprint. The rubble stone itself, which is the main material, has a very low footprint, but smaller components of the building make the carbon footprint high. Steel occupies one of the highest positions in the Construction Material Pyramid. Thus, only a couple rods of 10 mm each combine to a bigger carbon footprint than a square meter of concrete. However, these elementds are contributing to making the schools earthquake resistant.







1 m2 rubble stone façade



1 m2 concrete block façade

Building Material Origin

Smart Shelter Foundation chooses local materials and building methods for their designs. It is mostly dictated by practical reasons and efforts to reduce construction costs, but proves to be a great approach to make the school buildings more sustainable.

Biological materials:

- mountain stones - used mostly in the foundation, mixed with cement mortar
- Sal wood - sourced from the community village, it is a renewable and sustainable material; wood is used to produce roof trusses, window and door frames and furniture

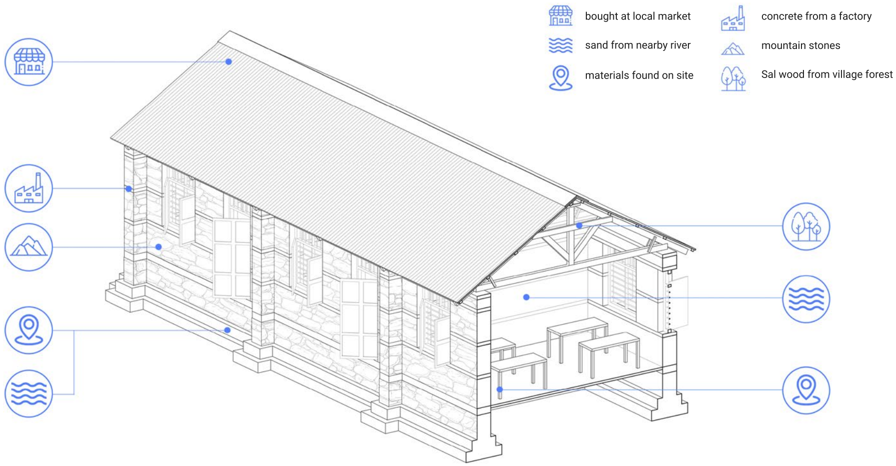
Technical materials:

- reinforced concrete - this material plays a crucial role in the structure of the building and ensures its stability; however, it is unlikely that reinforced concrete will be recycled
- concrete blocks - used in one of the presented building methods
- plaster and paint - used for the finishing
- CGI sheets - roof cladding
- triplex boards - used for ceiling cladding; they are also a manufactured material (they usually use recycled paper which reduces their carbon footprint)
- connecting materials - steel rebars, galvanized steel wires and nails; these materials are industrially produced and bought at a market

The materials that can be seen as critical in this region are specialised connectors (sometimes used in Smart Shelter schools to connect the roof truss to the wall) and plastic elements - they are very rare, but from pictures it can be assumed that the floor is cladded with linoleum. In general, the project uses very few critical materials.

The materials are transported from markets or factories to a drop-off point as close as possible to the construction site, from where they are offloaded, shoveled into baskets, and hauled to their final destination by foot. According to the architect, the choice of materials in Nepal was very limited 15 years ago, when the schools were built.

The map on the right page shows the location of schools built by Smart Shelter Foundation, the local markets and cement factories where the materials were bought, and rivers that were the main source of the sand used in the production of concrete and plaster finish.


bought at local market
sand from nearby river
materials found on site
concrete from a factory
mountain stones
Sal wood from village forest


N
Pokhara Municipality
Kalika
Bhachok
Mijure Danda
Prithvi Highway
Leknath Municipality
Rupakot
Thumki
Deurali
Siddha
Rivers
Main roads
Mountain roads
SSF building
Main markets
Cement blocks
Local bazaars
0 1 2 3 4 5 km

R-Strategies

The earthquake resistant schools are a very local project, based on nepalese building techniques and locally sourced materials. Their limited budget, detailed projects and cooperation between the architect and the villagers naturally lead to implementing a number of R strategies. However, we can still see space for potential improvement. In this analysis the strategies that are already present are written in regular text and our critical analysis in italics.

