

A critical assessment of concrete and masonry structures for reconstruction after seismic events in developing countries

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ABSTRACT: Haiti is not alone amongst developing nations that have suffered losses due to the poor construction of concrete and masonry structures in an earthquake. In the wake of the disaster, a considerable amount of public sympathy and substantial funding was raised that supported short term, front line activities. However, there is little recognition of the need for adequately funded systems of organization and long-term support, particularly with respect to the design, structure and reconstruction of buildings. Much of the research and proposals made for the better rebuilding of Haiti, primarily focuses on the creation, education, and enforcement of “better” construction methods, life safety standards and codes imported from developed countries. These fail to address the other, perhaps more important, social and economic issues that led to sub-standard structures in the first place. Masonry and concrete buildings are typical throughout Haiti, and are continuing to be proposed for reconstruction. Research has shown that the structures of these concrete buildings are both unreliable and ineffective when natural disasters occur, due to compromised construction in the quality or quantity of materials. It is noted that the Haitian construction of recent buildings and particularly those that have collapsed in the 2010 earthquake were all built with poor concrete mixes. When mixing the concrete, builders would use the poorest quality of sand for concrete and save the more valuable sand for the exterior stucco of buildings. This also holds true for the amount of rebar used in the concrete as well. This paper concludes that continuing to rebuild with structural systems that can be easily compromised during construction due to economic hardship or societal inaction is not sustainable. The authors propose the use of structural systems that cannot be easily compromised, can be visually inspected after construction for code compliance, and analyze the barriers to their use in developing countries.

1 INTRODUCTION

1.1 *Lessons from Haiti*

Haiti is among the 20 poorest countries in the world and is one of the most environmentally devastated. Since the island nation lies on the Enriquillo Fault, between the Caribbean and the North American tectonic plates, Haiti’s poverty is amplified by the geology of the region. As a result of the 2010 earthquake, there has been an estimated 250,000 homes and 30,000 workplaces and shops either destroyed or badly damaged. Because of Haiti's use of poor construction techniques, and the general use of concrete, the 7.0 earthquake caused more than double the fatalities of any previously recorded event of that magnitude. Haiti will continue to be vulnerable to earthquakes. Although the plight of Haiti in the aftermath of the earthquake has attracted funding and sympathy, less consideration has been made for the long-term support of constructing sustainable, seismic resistant buildings. Post disaster evaluations have revealed that the majority of Haiti's destruction was simply caused by the poor quality of construction materials which proved too weak to resist the lateral and horizontal forces generated by the earthquake (Audefroy 2011).

Engineers, architects, scientists and others have already recognized that the process of construction is dysfunctional with no building codes in place and economic incentives to cut corners. Although the awareness of poor techniques have been made, engineers and architects are still proposing systems that are destined to be hazards once the next disaster occurs due to their continued use of masonry and concrete. Not only is the use of concrete economically and environmentally unsustainable but it is also the most vulnerable material when seismic activity hits the surface (Bilham 2010). Virtually all the buildings destroyed in the 2010 earthquake were poorly constructed, non-engineered, masonry and concrete buildings. Along side the poorly considered mixtures and the lack for reinforcement, the overall weight of the large mass of these buildings caused the majority of injury and death (Farmer 2011).

1.2 *Rationale*

Despite the fatalities due to these substandard structures, similar masonry and concrete buildings are continuing to be proposed for the reconstruction of Haiti today. Multiple non-profit organizations, architects and structural engineers have already donated an enormous amount of their time and resources into the development of a more seismic resistant and sustainable built environment that can provide structural longevity and disaster proof living (Middleton 2010). But even with the considerable amount of action that has already taken place, there are still multiple structural controversies that could, in time, affect the safety of Haiti. No consideration is given to the fact that some of the modern materials specifications (specifically concrete) are not applicable in certain tropical areas under seismic vulnerability. In developed countries, architects and engineers know how to mitigate the effects of earthquakes. Due to the poverty and continued lack of resources in Haiti, rapid and substandard construction will continue to take place. If research has shown that the structures of these concrete buildings are unreliable when natural disasters occur (Bilham 2010), then one major question this paper will address is why masonry and concrete is still being used in the reconstruction of Haiti.

2 BACKGROUND

2.1 *Haiti as case study*

Poorly constructed reinforced concrete multistory buildings have become the replacement of traditional construction forms and with little effective social understanding or demand for seismic quality, and shortfalls in the governmental and legal framework that would ensure it, a huge vulnerable building stock has emerged over a wide region of developing countries (Gulkan 2004). The controversies that have specifically raised in Port au Prince, Haiti today is the assessment of concrete and masonry structures for reconstruction. As most current methods of design, architects and engineers should understand the basic seismic tectonics of structural systems. But because Haiti has such a depleted source of materials and codes, structural systems remain vulnerable to natural disasters.

