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RESETTLEMENT OR RESILIENCE? THE TSUNAMI SAFE(R) PROJECT

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ABSTRACT: This paper reports on the ‘Tsunami safe(r) project’, developed at MIT SENSEable City Laboratory, and discusses how technology could provide alternatives to the relocation of the coastal population in Sri Lanka. In particular, the focus is on building and digital technologies. Could structural guidelines extracted from the analysis of surviving structures and the implementation of an early warning system using cell phones provide a more effective solution to relocation - promoting a less hasty, more sensible recovery of the disaster-torn areas? While the cell phone component of this project is still in the research phase and is not discussed here, the housing part is currently being implemented by the Prajnopaya Foundation, which is involved in the construction of over 1000 houses in Sri Lanka. The design of a 400 sq. ft. prototype has been developed and is described in this paper. According to structural simulations by Buro Happold Engineers (London), the final low-tech-construction, high-tech-design structures should be over five times more resistant than the existing ones in the case of an incoming tsunami. The paper ends by reviewing the built prototypes and commenting on the issues that were encountered during construction. Conclusions suggest that, if coupled with an effective early warning system, the Tsunami safe(r) house could effectively represent a different approach to post-Tsunami reconstruction.

1. INTRODUCTION

In the wake of the Indian Ocean tsunami disaster of December 2004, most governments in the affected countries have announced policies to resettle the population away from the coastline. For instance, on January 17, 2005, the Sri Lanka Public Security Ministry announced the relocation of its coastal communities, estimated at 800,000. Building restrictions have been proposed, prohibiting construction within 100m (in the Southwest) or 200m (in the Northeast) from the sea [1].

Such policies, however, come at a high social, cultural, environmental and economic cost. They have been criticized by Sri Lanka's fishing community, amongst others, who described the government's move as “arbitrary.” The President of the World Fishermen's Association, Herman Kumara, told the BBC that the fishing community was never consulted before the limits were enforced [1]. Several UN agencies also expressed their doubts [2]. From an economic perspective, in addition to the large costs of relocation, there is a potential risk of structural damages to the economy. The disaster already destroyed over 400,000 jobs in the affected districts in the eastern, southern and western coasts. According to the International Labor Organization, "the majority of job losses in Sri Lanka have occurred in the fisheries, hotel and tourism industry - including eco-tourism, which was starting to expand - and the informal economy” [3]. The economic recovery of these sectors could be compromised if resettlement proceeds as planned.

The aim of this research is to investigate the development of technological strategies that could guarantee future safety at lower social, cultural, environmental and economic cost. In particular, the focus will be on digital and building technologies. The implementation of an early warning system using cell phones (a) and the development of a Tsunami safe(r) house (b) could provide a more effective solution to relocation – promoting a less hasty, more sensible recovery of the disaster-torn areas.

While work on (a) is still being carried out both by the authors and other research groups (see for instance [4]), work on (b) has been almost completed in partnership with the Prajnopaya Foundation, a Buddhist NGO [5]. This paper aims to present our final scheme for the 'Tsunami safe(r) house' (developed at MIT SENSEable City Laboratory) assess its structural performance, review the design process and finally comment on how it might help meet the initial target of avoiding relocation away from the coast in disaster-torn areas.

2. CONTEXT

This section discusses how observations in the aftermath of the tsunami identified the need for a dwelling type whose design would address the possible effects of an inundation.

In extreme flooding, the building's structure is not able to protect the life of the dwellers. Unlike in earthquake regions, life safety cannot be guaranteed by upgrading the capacity of the building fabric to withstand inundation forces, but only through an effective early warning system. However, reducing the economic loss and recovery time makes a strong case for improved construction quality.

Similar to the aftermath of earthquakes, the areas affected by the tsunami offer a unique opportunity to observe, survey and learn how to improve safety and reduce losses in future events. Teams of engineers visited the sites affected by the Indian Ocean tsunami and earthquake (see for instance [6], [7], [8], [9]) and reported the effects of the inundation and ground shaking on building structures and infrastructure. A co-author of this paper took part in the mission sent by the Earthquake Engineering Field Investigation Team (EEFIT), a permanent group of engineers with UK affiliations who have sent missions to twenty-one post-earthquake events in the past twenty two years. EEFIT published a web-based tsunami report in 2005 [10] as well as a more extensive report.