Refuse:

- It can be said that the whole design is centered around refusing. It minimizes the costs and the level of complexity as much as possible in order to make the school project more accessible and easily understood by the locals.
- The buildings follow local techniques and customs and therefore don't have any thermal insulation or glazing in the windows.
- There are no toilets in the new school buildings - children use sanitary rooms in other buildings on site.

Rethink:

- The school buildings are designed according to a set of earthquake resilience rules developed by the architect, significantly improving their durability compared to other schools.
- The process includes choosing the materials and contractors by the villagers.
- *Especially in the concrete blocks method the connections between different building elements can be rethought to follow the principles of circularity - maybe design for disassembly?*

Reduce:

- The process is designed to reduce the environmental impact of transportation - all materials are sourced locally and don't require long-distance shipping.
- *For this strategy rubble stones method is undoubtedly a better choice - they don't require producing a new material.*

Reuse:

- *The wooden structural elements are made of wood from nearby forests. It can be considered if it's possible to reuse some of the wooden beams from buildings affected by the earthquake instead - it is possible that only the brick walls broke and the wood stayed in good condition.*

Repair:

- The architect provides service

in case a part of building is damaged - when a tree fell on one of the schools, they repaired a part of the roof that was damaged.

- *Good execution of construction - rare need for repairs*
- *It seems like the repair works, although not often necessary, are difficult to execute by the locals; the building parts are tied together very well - if there is a need to repair the steel wires that tie the roof truss to the wall, there's a high probability that the concrete beam will have to be destroyed and replaced in the process.*

Refurbish:
- The architects use some windows from schools that existed in the same spot and got damaged by the earthquake; the windows and doors are refurbished and painted.
- *Currently the school doesn't have any thermal insulation or even glazing in the windows. It is possible that in the future it will need to be refurbished to meet more strict regulations - this will require wall insulation, roof insulation and glazing.*

Remanufacture:
- Rubble stones from the earthquake used to build walls.
- *The window frames can be taken out and remanufactured if they need to be adjusted to new regulations.*

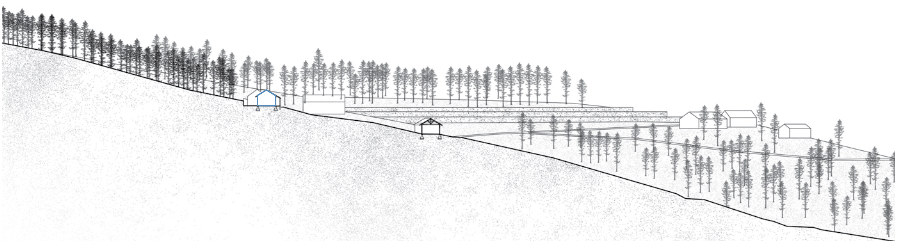
Repurpose:
- Rubble stones from the earthquake used to fill in the floors.

Recycle:
- The triplex boards used for ceiling cladding are made of recycled paper pulp.
- *Unfortunately, it will be very difficult to recycle any of the materials used in the building. Theoretically it is possible to recycle cement blocks, but it's a complicated and energy-consuming process, definitely not possible in the remote mountain villages. It would be even more difficult, as the blocks are connected by and some even filled with cement mortar. There is a potential of recycling the metal roofing sheets.*

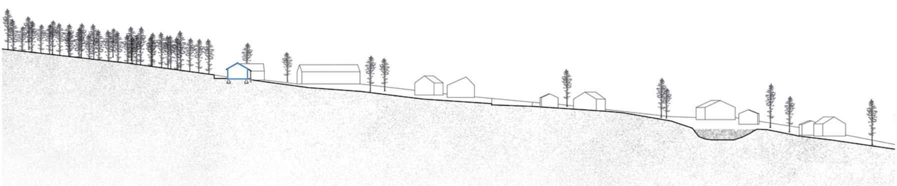
The NEW Nexus

Because the mountain schools are designed as shelters, they have very little demands in their operation. They do not provide electricity, heating, or sanitary installations. The local temperature in the Kaski district in Nepal can fall as low as 3°C in January.
As the building has no thermal insulation nor glazed windows, the heat energy produced by the users of the building themselves is not enough to maintain a comfortable room temperature during colder periods of the year. According to the architect, this is dealt with by using blankets in winter, a common practice in Nepal where almost no building is insulated.