Typically in Haiti, one will increasingly find modern block and concrete houses in both provincial villages and urban areas (Advameg Inc 2012). In the more southern areas of Haiti, houses are constructed of hollow block concrete similar to the construction you see in the Philippines. Over time, research has shown that the structure of the concrete houses are both unreliable and ineffective when natural disasters occur (Bilham 2010). Like previously mentioned, much like Haiti, developing countries around the world have disregarded standard construction techniques due to the lack of resources, knowledge and labor. Because of the minimal resources, the Haitian construction of recent buildings and of those that have collapsed in the 2010 earthquake were all compacted with poor concrete mixes (Fierro 2010). While mixing concrete, local labor and builders will use the poorest quality of sand and save the more valuable sand for the exterior stucco of the buildings. As a result, over 90 percent of all structures in Haiti cannot withstand the after effects of natural disasters (Audefroy 2011).

This is where the role of advanced architectural and structural designers need to be aware when considering reconstruction in Haiti. Even two years after the devastating earthquake there is still little care for the seismic vulnerability and the longevity of future buildings. One could argue today that their international practices can produce sustainable concrete structures that

deny the use of poor mixtures and low quality labor. But what they are not taking account for is the quality of concrete, post earthquake. The question then is how sustainable can concrete be after it has deconstructed in a natural disaster. The sustainability of concrete in Haiti seems almost impractical and irresponsible. The simple fact of knowing that concrete, reinforced or not, will not outlast any earthquake in the Caribbean, should be the first clue to completely deplete it from all future design proposals. Both the local and international stakeholders of reconstruction in Haiti should reconsider sustainable structural systems that will indefinitely remain functional after a natural disaster hits.

2.2 *Other developing countries with seismic events*

Haiti is not alone amongst developing nations that have suffered losses due to poor construction of concrete in masonry structures. In fact, there are several examples of the same controversies in the use of substandard construction and the devastating after effects that come with it. What is important to note is these same nations also provide alternative exemplary structures that have withstood the effects of seismic activity and can become a model for the reconstruction of Haiti. But to first understand what systems are necessary for the safety and needs of Haiti, it is valuable for us to investigate both the structures that have failed seismic activity and those structures that have withstood. It is also important to use examples that generally have similar climates and/or similar responses to seismic activity.

Like Haiti, a major geological fault line runs right through Istanbul, Turkey, creating a target for unstable structural systems when natural disaster hits. Much of the city was built as a frantic effort to respond to a large growth in population that ultimately led to an inventory of buildings with poor and unmonitored structures (Pyper 2010). Along side the poor efforts of "shoddy" construction, 90 percent of these structures were either constructed with adobe or concrete, both of which are most vulnerable to earthquakes. After the 6.0 magnitude earthquake hit Istanbul in March of 2010, only 51 people died but almost all buildings constructed of masonry were destroyed. The construction material was so poorly mixed with sand and random pebbles that after the deconstruction of the earthquake, the walls fell into pieces with minor force, crumbling easily through the fingers.

The Philippines, one of the top five most earthquake-vulnerable developing countries along with Turkey, has similar building frailties when considering the poor construction of seismic resistant structures. With non-engineered and non-supervised building examples, the construction of the Philippines is generally reinforced concrete with hollow brick infill. And although strict building codes are in effect there is a common act of code violation that ultimately makes the reinforced concrete vulnerable to any seismic event. The 7.7 magnitude earthquake in 1990 killed nearly 2,000 people due to the unreliable techniques of masonry construction. It is also important to state that several portions of deconstruction do occur during landslides, but the earthquake vulnerability still plays into effect when we discuss the topic of substandard construction.

3 METHODOLOGY

Despite the loss of courage and hope, the opportunities for Haiti are far more favorable than those of the 'fragile states' in other developing countries. Due to the country's lack of codes, labor and resources, a new sustainable effort can be cultivated and Haiti can enroot new methods of structure and systematic codes that not only improve the safety of all Haitians.

This paper is critical of using masonry and concrete construction in Haiti. Two years after the earthquake, little has been considered in order to "build back better" seismically. In Haiti, there is a still a higher social status that is assigned to a building made of concrete than a building made with rock or wood, even though concrete does not perform as well thermally or seismically as a different frame system would. As the discussion of this paper has specifically centralized on the controversies of old and new construction methods of Haiti, now is the turning point to discuss the opportunities and the introduction of other sustainable materials that could possibly be the answer to seismic resistant strategies. As the international community helps the country rebuild, the know-how and the materials for the work should come from Haitians, not for-

eigners (Fiero 2010). But by utilizing the knowledge we have in the technology of science and structural engineering, together Haiti can build a strong community.