In the visited districts of Kalutara, Galle and Matara in southwest Sri Lanka, the single storey masonry dwelling units were damaged and collapsed due to the overturning of walls under the pressure from inundation [Fig. 1]. Scouring of founding strata caused the failure of foundations. Reinforced concrete buildings varied in response, with damage generally limited to the non-structural infill walls [Fig. 2]. Another aspect is that most structural failure occurred on walls facing (parallel to) the incoming tide waves, while those standing against (perpendicular to) the waves remained substantially intact after the impact, as shown below in [Fig. 5].

The reconstruction efforts offer the opportunity to rebuild houses that both consider the effects of inundations and improve the quality of living space.

Fig. 1 - Typical damage to masonry dwelling (Courtesy of EEFIT)

Fig. 2 - Reinforced Concrete frame with non-structural infill (Courtesy of EEFIT)

3. THE DESIGN BRIEF

The brief was developed by the Prajnopaya Foundation, a Bhuddist NGO based in Boston and one of the first ones to start building houses in Sri Lanka in the immediate aftermath of the Tsunami. Their initial brief aimed at building as many houses as possible, based on the following specifications:

- Each house should be a single family house.
- The size of the house should be approximately 400-500 square feet.
- The houses should be built using local materials available in Sri Lanka.

o The maximum cost of each house should be approximately 1,500 USD.

Following the above brief, the Prajnopaya Foundation started construction efforts in Sri Lanka (they plan to build a total of over 1,000 houses), partly in collaboration with the local Sri Bodhiraja Foundation. The brief the authors of this paper received from them was the following: could we ameliorate the traditional post-tsunami design, implemented by most NGOs, within the constraints set by their initial brief (above)?

Fig. 3 – Traditional house being rebuilt in Sri Lanka

The houses built in Sri Lanka by most NGOs are based on standard designs such as that shown in [Fig. 3]. They usually use rubble foundation, concrete blocks for the walls, and imported timber or local coconut rafters and tiles for the roofing. This typical design seeks to provide structural strength by building four solid walls to enclose the house. This is however not ideal from a climatic point of view, as it does not allow proper ventilation. It should also be noted that the four-solid-wall design has proved in many cases not to be good to withstand lateral forces induced by waves.

As designers, we asked then: how to ameliorate the standard design while fulfilling all the constraints that were set out in the Prajnopaya brief? It should be noted that we were not looking for a house that could provide 'total' safety or that could be considered a safe-haven during a tsunami. Our task was simply to develop a design that would minimize losses during an eventual tsunami, making an eventual post-disaster rebuilding less difficult. It was a kind of 'optimization under constraints' [Fig. 3]; something that, coupled with an effective early warning system via cell phone, could be an alternative to the relocation of the coastal population away from the sea.

