MITIGATING RISK IN THE DEVELOPING WORLD: CHALLENGES AND RESPONSIBILITIES OF THE GLOBAL STRUCTURAL ENGINEERING COMMUNITY

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Abstract

On January 12, 2010 a devastating earthquake struck the Republic of Haiti. Despite measuring just a moderate 7.0 on the Richter scale, this earthquake is considered one of the most catastrophic natural disasters in recent history, exposing the vulnerabilities of established construction practices in a country plagued by poverty and political unrest. Over four years after the earthquake, despite the millions of dollars pledged and the great interest from the global structural engineering community, the sad reality is that most families displaced due to the earthquake do not have a clear road map toward permanent housing. While many agreed that sustainable redevelopment and self-reliance was essential for Haiti, international good will and intentions were insufficient to deliver such solutions, particularly in the domain of urban residential housing; currently the only construction practices that can compete in the free market, i.e. in absence of foreign aid and donor funds, are the same ones that created the vulnerabilities in the 2010 earthquake. Unfortunately this is not just the story of Haiti. Many parts of the developing world share the same vulnerabilities against seismic hazards, especially resulting from residential construction practices among low income families. This paper reviews the experiences of the authors in Léogâne, Haiti, and Quito, Ecuador during their development of an empowerment framework for (a) assessing seismic vulnerabilities, (b) understanding the economic/cultural/societal origins of these vulnerabilities and (c) offering alternative solutions when operating in such unique resource-constrained environments. In the process, this paper discusses the ethical responsibilities of the structural engineering community to develop affordable, sustainable solutions than enhance seismic resilience for underdeveloped communities, so that the conditions encountered in Haiti today can be avoided altogether.

Keywords: Developing world, Haiti, Rebuilding, Empowerment

1 Introduction

On January 12, 2010, a 7.0 magnitude earthquake devastated the Republic of Haiti, striking 25 kilometers southwest of Haiti's capital city, Port-au-Prince. The 2010 Haitian earthquake, which killed an estimated 300,000 people and left approximately 1.3 million people homeless, is considered the most destructive event any country has experienced in modern times when measured in terms of the people killed as a percentage of the country's population [1]. The immense loss of life and livelihood caused by this earthquake becomes even more alarming when compared to other seismic events in recent history. The 1989 Loma Prieta Earthquake, which struck the western coast of the United States and registered a similar moment magnitude of 6.9, resulted in only 63 deaths, the majority of which were caused by a single bridge collapse [2]. The 2010 Maule earthquake in Chile, occurring a month and a half after the 2010 Haiti earthquake and registering a magnitude of 8.8, possessing orders of magnitude larger destructive potential, resulted in just over 500 casualties and significantly smaller economic impact [3]. These comparisons illustrate the challenges in translating the vast knowledge the global structural engineering community possesses in building earthquake-resilient infrastructure, to environments with heavy political, resource and economic constraints in the developing world.

This has created significant vulnerabilities, prevalently in the urban residential sector, where poverty and a lack of access to resources have established unsafe construction practices that dominate the market [4]. Unfortunately, this reality is not exclusive to Haiti (Fig. 1). Densely packed, underdeveloped neighborhoods, often referred to as urban slums, exist throughout the world and are growing [5]. Recent history has revealed an overwhelming trend of populations shifting from rural settings to urban centers, only to find themselves resigned to these slums. With this steady stream of new inhabitants, these slums continue to grow, and in many cases so too does their exposure to seismic hazards [6]. The aforementioned vulnerabilities in the flawed residential construction practices are, therefore, destined to have tremendous consequences for populations around the world living in environments similar to Haiti's constrained economic and political conditions. Therefore, there is a pressing need to mitigate seismic vulnerabilities and risks in the developing world. This paper reviews the experiences during the authors' efforts to address this problem over the past four years, starting with their assessment of the rebuilding efforts in Haiti, and offers insights on the ethical responsibilities of structural engineers to develop affordable, sustainable solutions and implementation mechanisms that enhance seismic resilience of underdeveloped communities.

Fig. 1. Typical home in Léogâne, Haiti, (a) built with CMU (concrete masonry unit) walls and undersized columns (note shear failure in wall in the background); (b) shear failure of CMU wall transferred forces into neighboring column; (c) compared to typical CMU home in Quito, Ecuador, having same construction modality as home in Haiti. Note the complete absence of beams in both homes.