3.1 *Conventional structural materials*

It is likely that despite the dangers outlined in this paper, concrete will continue to be used in Haiti. The reconstruction of Haiti has become a project for international firms to "play in." Building designs are getting bigger and heavier, and production and labor is growing extensively. Aside from all the concrete that get imported, all the debris in Haiti will never disappear. The main problem with industrial, international materials is they have to be imported into Haiti, causing designers to cut costs elsewhere in the project design. Reinforced concrete is a very reliable building system, but only if it is constructed properly. Concrete and masonry construction has historically been sub-standard in Haiti. In order to rebuild safely with concrete in Haiti, there would need to be widespread training and quality control (Bhatty 2010). Conventional reinforced concrete should ultimately be used only where it is necessary.

3.2 *Traditional and locally sourced structural materials*

There is little time for trial and error in the process of new strategies for seismic resistant design. The reconstruction of Haiti needs to be executed efficiently and wisely. Although Haiti provides new opportunities for development, now is not the time for both controversies on continuous sub standard construction and the redevelopment of masonry. It has been proven that replacing traditional local materials with concrete and concrete blocks is economically unsustainable and ultimately making structures more vulnerable (Audefroy 2011). And as a result of replacing traditional materials, people are rebuilding the best they can, without applying any anti-seismic technical specifications.

After investigating alternative methods of design, it has been found that traditional construction systems often demonstrated better resilience to earthquakes than any other buildings constructed with modern materials, specifically relating to masonry. If we can begin to draw from these traditional practices and recognize that this knowledge needs to evolve and innovate, then essentially we can finally have the potential to reconstruct Haiti.

4 **LOCALLY SOURCED MATERIALS**

To use as many in country and local materials as possible can not only build on existing labor and skill resources, but also encourage the creation of local industry. One factor that could influence the success of building in Haiti is the education of the local workforce. We are not only designing a building but we also need to consider the construction process and how to train the workers to assemble the building code. If local materials are the key concept to future sustainability, we need to be smart about how we utilize the material and truly understand what makes a seismic reinforced structure. Just like any industrial material, locally sourced materials can be seismically responsive and have a long lifespan if built correctly.

4.1 *Concrete debris*

After two years when the earthquake hit, most of the damaged areas in Haiti are still in ruins, and the extensive amount of concrete rubble and construction debris have formed huge barriers to reconstruction (DesRoches et al. 2011). But according to science and research, there has become a successful and sustainable strategy for managing concrete debris and using it as a construction material that has ultimately been tested to have the same compressive strength as the concrete used in the United States. As of today, the substandard concrete that Haitian's make has a compressive strength of 1,300 psi, which is less than half the minimum strength for any U.S. concrete (DesRoches et al. 2011). When Professor DesRoches from Georgia Tech ran studies, he manually crushed rubble samples with a hammer to provide coarse aggregate, used sands collected in Haiti, and mixed the batches by hand. The goal was to reach the minimum requirement of 3,000 psi by using concrete debris. However, the concrete as a recycled aggregate can only

work effectively if the mix of materials is consistent and easily measured. The idea of recycling concrete debris is a positive approach for future designers, as it can help remove the remaining debris. However, the re-use of rubble as aggregate for new construction is currently problematic in Haiti due to the need for precise measurements and testing.