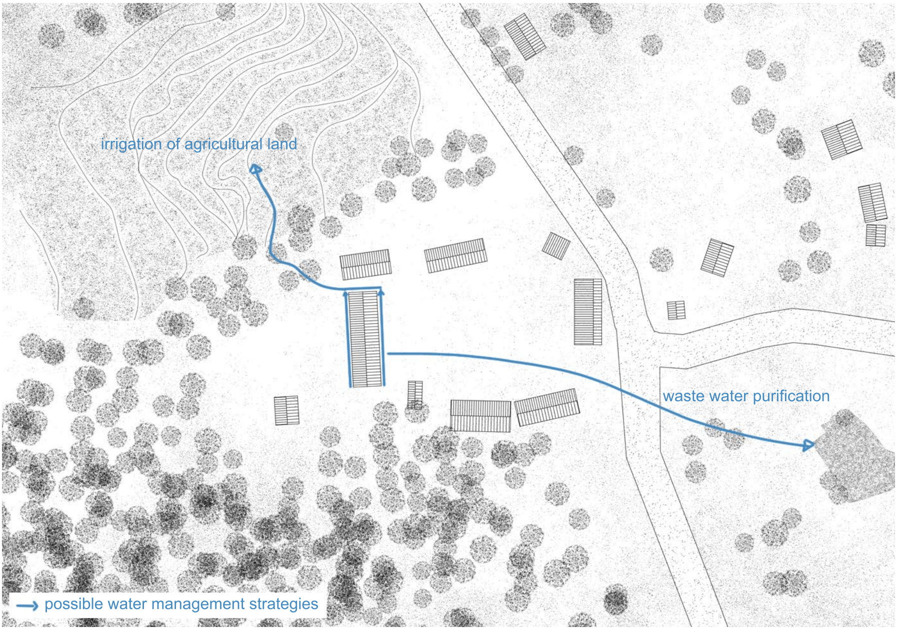
Sanitary needs or food production are not covered in the schools' operation and the rainwater percolates in the fertile soil surrounding the building without further use.
Even though the schools can be seen as alien to a Nutrients-Energy-Water Nexus, there is a potential for the implementation of a circular use of the site's resources. With an annual precipitation of approximately 4851mm, rainwater could be used for a sanitary system or drinking water storage . Furthermore, a clever distribution of rainwater could make the irrigation for agriculture of adjacent land possible which would give an opportunity to integrate agriculture into the school's educational schedule and foster a more resilient community.



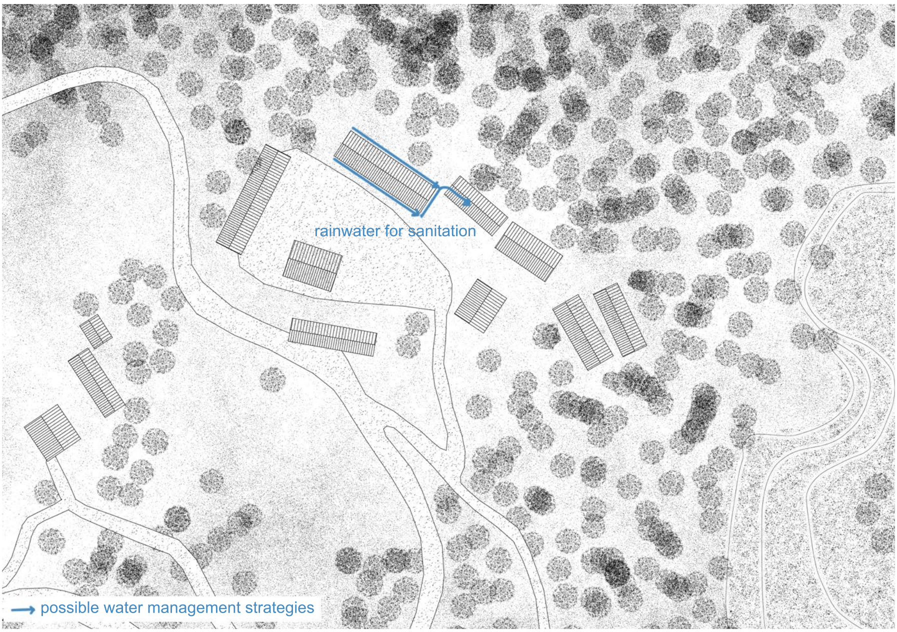
1:2000 section | Chandra Prava Secondary School in Bhirchowk | rubble stone