2 Challenges in the reconstruction efforts in Haiti

Haiti represents a great case study for better understanding the challenges to providing sustainable solutions in resource-constrained environments in the developing world. In the immediate aftermath of the 2010 earthquake and over the past five years, this catastrophe has attracted the attention of the global engineering community and many aid organizations [7-10]. One would expect that such attention would have generated sustainable solutions to the housing crisis. Despite the millions of dollars in foreign aid generated and the well-intended efforts of the international community, the sad reality is that the majority of the families displaced due to the earthquake remain without a clear roadmap toward safe permanent housing they will be able to call home [11] (Fig. 2). While many agree that sustainable redevelopment and self-reliance are essential for Haiti, few appreciate how they can be practically achieved, particularly for urban residential redevelopment.

Fig. 2. (a) Transitory sheltering for families in Léogâne, Haiti, (b) whose hand-painted addresses on customized shelters suggest an understanding of the long path to a permanent home, (c) while others remain in informal shelters.

To understand these challenges one needs to consider the circumstances that have contributed to the existing practices and vulnerabilities. As one of the poorest nations in the Western hemisphere, with high import taxes and severe deforestation, construction practices cannot rely on the many engineered materials that are required for traditional code-compliant designs used in other seismically active regions due to the lack of an affordable local supply chain. Lack of education, codification and oversight to regulate construction processes are also contributing to the vulnerabilities originating from the economic desperation and inaccessibility of financing for homes [4]. Most homes can be classified as non-engineered construction [4, 9], built in the absence of any formal building code, unfolding in incremental stages over many years as savings are accumulated, resulting in high variability in materials and workmanship. Due to the lack of affordable construction-grade wood, for use either in formwork or as a building material, and the high cost of steel, Haitians resort to using heavy masonry walls made of hand-pressed concrete masonry units (CMUs) and lightly reinforced, undersized concrete columns, frequently with no beams, leading to systems with inadequate strength and ductility. This combination creates systems that perform well under the strong winds common in the Caribbean but proves to be extremely vulnerable under seismic events, failing through brittle collapse mechanisms [4]. These factors create a challenging environment for providing long-term enhancement of local capacity, requiring thoughtful policies and incentives [12].

A common engineering approach for addressing similar vulnerabilities in the residential housing sector, for example after similar catastrophic events [13], has been to tweak existing practices and introduce new design code provisions. However, the complete absence of government oversight for informal construction practices erects considerable barriers to implementing this customary approach, something that was not realized by the many actors operating in this domain immediately after the earthquake. Focus was placed on providing "minor, low-, or no-cost improvements to existing ways of building" which was expected to prove easier "than to introduce a completely new technology or reintroduce a traditional building method" [14]. Based on this concept the simplest remedy would be the formal introduction of confined masonry construction to Haiti, which, given the severely limited availability of local construction-grade materials and the functional requirements of Haitian urban housing, surfaces indeed as an immediately implementable solution [10]. As such, confined masonry has received the most attention from groups like the Confined Masonry Network (http://www.confinedmasonry.org), Build Change (http://www.buildchange.org/haiti.html) and MCEER (http://mceer.buffalo.edu/education/UniQ/), whose education and outreach programming focused on proper use of CMU and other masonry-based systems familiar to Haitian builders. Unfortunately, engineering adequate seismic resilience of these "existing ways of building" through higher quality CMU and larger quantities of steel can triple the price of a home [15], putting relevant safe construction practices well beyond the economic reach of the majority of Haitians [16]. So while this may be an immediate solution for some, it cannot be mistaken as a solution for all. Though some would advocate substantial subsidies by foreign entities to enhance affordability and support a large-scale implementation, this poses the legitimate danger of creating perpetual dependence on foreign aid for even the most basic infrastructure needs.

(a) (b) (c)


Fig. 3. Time lapse of home that experienced (a) pancake collapse in Léogâne, instigated by insufficient columns and heavy partitioning [documented in March 2010], (b) undergoing reconstruction in August 2010 following re-education of the head mason [documented in August 2010], and (c) continuing to a second floor with the same principles that created the original vulnerabilities [documented December 2011].