4.2 *Interlocking stabilized soil block*

Interlocking stabilized soil block (ISSB) is a demonstration to how environmentally friendly building materials and construction technologies can be made affordable and effective. UNHabitat, a program for the redevelopment of Uganda, states that by using stabilized Soil Block, we can help mitigate climate change by avoiding carbon emissions during the production of building materials and construction as well as by saving thousands of trees (Perez 2009). The research on ISSB has been noted to be only used in areas like East Africa, but because of the similar labor production and the use for good and bad soil, the ISSB is an extraordinary material that can become effective in a climate like Haiti. The process of stabilized soil block is similar to the construction of earth architecture which has been a historic process of Haitian construction centuries ago. To be able to utilize a similar method that existed in the culture of Haiti is a positive step towards seismically sustainable design. A key step in the evolution of this material was the creation of the CINVA-RAM press in the 1950's by the Chilean engineer Raul Ramirez for the inter-American Housing Center in Bogota, Columbia (Perez 2009). Since then, the methods of producing earth blocks has progressed resulting in diverse types of motor-driven and manual presses. The advantages of the block includes the elimination of shipping costs, the low moisture content and the uniformity of the ISSB which then minimizes the use of mortar and labor costs. Secondly, if the ISSB continues to be mixed with cement, the amount used is greatly reduced down to a 50kg bag of cement for 130 stabilized soil blocks (Perez 2009). The main issue with ISSB is the general consistency that is produced with the block. The block quality is not so much defined by the hand machine but by the quality of the raw materials. In order to make a more consistent mixture, workers must have an exact measurement of clay, silt, and small gravel to make a strong soil block. Another problem with the ISSB is the inconsistent compressive strength. Due to combinations of mixtures, drying time, and the use of water, the compressive strength could vary between 300 and 1,200 pounds per square inch (Perez 2009). The only way to keep a consistent compressive strength is if Haitians gain the knowledge and equipment that can evenly divide the use of material. The advantage of the ISSB will someday improve when alternative stabilizers such as concrete rubble, synthetic fibers, or natural resins become provably effective.

4.3 *Bamboo*

Bamboo is currently rare in Haiti, but its use as an import can spawn plantings and produce local jobs to grow building material. Because bamboo delivers more useable fiber, faster, than conventional softwoods such as Southern Pine, and is a better fit to Haiti's climate, bamboo appears to be one of the best targets for a "construction agronomy" strategy (King 2010). The sustainability factor is also extremely beneficial considering the material can reverse deforestation as well as provide economic opportunities to Haitian farmers. Bamboo houses are very low weight and can use basic materials for house components such as wire, chicken mesh, small amounts of cement, and bolts. Bamboo can also tolerate high values of deformations in the elastic range and when properly constructed are again extremely ductile (Siete 2002). Research has also discovered that bamboo can be used in construction much like the Haitians build today with plaster and cement. The advantage though is the savings in cost and the benefits of the environment. The construction process uses whole bamboo as main load bearing elements, split bamboo mixed with mesh and cement as infill, and bamboo corrugation with plaster as roof cladding and window shutters (Beraldo 2000). The main problem with Bamboo is that it takes a lot of care and time management in order to keep any building sustained. The harvesting, cutting, drying and every other little step that it takes to use bamboo as a construction method is very time consuming and critical for the building to withstand a large lifespan. Once the bamboo is cut, insects may attack. For that reason, it is highly recommended that bamboo immediately goes through a special immunization and drying process in order to reduce the insect and beetle at-

tacks. Bamboo should also be harvested only during the dry season in Haiti, and must be dried for almost 12 weeks before it can be used as a building material (Beraldo 2000). A second consideration if bamboo becomes a material of choice in Haiti; bamboo is fast growing which means it is fast spreading. Haitians will have to be smart about how they plant the material and sustain it without it going out of control. And finally, when considering the compressive strength of bamboo, it is much like that of the ISSB, which can fluctuate enormously between 290 to 1,305 pounds per square inch depending on the length, thickness, and mixture of materials that you share with it (Siete 2002).

5 STRUCTURAL SYSTEMS

As this paper has been addressing, there are a considerable amount of propositions for rebuilding Haiti. Some better than others, all of these processes of materials are valuable considerations for redeveloping Haiti. But the conclusive methods for redesign is to develop ways to build healthy, seismically safe buildings using the simplest of materials in order to reconstruction the effort in Haiti; while also reducing the costs of imported and international materials that are essentially not beneficial to the culture of Haiti. While locally sourced materials have become the general focus and most important technology for redesign, we have found that even those processes can be improved and altered in order to maximize the overall construction of Haitian buildings. With the support of new technology and science, these future solutions about to be presented can hopefully solve the system barriers that local materials carry and can also let the know-how of materials for labor come from locals, while using sustainable structural systems that cannot be compromised within code compliances.