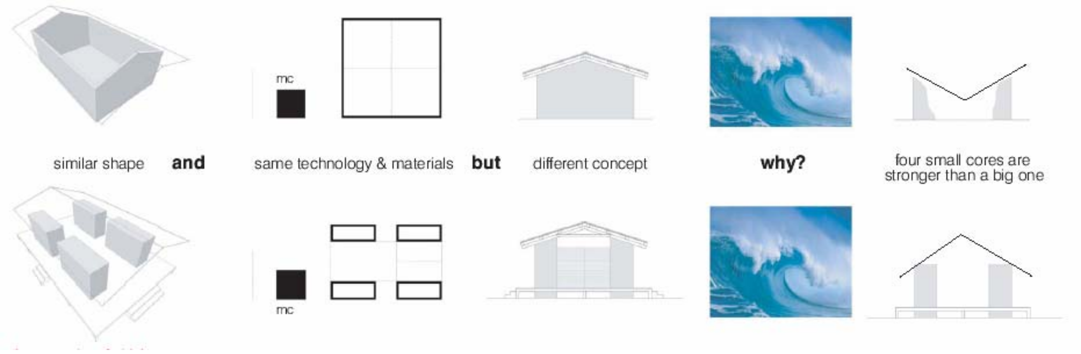

Fig. 4 – optimization within constraints

4. THE DESIGN OF THE TSUNAMI SAFE(R) HOUSE

By studying the ruins of structures collapsed during the tsunami, we observed that most structural failure had occurred at walls facing (parallel to) the incoming tide waves, while those standing against (perpendicular to) the waves had remained substantially intact after the impact [Fig. 5]. The collapse of the walls further triggered the collapse of the roofs they carried. As most houses in Sri Lanka were built (and still are built in the reconstruction process) with cement blocks without steel reinforcement inside and without structural ties to their foundation, the perimeter enclosure was extremely vulnerable to external impacts.

Fig. 5 - Partially collapsed structures after the 2004 Tsunami in Sri Lanka

Based on the analysis of this collapse mechanism and the structural limitation that resulted from conventional construction techniques, our design adopts a two-fold strategy. On one hand, with respect to construction techniques, it introduces steel reinforcement bars into the cement walls and steel structural ties to the foundations [Fig. 6] On the other hand, it redesigns the exterior enclosure of the building by "folding" the exterior walls into four structural "cores" at corners of the house. [Fig. 7] The folded walls can better resist the external impacts as the surface area of the structure directly facing the incoming wave decreases (please refer to the structural analysis performed by Burro Happold, London, and described in the following section in this paper). Most of the infrastructure of the house (water, electricity) is contained within the cores and thus less vulberable. The infills in between the cores introduce porosity into the design and allow for the water to flow through and around the cores to minimize impacts on the structure [Fig. 8]. Since "the roof stays as the wall stands," such design aims to preserve the basic structure of the house during a tsunami and to limit the potential damage to the infill elements between the four structural cores. Therefore, it can provide basic shelter to those affected and allow a faster rebuilding process around the surviving core structures in the aftermath of the disaster.

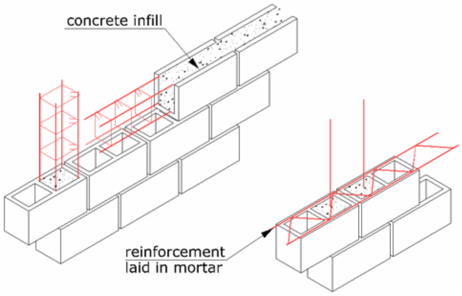

Fig. 6 –CMU blocks reinforced with vertical bars

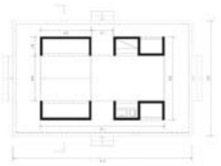

Fig.7 - Structural core formation

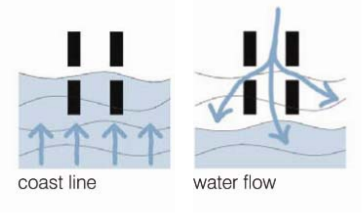

Fig 8 - Porosity diagram

The gaps between folded cores become an important part of the design. They are in-filled with wooden horizontal louver panels. The bottom three feet have plywood backing to form an opaque base that preserves privacy and prevents animals from entering, while the rest remains perforated. From a design perspective, the infill elements introduce "lightness" against the solidity of the structural cores. They allow perforation in the enclosure, which could be referenced back to the work of the Sri Lankan architect Jeffery Bawa and other vernacular architecture in the country. Perforation was consistently part of Bawa's architectural language and detailing, such as the partition detail in the Dr. Brotholomeusz House (now Gallery Café) in Colombo (1961-63) and the perforated concrete walls of the steel incorporations offices at Oruewela (1966-69). [Fig. 9] Perforation was also part of the vernacular architectural language, especially in the southern and eastern part of the island where Islamic influences could be seen on local construction. [Fig. 10] Both the wooden framing and the louver panels are painted to form a protective coating against the saline sea breeze. Furthermore, the infill elements are easy to work with and allow upgradeability and adaptability should the financial condition of the residents improve. More robust shutters can be fitted in to increase security.