1:2000 section | Kalika Basic School in Syastri | concrete blocks



1:2000 siteplan | Kalika Basic School in Syastri | concrete blocks

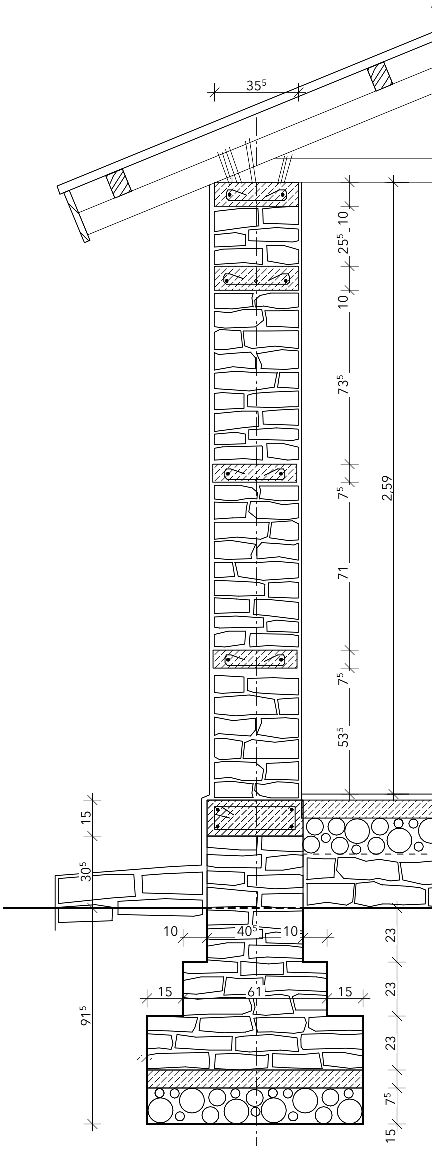


1:2000 siteplan | Chandra Prava Secondary School in Bhirchowk | rubble stone

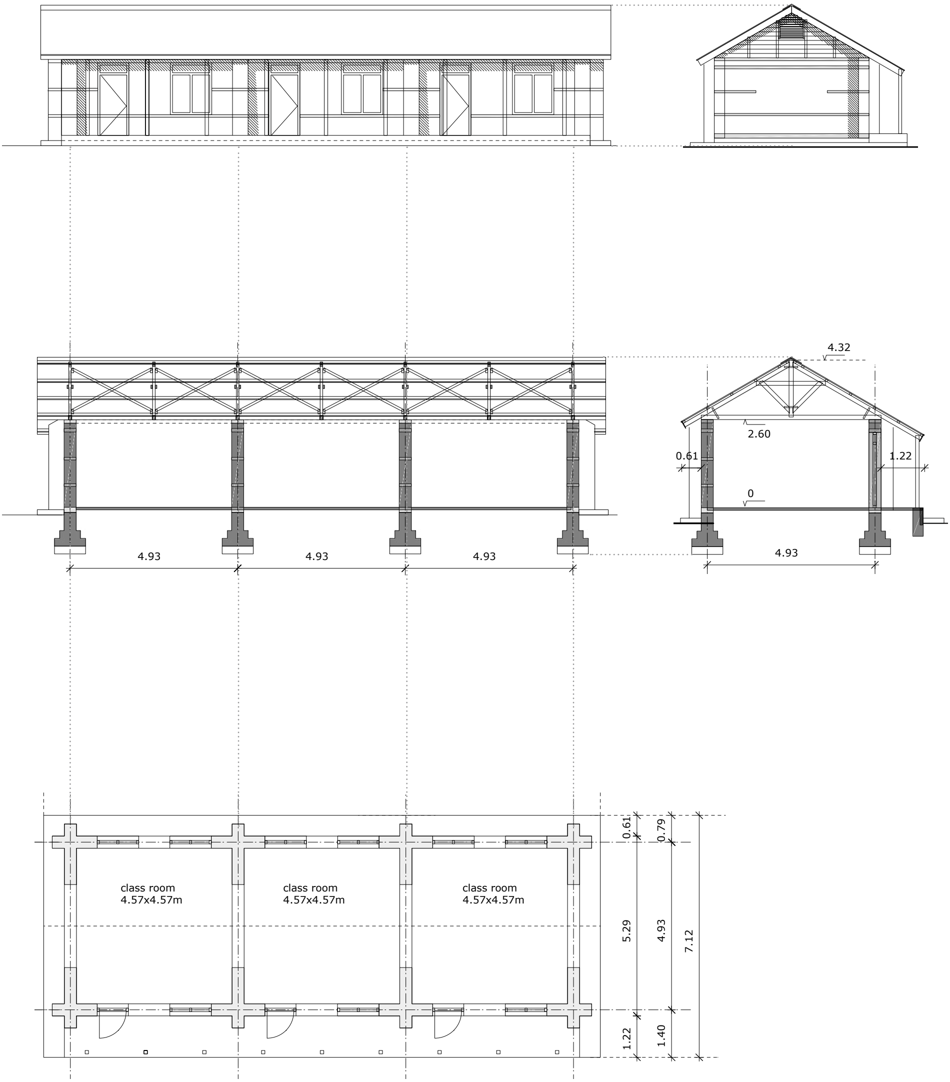
Design for Standardization

When analysing the schools, it becomes quite evident that their design prioritizes standardization. Smart Shelter Foundation have developed a comprehensive set of rules, which define the shape, dimensions, and construction methods of the buildings, with the goal of achieving earthquake resilience. This has resulted in several schools which follow the same philosophy and display minimal differences, mostly concerning the dimensions of their classrooms and of the openings in their facades. However, even these variations exist within a carefully defined margin.