5.1 *Rubble and rice hull ash hybrid*

With the advancement of technology and science, several investigations have made it possible to make concrete just as effective by using industrial waste materials rather than the overall unsustainable method itself (Gambhir 2004). Rice hull ash is a by-product of the rice processing industry that is either burned in the field or goes directly to land fills. When burned at a very low temperature it is an outstanding pozzolan, which is a siliceous material, that possesses little or no cementing property, but will in a finely divided form chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties (Denning 2012). Material testing has demonstrated that it can replace up to 90% of limestone in addition to being used as biomass to generate electricity (Naik 2006). Adding the ash to cement makes concrete stronger and more resistant to corrosion. The lightweight concrete produced using rice ash is an aggregate suitable mainly for making precast blocks and slabs for wall and partitions. If using recycled concrete comes into the picture, the opportunity for stronger and sustainable building increases. Concrete made using rice hull can have a compressive strength of 6,000 psi (Gambhir 2004). If the rubble worked alone in a building construction, it loses its workability more rapidly than conventional concrete and may require more mixing water to achieve the same workability as conventional concrete. Therefore, by incorporating a water-reducing admixture like rice hull ash with a very minimal amount of portland cement, not only will this product support smaller amounts of water-soluble cement poisons, it is also resistant to acidic and climatic environments such as Haiti (Naik 2006). The development of using such aggregates is still in the very early stages of research and the published data is limited.

5.2 *Cob, soil and rubble hybrid*

Cob is an old English word that refers to lumps of earthen material that are sculpted together to form walls. It is generally a mixture of clay or clay rich soil, sand, fiber, and water (Racusin & McArleton 2012). Cob construction as it has been constructed for centuries is inexpensive but very labor-intensive, but the advantages of cob construction in Haiti is the use for thermal mass and of course the reduction in costs. This process of cob construction is also a similar process to building that Haitians are already familiar with which can essentially become an easy transition. The only problem that cob construction generates is that the walls can become extremely heavy,

and if water is absorbed, the structure is immediately weakened and more vulnerable to seismic activity (Racusin & McArleton 2012). If the process of cob construction were combined with the building techniques of Haitian concrete (slightly modified of course) the adaptability and lifespan of this structure would increase substantially. The use of excess soil and recycled rubble can support a similar function to waterproofing that creates a dry foundation and retards migration into cob walls. Much like a stone wall, the compaction of soil and the foundation of rubble, the process of cob construction should ultimately withstand a natural disaster in Haiti. Another proposal of combining rubble with cob construction is crushing the rubble into a fine grain that can then be mixed in with the portion of sand in the cob walls. In fact, according to Daniel Chiras' book, *The Natural House*, sand that has a coarse or jagged texture, produces a wall with greater compressive strength. Along side compressive strength and recycling material, the advantages are the processes that it takes to make cob construction. Very similar to the sub standard process Haitians labor against today, this process can easily be mixed with hands and in such things like wheelbarrows, plastic lined pits, and mortar mixers. It is even recommended that laborers do not use concrete mixers because the cob mixture sticks to the walls of the mixer (Chiras 2000).

5.3 *Cob and bamboo hybrid structure*

Bamboo houses are designed to exceed seismic and hurricane requirements of international building codes. Intense research on bamboo resulted in a significant increase in strength and durability, along with extended maintenance intervals compared to other traditional approaches (Beraldo 2000). With the structural qualities of cob construction, bamboo only increases its adaptability for seismic responses as well as its potential for thermal mass. As discussed previously, bamboo is also an opportunity for Haitian farmers and while improving the local economy of Haiti. Bamboo and cob construction can introduce affordable, high quality and durable structures that are more environmentally responsive than any other design approach presented in Haiti. The hybrid cob and bamboo construction is fairly simple compared to the previous solutions explained above but again very labor extensive. A proposed structure with this technique would start with a ground floor made of cob walls and a brick foundation. The foundation could be construction with a simple soil block or the reuse of rubble that is placed underground with a horizontal damp proof that would protect the walls against dampness. The process of bamboo is inserted in the walls similar to a wattle and daub method, and then in filled with the cob construction. The ceiling and roof would have a hybrid system with bamboo beams and a coat of cob, which then becomes the treatment against insect invasions. The two materials can work together to support both the longevity of a single material as well as increased structural responsibility. What makes this hybrid effective is the continuous use of local materials that have historically given complete resource for us to know this structure is sustainably and seismically responsive.

6 CONCLUSIONS

Until there is recognition of the social and economic issues associated with substandard construction in Haiti, concrete and masonry will be used as the primary materials in a "build back better" technique that will likely fail to create seismically durable structures. Unfortunately, regardless of the multiple aspects of concrete construction that can be structurally compromised to reduce initial cost, Haiti will not be able to avoid the use of concrete in the short term. If architects, engineers and builders reconsider the use of concrete and masonry in developing countries and instead embrace new as well as traditional building systems outlined in this paper, Haiti might have the opportunity not just for resilient buildings but a more vibrant local economy. All reconstruction financed by both local and international sources should meet life safety standards and consider alternative structural systems that cannot be easily compromised, can be visually inspected after construction for code compliance, and use local, sustainable materials. First, these construction methods also need further study in order to be considered for reconstruction in Haiti.

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