Inabilities to fully comprehend the constraints facing Haitian families have also contributed to naïve assumptions that seismic resilience could be achieved by simply "importing" and enforcing US or International Building Codes. However, there is a fundamental flaw in this approach the lack of affordable construction materials, including the steel necessary to provide strength and robust ductile behavior for reinforced concrete systems or the quality masonry needed for confined or load-bearing masonry construction (common advocated systems for providing seismic resilience), makes the expense of this style of construction too great to serve the needs of the majority of Haitians. It is this lack of understanding that leads to the recommendation from the structural engineering community that "…building code [adoption] and [strict enforcement]" is THE solution to the Haitian urban housing dilemma [17]. This has contributed to the well-intentioned aforementioned efforts to educate masons, architects and engineers to facilitate Haitian-led masonry reconstruction. This certainly has helped to advance the government's ambitious goal to formalize "the professional construction sector with laws and regulations relating to earthquake-resistant and hurricane-resistant materials and implementation" [18]. Unfortunately, the lack of resources to purchase the necessary materials can lead to the re-creation of the same vulnerabilities that proved deadly in the 2010 earthquake. Solely encouraging the continued use of masonry-based structural systems by providing education and one-time access to high quality construction materials through relief funds, suggests to Haitian builders that such housing designs can be made truly resilient and that simply is not accurate, especially if one considers the materials available to the typical Haitian family in the absence of foreign aid. The scenario depicted in Fig. 3 unfortunately demonstrates the dangers of well-intended efforts to facilitate the reconstruction of the residential housing stock in Haiti without a holistic understanding of the problem.

This reality makes it evident that the poorest of Haitian families need to be presented with alternative affordable housing models employing new structural systems and/or materials. Sadly efforts to do so have been unsuccessful thus far. Take, for example, the Building Back Better Communities Expo, sponsored by the Clinton Foundation. Not only did a number of designs fail to meet basic engineering requirements, but many of the housing models retailed for $20,000–$30,000, with only an estimated 10% relying exclusively on local materials [19]. Without mandating that proposed options meet key criteria for hazard resilience and sustainability (in absence of donor funds), time and money will continue to be wasted and the true vulnerabilities in Haitian infrastructure will not be addressed.

It is evident today that the structural engineering community and NGO's interested in this problem have failed to provide sustainable solutions accessible across the income spectrum. Interviews with displaced families [16, 20] confirm that the vast majority remain without a pathway toward homeownership. While some more affluent homeowners have begun reconstruction of homes that very much mimic pre-quake designs (see Fig. 3) with modest increases in reinforcement, they are reluctant to cast concrete floors/roof slabs, acknowledging their continued mistrust and fear of traditional systems. Many others who have the means to reconstruct remain hesitant to do so due to the lack of alternatives to brittle masonry construction. Such observations have been echoed by a recent OXFAM International report: "Positive examples of permanent housing solutions are scant. Too much focus has been placed on the construction of physical structures rather than on setting up the sustainable delivery mechanisms that will stimulate the creation of sustainable communities and private investment in the sector" [21]. This acknowledgement coincides with a recent shift in focus to seeding the necessary processes for providing alternative, sustainable construction practices that will address the pervasive vulnerabilities in residential home construction and support a Haitian-led (rather than foreign-actor led) rebuilding effort. This shift is now being embraced by both the Haitian government as well as the numerous international actors operating in Haiti. The question that remains unanswered is how can this be accomplished?

3 An empowerment approach to evaluating and promoting solutions

Though undoubtedly the lack of permanent solutions can be partly attributed to the urgency needed to meet the housing demand created by the earthquake and the ambitious initial goals of providing 100,000 homes within five years [18] (a goal never reached), they are ultimately derived from the inability to holistically understand the economic, social and financial constraints of Haiti, resulting in the disregard for region-specific challenges and promotion of solutions detached from local context.