Fig. 9 - Interior view of the Gallery Café in Colombo

Fig. 10 - Perforated wall with Islamic influence

From a climatic point of view, the lightness and openness of the perforated infill takes full advantage of the sea breeze and the tropical sun. Light can penetrate into the heart of the house, and cross ventilation is optimized by the louvered panels. The available cross ventilation also ameliorates the discomfort generated by the radiant heat from the roofing clay tiles, which act as a heat mass under the scoring sun. When compared to conventional houses, the new design would remarkably improve the living conditions of the residents by creating a better lit and ventilated interior.

The design of the house uses local materials. The walls are constructed with typical cement blocks (with holes for reinforcement penetration). The roof takes the form of a traditional pitched roof of 30 degree slope, to better drain the monsoon rain. The roofing tile is made from local clay, which performs better as a thermal insulator than the alternative corrugated tin roof. The primary roof framing members are all made of solid timber: four horizontal beams span across the width of the house, each of which has a vertical post in the middle to support the ridge beam on top. Roof rafters and purlins are the ubiquitous coconut fiber members, and they serve as secondary members to accommodate the roofing tiles. Unlike conventional roofs, however, the primary members are all anchored to the top of the cores to serve as restraining heads for the walls in order to further strengthen the structural capacity of the cores.

Each of the structural cores has a dimension of 1.2m x 3.2m (4' x 14'). Based on programmatic requirements, the walls of the individual cores are folded differently into various configurations, as shown in [Fig. 7]. This allows for a flexible division of space within the house to suit the needs of residents and the particular local context[1]. Programs within the cores could also be tailored, such as trading storage space for a bigger kitchen or turning one of the storage cores into a third bedroom [Fig. 11]. The core could also extend into the adjacent space to form a bigger space, such as the two facing C-shaped bedroom cores sharing the in-between space with the wooden shelves partition.

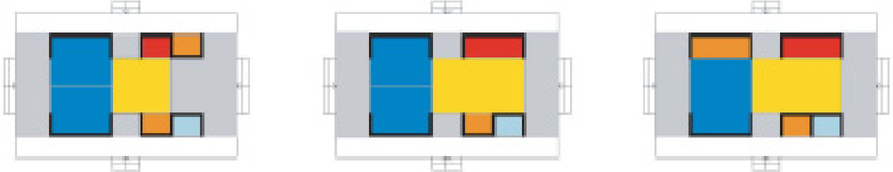

Fig. 11 Diagram showing programmatic flexibility

In Sri Lanka, families of different generations tend to live together, rather than create their own small nucleus family as in most western cultures. The design of the house provides potential expandability by building additional core elements as families grow [Fig. 12]. A simple expansion could be linear with additional cores added to the ends. However, expansion could also happen laterally to form courtyards, resulting in a more complex residential space to better fit different family structures.

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[1] Sri Lankans are accustomed to entering their toilet from outside of their house. Some even have them completely detached from their houses. The flexibility in the core arrangement allows the design to adapt to such local context. Furthermore, in some Sinhalese communities, women prefer not to sleep with their husbands in the same space during menstruation. The provision of two bedrooms and the possibility of converting a third one in the design could easily serve this cultural practice.