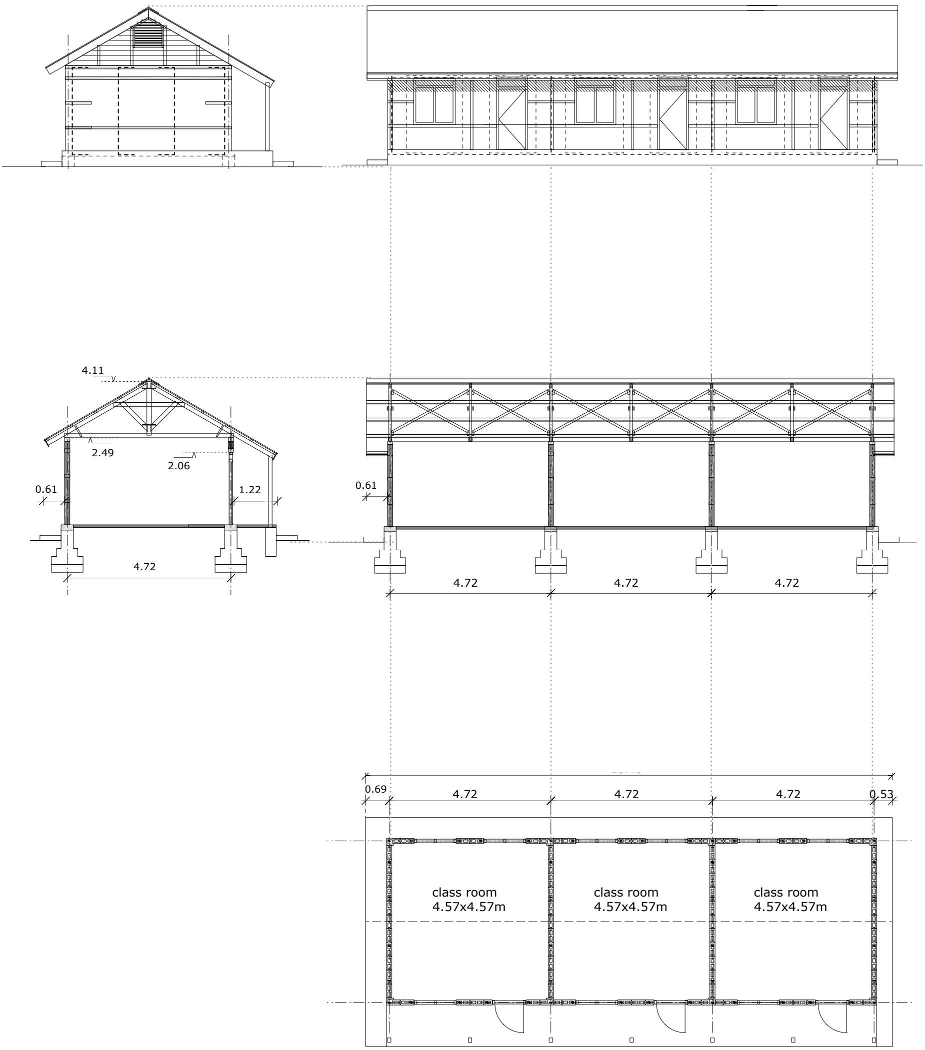
This standardized design allowed the architects to utilize Nepal's resources in the most efficient possible way, minimizing the amount of waste. Given that a significant portion of the materials was obtained locally, it was important to ensure that the creation of the buildings had minimal impact on Nepal's natural environment. Moreover, since transportation of the materials to the building site was challenging, it also aided in minimizing the required number of trips. Finally, the standardization of the materials and the construction allowed for the buildings to be understood by the locals. This was crucial in the philosophy of the buildings, as the schools were mainly constructed by the villagers themselves.



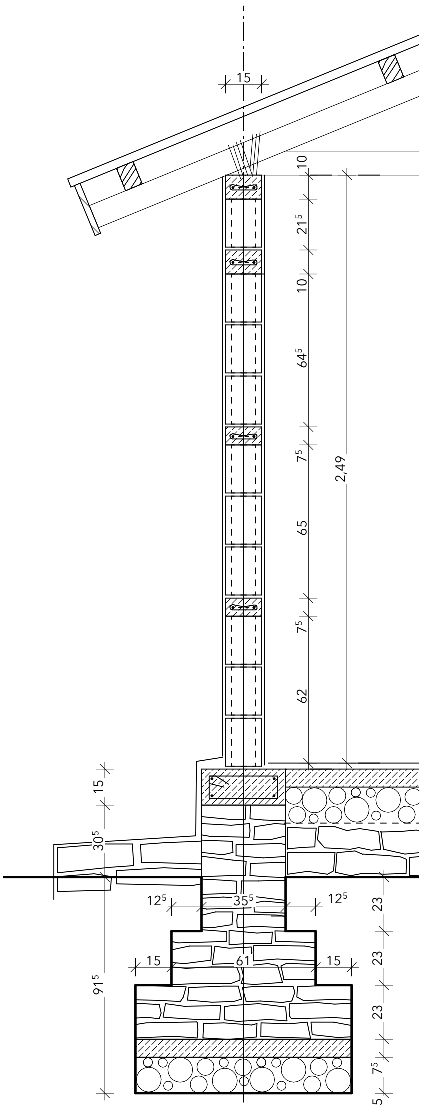
rubble stone construction: façade section



rubble stone construction: projection of floorplan, longitiudinal- and cross-sections



concrete block construction: rojection of floorplan, longitiudinal- and cross-sections



concrete block construction: façade section

However, it is important to note that circular practices entail the reutilization of secondary material streams, which places substantial demands on standardization systems. Assessing the performance of materials or components that have previously been used becomes therefore a critical concern. Indeed, in the case of the schools, rubble stones and wooden elements from the debris caused by previous earthquakes have been utilized. All the schools managed to survive the earthquake of 2015 with very minimal damage. However, these concerns still need to be taken into consideration.