This understanding is a necessary step, though, in providing thoughtful solutions that can ultimately empower the local population, solutions that avoid importation, imposition by foreign entities, or heavy subsidization and instead contribute to self-reliance. As the reconstruction efforts in Haiti have proven, if alternative housing models do not consider the multi-dimensional challenges faced by poor populations, the models will inevitably fail. Approaches are needed that do more than evaluate the problem from a strictly engineering lens, as solutions generated from this type of thinking will, at best, result in housing paradigms that are dependent on foreign aid or on the intervention by international entities. Rather, the proposed approaches need to acknowledge that within the developing world, each city, and furthermore, each local community, brings its own story to the table, presenting a unique economic, social, and cultural context that introduces hidden complexities to the general problem of inadequate construction practices. Through a thoughtful understanding of these complexities, the authors have proposed an empowerment model for developing recommendation when operating in such environments [11]. This model seeks to shift practices in such a way that they can be sustained without intervention by foreign entities and relies on four key tenets/pillars:

1. *Resiliency* that ensures life safety and protection against natural disasters and other environmental factors; it requires an understanding of hazards and vulnerabilities.
2. *Feasibility* that ensures practical implementation using locally available technologies, capabilities, and materials; it requires an understanding of capacity constraints.
3. *Sustainability* that ensures indefinite support using local resources (economic and natural), technologies, and skill sets of the community and can adapt with their evolving needs; it requires an understanding of market constraints.
4. *Viability* that ensures the support of local stakeholders as culturally appropriate so that ideas are not just accepted, but embraced and promoted; it requires an understanding of cultural context.

Although, from an engineering perspective, resiliency (safety) and feasibility (constructability) may be considered the most important, all four tenets must be simultaneously addressed if the solution can be hoped to have lasting impact. Consideration of just these two tenets leads to the failed policies promoted in Haiti the past four years, policies that provided solutions that work perfectly on paper, but when implemented in the field failed due to misunderstood social, economic or cultural realities. The tenet of sustainability is especially important in that regard; the solution must be accessible to the target population without dependence on foreign aid. Since the solutions will be developed by the local community and must compete in the open market, viability also becomes crucial; families need not only have the financial capacity to afford the new housing modalities, they must also *want* them and recognize them as a dignified home in order to part with their hard-earned savings to build them.

This empowerment model then provides a requirements matrix for any solution proposed for Haiti, as summarized herein and detailed further in [11]:

1. Resiliency: Solution should provide strength and ductility against both earthquakes and hurricanes (having opposing resiliency-requirements), while accommodating flood and landslide hazards and promoting foundations system that account for the weak, and at times, unstable soil conditions. The predominant pre-existing construction models have a heavy reliance on CMU walls (see Fig.1 and Fig.3). These heavy walls behave well under the frequent hurricanes but, due to lack of reinforcing steel and proper system-level integration, proved to be highly vulnerable in the 2010 earthquake. The dominant failure mode was shear cracks in the rigid masonry walls that attracted seismic forces but lacked the strength to withstand them, transferring the forces to neighboring undersized columns (see Fig. 1 earlier), which led in many instances to the immediate collapse of the structure. It should be stressed that the last significant seismic event the country experienced dated more that a century ago, something that has contributed to the community's biased risk awareness toward annual tropical cyclone hazards. The 2010 event, though, provides a sobering reminder of the multi-hazard threats to this region.

2. Feasibility: Solution should rely primarily on the staple of Haitian construction: concrete, with judicious reliance on more expensive imported materials such as steel and wood (imported due to the deforestation of Haiti). The solution should formulate processes that fit well with the predominant labor model employed for low-income residential housing: a master builder in a community who is rarely formally trained and who helps everyone build their homes relying primarily on manual processes (due to lack of access to machinery such as concrete mixers). While these master builders have considerable expertise in concrete and masonry construction through informal instruction and years of practice, they still must operate within the constraints created by a lack of financial resources, catalyzing an industry lacking proper quality control. Concrete, for example, is manually mixed (resulting in high variability of strength) and then shoveled into buckets and manually poured down slender columns from the top of full-height CMU walls, while CMU blocks are manually pressed with frugal proportions of cement and cured in the sun to yield a brittle, weak final product. Therefore, while concrete appears to be the most rational material choice, numerous associated challenges exist for establishing hazard-resilient concrete construction. The absence of standards and oversight means that any housing alternative needs to establish processes for achieving quality control within the construction sequence. Otherwise, economic desperation will lead to continued questionable practices that can ultimately manifest as seismic vulnerabilities.
3. Sustainability: The solution should operate well within the financial realities of a country in which 83% of households earn less than $240 USD per month and in which the lack of a mortgage system dictates incremental construction practices (i.e., build as money become available and for extensive periods –up to a decade for a single home) rather than an up-front financing of homes. The cost of a non-seismically engineered three-room home in Haiti, the exact same homes that collapsed in 2010, ranges between $6,000-$8,000 USD, and it practically doubles if professional construction crews are hired. Thus, solutions must be rooted in the construction modalities (master builder model) currently executed in the low-income construction sector, without substantial increases in cost. While Haitians are now aware of the risks associated with established construction methods, lack of steady income and financing sources leaves families with little to no options for rebuilding.
4. Viability: The solution should comply with the preferences of families by providing homes that accommodate privacy (single family, multi-partitioned homes) and satisfy security concerns (prevent intruders from entering), while also accommodating aesthetics that are biased towards the modern appearance of concrete construction.