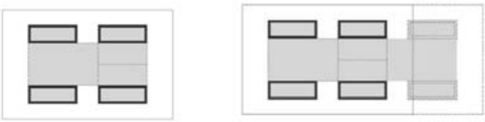

Fig. 12 Diagram showing potential expansion

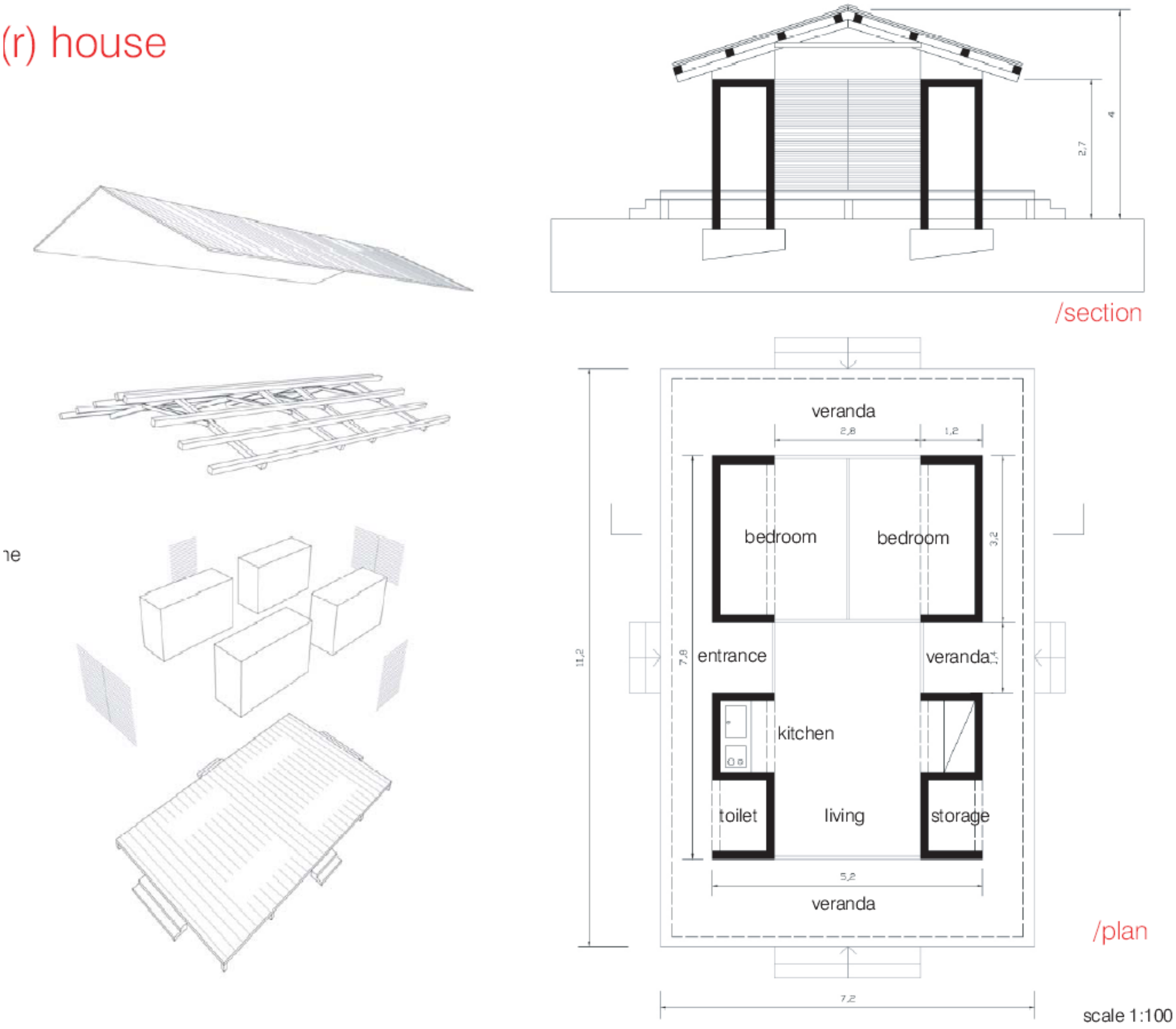

Fig. 13 –The Tsunami safe(r) house design

5. THE CALCULATION METHODOLOGY

In this section, we shall show the results of a comparative study between the proposed safe(r) house and a typical building configuration of approximately the same footprint and construction cost. A number of assumptions relating to the geometry, materials and loading have been made, which, whilst might affect the absolute performance, will not invalidate the relative performance to the two cases.

Two methods were used to analyse and compare the performance of the structures: a masonry design method, based on British Standard BS 5628, and a deformation comparison, assuming elastic behaviour.

5.1 Using Masonry design methods

The capacity of non-reinforced walls against horizontal loading is governed by the magnitude of the tension capacity generated in the mortar beds and the length of the lines along which failure of the panel occurs.