The design of the schools doesn't seem to take into account elements such as adaptability or easy disassembly. This is quite logical if we consider the context they were created in, as materials and technical knowledge were very limited in Nepal. SSF decided therefore to prioritize elements such as safety, durability and accessibility to the local masons and carpenters. It is possible that the layouts of the buildings could serve different uses, due to their simplicity, however their construction lacks flexibility, thus limiting their possible functions. As circular practices become increasingly important, addressing these issues will be crucial for the long-term sustainability of such projects.

Roof-Wall Connection

The connection of the walls to the roof is done by wrapping wires around the rebars in the top beam which, after casting the concrete around it, tie the wooden truss to the wall. According to the architect this is a measure taken because of the lack of availability of special steel connectors that would usually be casted into the top beam. The simple method of using galvanized steel wires is expected to ensure a cheap and easy to install connection that sources available material. The analysis of this detail in a 1:2 model led to questions regarding the connection's longevity. Because the wires are tied to the steel rods and casted into the concrete, in case of damage of e.g., an earthquake, the connection would be difficult to restore properly without replacing the top beam. Additionally, water might enter the concrete beam and to the steel rods leading to corrosion in a structural element that is meant to ensure the building's earthquake resilience.

Therefore, we designed a different detail to investigate a possible solution to its original problems. Resting the truss on a horizontal wooden beam improves repairability and prevents water from entering into the rebars, as the horizontal beam only needs to be bolted to the concrete.

original connection | model 1:2

improved connection | model 1:2

original connection | model 1:2

improved connection | model 1:2

Stakeholders & Value Chain

Circular design challenges the traditional role of the architect while, at the same time, revealing many exciting possibilities.

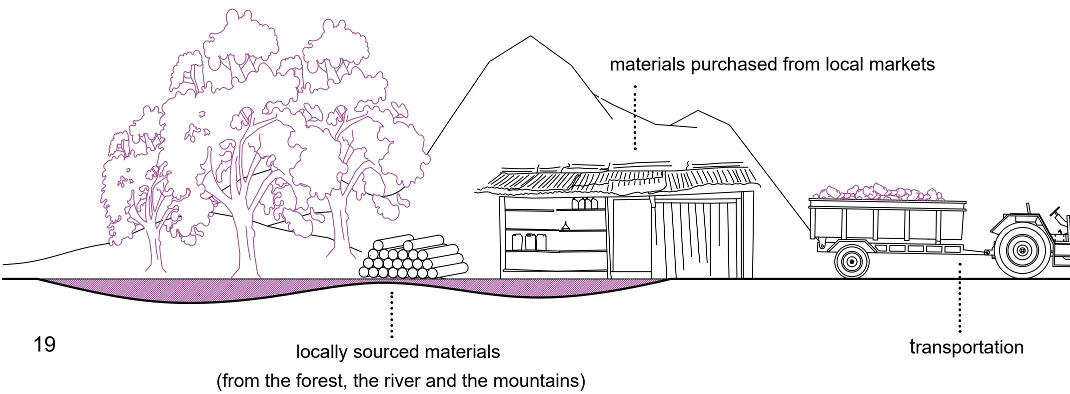
For instance, architects often need to rethink their choice of materials, as circular design prioritizes using sustainable and recyclable materials that are ethically produced. These materials can be locally sourced to reduce transportation emissions and support local economies. Traditional materials, although widely available and usually lower cost, might not comply with circular design principles.

However, the architect needs to also consider the environmental impact during the building's operational stage, incorporating elements such as passive solar design, effective insulation, and renewable energy sources.