Wall panels on both elevations of the building are compared. Loading is assumed to be of hydrodynamic nature, uniform along the full height of the building. A weak mortar mix is considered for all cases. No wall head restraint is assumed for the traditionally-built wall while this is restrained in the proposed construction. In the traditional building, wall thickness is assumed 225 mm. Two cases of 150 mm and 225 mm have been considered for the proposed wall clusters.

The moment capacity of a failure plane is given by the equation:

$$M_{CAP} = {}^{f_{kx}}\!/_{\gamma_m}\, z$$

Where

f_{kx} is the characteristic flexural strength appropriate to the plane of bending

γ_m is the partial safety factor for materials

z is the section modulus of the wall profile

Imposed bending moments from the horizontal load are given by:

1. For failure planes perpendicular to bed joints = $\alpha W_k \gamma_f L^2$
2. For failure planes parallel to bed joints = $\mu\alpha W_k \gamma_f L^2$

Where:

α is a coefficient governed by the panel geometry and edge conditions

W_k is the characteristic lateral load

γ_f is the safety factor for loads

L is the length of the panel between supports and

μ is the ratio of flexural strength between orthogonal bed joints.

Results

Wall capacity ratio of proposed wall configuration	**Safe(r) house – 225mm thick non-reinforced wall**	**Safe(r) house – 150 mm thick non-reinforced wall**
Short elevation/return wall	**5.3**	**2.4**
Long elevation	**5.2**	**2.3**

The table above shows the improvement of the clustered wall cores against the traditional linear wall configuration. Wall thickness has a significant effect on the wall capacity.

Considering the loading as hydrostatic and given by the equation $1/2\,\rho v^2$, the results in the table would indicate that inundation velocities up to 2.3 times greater could be resisted.

The inclusion of small amounts of reinforcement fed through the CMU blocks and cast in-situ would increase the performance of the walls and could easily be phased in the construction of the wall at little cost. The roof structure is tied to the wall head with dowels cast into the same concrete-filled wall sections. Reinforcement will be required in the shorter return walls to resist the concentrated shear forces and would need to be tied to the mass foundations to provide resistance to overturning.

5.2 Comparison of Elastic Deflections Using Finite Element Analysis

A simplified model, where wall heads in both buildings are unrestrained, was developed to understand the equivalent elastic behaviour of the configurations. This does not represent the true behaviour of the wall panels, which, as we said above will form distinct failure lines. The purpose of this study is to analyse the stiffness characteristics of the two wall configurations. Wall collapse can also be caused by instability due to the excessive horizontal movement [Figures 14, 15, 16]. The model has shown that, with equivalent wall thicknesses, the out-of-plane horizontal movement of the traditional configuration was up to five times that of the wall clusters of the safe(r) house.

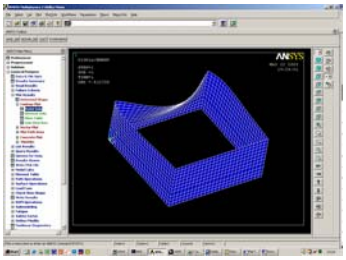

Fig. 14 Traditional dwelling: elastic deformation under horizontal load

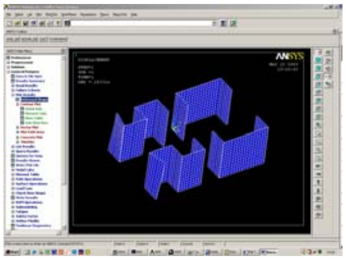

Fig. 15 Safe(r) house: elastic deformation under load parallel to coastline

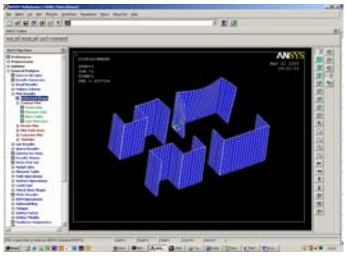

Fig. 16 Safe(r) house: elastic deformation under load normal to coastline

6. THE CONSTRUCTION OF A PROTOTYPE

As soon as the design of the prototype was developed, a site was acquired by Sri Bodhiraja on private land donated by the owner and situated on the Eastern Coast of Sri Lanka, in the town of Balapitiya, District of Ambalangoda. The site sits just behind the one hundred meters buffer zone line from the coast, next to the foundation of the owner's old house that was destroyed by the tsunami. The cores are oriented perpendicular to the sea, and the front door of the house faces the road that is soon to be developed.