Moreover, circular design advocates for creating buildings that can be easily dismantled and repaired or even entirely repurposed, thus reducing waste and having a lower environmental impact overall. Therefore, the architect needs to constantly search for the balance between adaptability, durability, and aesthetic values, over rethinking his own design approaches.

In their effort to create circular buildings, architects will need to collaborate closely with various stakeholders: manufacturers, suppliers, engineers, recyclers, and, of course, their potential users. It is crucial to keep an open mind and a willingness to learn from everyone involved in the process.

However, the innovative approaches of circular design can involve higher upfront costs, which may cause hesitation for the clients. Architects need to help them understand the significant long-term environmental and economic benefits of such buildings.



The team at Smart Shelter Foundation began by identifying the needs of the villagers, who actively participated in every step of the execution process, becoming responsible for the purchase of materials and the hiring of local laborers. For this reason, a Construction Committee was established by each village, consisting of the village chief, the school headmaster, some village elders and local laborers.

Each village contributed financially about 20% to 30% of the total budget. SSF was in charge of securing the remaining funding and handling all technical aspects, such as designing the earthquake-resistant buildings, creating architectural drawings, and preparing cost estimates. SSF closely collaborated with SEED Foundation Nepal, which was responsible for all the administrative and communication matters with the village committees.

A lot of the materials (such as mountain stones, sand, pebbles and wood) were sourced locally, while materials such as concrete blocks, reinforcement steel, tin sheets and paint were purchased in local markets. A deal was made with a local concrete block factory, to ensure that the correct amount of cement would be used.

Throughout both the pre-construction and construction phases, comprehensive training was provided to the local masons and carpenters. The training sessions were held in collaboration with SEED, as well as CWS Hong Kong and World Vision Nepal.

After the construction process, the villagers are responsible for the maintenance and repair of the schools, aided on occasion by SSF. Considering that the aim is for the villages to have complete ownership of the schools, it is possible that the locals will also be responsible for the potential disassembly and repurposing of the buildings, potentially aided by other stakeholders.

Lessons Learned

School buildings are an essential part of a functioning society, which underlines the importance of their structural safety. The Smart Shelter Foundation has not only succeeded in building earthquake resistant schools, but also in imparting structural knowledge to the villages by working in close collaboration with them.

Apart from the introduction of earthquake resilient building strategies such as horizontal tie beams and vertical steel rods in a hollow concrete brick construction, it becomes clear that considering the factor of environmental impact adds a second layer of value to the building. Remanufacturing and repurposing rubble stone from destroyed buildings has proven to positively impact not only the affordability of the school buildings, but also their carbon footprint.
On the other hand however, the use of steel rods for the beams and walls is counteracting these environmentally positive effects. The walls are constructed of either rubble stones or concrete blocks bonded by cement mortar which makes disassembly and recycling a very challenging process.
This presents the issue that the buildings are not designed with an end-of-life scenario in mind, as their different components can't easily be reused or adapted to different possible uses.
As the school buildings are designed for a low budget, cuts were made in comfort as well as in building quality. Even though the architect explained after an enquiry that buildings in Nepal are commonly constructed without insulation and that inhabitants have adapted to that, recent projects in Pakistan and Nepal showcase the use of straw as a cheap way of improving building comfort.

The quality and longevity of specific details like the roof-wall connection suffer from the lack of adequate building material in the area. However, other methods of construction can be implemented that increase repairability and longevity of the connections. The standardization of the schools' layout results in buildings that are mostly unable to integrate the site's specific resources into a greater scheme of circular building operation. This leaves a great potential unused and can be researched further.

Colophon

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Studio:
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Tutor(s):
Job Schroën
Freek Speksnijder

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https://www.materialepyramiden.dk

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https://www.smartshelterfoundation.org

https://en.climate-data.org/asia/nepal

Schildkamp, M., & Araki, Y. (2019). Cost Analysis of Mountain Schools in Nepal: Comparison of Earthquake Resistant Features in Rubble Stone Masonry vs. Concrete Block Masonry. Frontiers in Built Environment, 5. https://doi.org/10.3389/fbuil.2019.00055

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