As the construction of the prototype began, a few changes were imposed on the design. The raised platform that was originally part of the design was scrapped for two reasons: first, its hazard considering that animals such as snakes and scorpions could hide under it; second, its cost. Instead, we had to resort to rubble foundation traditionally used in Sri Lankan houses. Another change concerned the height of the walls forming the core: this height increased as a result of some problems in the collaboration with local contractors, who were mostly familiar with building traditional houses and did not have the technical skills to understand our technical drawings. Fortunately, some of our team had the opportunity to travel to the site to supervise the completion of the construction of the house, engaging in a better dialogue with the contractors and avoiding further complications, especially in the design of the partitions between the core walls. While on the site, the team designed and provided specifications for the construction of the louvered enclosures around the house and suggested enlargement of the veranda behind the house.

With the completion of the house, it should be noted that there was an increase in its total cost, which raised to approximately 3,500 USD. However, this should not be attributed to the design itself but to the increasing scarcity of building materials in the aftermath of the tsunami, now that a very large number of houses are currently being built in Sri Lanka. This effect is affecting all NGOs and our amount remains lower than the average cost of a typical NGO post-tsunami house, which seems to vary, based on our site surveys, between 2,750 USD and 8,000 USD.

Fig. 17 Completed Tsunami safe(r) house

7. CONCLUSIONS AND FUTURE WORK

The Tsunami Safe(r) House project seems to shown that it is possible to achieve a more structurally, environmentally and financially efficient design using the local construction methods and materials. By reexamining the fundamentals of the conventional Sri Lankan house, this "high design, low technology" strategy allowed us to provide a new dwelling prototype that is strongly responsive to the local culture, climate and tradition. Furthermore, simulations show that the prototype will be up to five times stronger in the case of an incoming tsunami.

The research conducted in Sri Lanka this summer has given the design team the opportunity to be on the construction site and work with the local construction crew so that we understand the construction methods and techniques they are capable of performing and how traditional building materials can be used differently and innovatively to achieve our design. More importantly, the trip allowed us to observe first-handedly the way of life in Sri Lanka and experience how people live in a society that is strongly attached to its various forms of culture, tradition and religion. This proves to be extremely valuable as we are revising our design for the next houses to be built.

Currently, after completing the construction of the prototype unit in Balapitiya, additional government-owned land is being acquired in the southern city Hambantota to build more the Tsunami safe(r) houses. This will be a perfect opportunity to test our design at a community scale. As multiple of these houses are to be built within the neighborhood, it will be possible to investigate how the houses are related to each other as well as to the in-between communal spaces. We will study how the design needs to be adjusted to better fit the local conditions in Hambantota and how the aggregation of houses could provide social space to serve the community as a whole and improve its livelihood. Again, the community cohesiveness brought by the aggregation of the houses is as important as the structural integrity of the single house, and it needs to be further researched.

During the rebuilding process, one question kept on resurfacing: what would be the best way to respond to the government's coastal buffer zone, which is generally viewed as an arbitrary policy in response to a catastrophic event with a return time of 500-2000 years?

It is important to consider that we are not only addressing a construction problem, but also a political and social one: i.e. politically convincing the government of a viable alternative to relocation and socially making people feel safer if they are to live on the coast. This is exactly the goal of the Tsunami Safe(r) House project. Through structural analysis and stimulations, we demonstrate that the design of the Tsunami Safe(r) House can be more than five times stronger than the conventional Sri Lankan house in resisting to incoming waves. It can therefore minimize losses during future tsunami and accelerate post-disaster reconstruction efforts. Coupled with an effective early warning system via cell phone (currently under research and development), this could provide a much sensible alternative to the current government policy of permanent resettlement inland. In short, the Tsunami Safe(r) House project serves as a politically and socially strategic response to the post-disaster context rather than simply a technical and practical one to housing tsunami victims.

8. ACKNOWLEDGEMENTS

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