Of course systems that evolve organically in resource-constrained settings inherently satisfy the four tenets of an empowerment model in that they are practices born of common experience with the support of the community. Unfortunately, these practices are often not informed by engineering knowledge and can prove vulnerable to infrequent extreme events, as was the case in Haiti. These four tenets can be further used to evaluate proposed solutions to mitigate risk or even develop rubrics for quantitatively assessing such solutions by measuring their compliance with the constraints matrix derived from the empowerment model. This can be established by scoring specific attributes of homes within a multi-criteria decision framework that incorporates the direct input of the local community to provide the relative importance (weights) of each attribute [11]. When considering the solutions that were implemented in the aftermath of the 2010 earthquake, analysis against the empowerment model reveals immediately the failure to satisfy one or more of the model's tenets.

Take for example, confined masonry construction. When properly constructed, it performs well during seismic events and even has the capacity to support multi-story buildings. Furthermore, it relies on the same materials and construction principles as traditional home construction in Haiti. Thus it is reasonable to expect that local construction crews or master builders can be easily trained to incorporate the necessary modifications to the system and their existing construction sequence. It is no surprise that it has become the most popular recommendation for seismic resiliency in low income housing as discussed in Section 2. Unfortunately, when measured against the economic sustainability tenet, it becomes clear that the cost of confined masonry homes exceeds the economic capacity of the vast majority of Haitian families. Moreover, it has met resistance due to some families' personal aversion to block (one indicator of viability tenet). As a result, the current reconstruction efforts show limited examples of the successful implementation of confined masonry across the income spectrum. Despite the aforementioned availability of formal training, financial hardships have forced families to return to the old, seismically vulnerable building methods, perhaps with a few positive but insufficient modifications such as increased quantities of transverse reinforcement in columns and some vertical reinforcement through CMU walls (but without other necessary features such as ring beams, horizontal wall reinforcement, and effective keying of higher-quality blocks). These challenges would have been immediately identified if the solution was carefully vetted against the empowerment model tenets.

Another example of a solution that has been discussed for Haiti is cast-in place reinforced concrete systems, a construction practice quite popular throughout the developing world [22]. This solution shares the same high-resilience characteristics as confined masonry and relies on materials readily available (concrete, steel). Implementation of this system in a single pour requires the ability to form an entire house and pour and vibrate large volumes of concrete. Access to precision whole-house formwork, ready mix concrete, pump trucks and vibrators all exceed local construction capacity. Moreover, this system can encounter additional constructability and cost issues when considering the densely reinforcement required in every load bearing wall, a necessary attribute in order to achieve seismic resilience and special-shear wall behavior in regions of high seismicity. Thus, even though this solution has been promoted in Haiti by international organizations relying on donor funds for large housing developments, its poor performance in feasibility and sustainability tenets immediately discounts low-income housing reconstruction when evaluated against the empowerment model.

It is no surprise that most proposed solutions score well against the resiliency tenet but fail in some other characteristic related to the empowerment model. The solutions provided within the Building Back Better Communities Expo discussed in Section 2 provide another validation point for this argument; reliance on locally available materials and capacity while competing within the open market should be essential pillars of any solution but were disregarded in most proposed recommendations. Such focus on only the engineering dimensions of the problem leads to contextually-inappropriate solutions. Thus, the empowerment model presented in this section provides an alternate, rational approach for arriving at solutions that can have long-lasting impact. Before moving on to discussing the paradigm shifts that are necessary to deliver such solutions for low-income housing in the developing world, the empowerment model is applied to another vulnerable community, Quito, Ecuador, which provides an important contrasting case study due to the lack of a major earthquake in recent history.

4 Understanding vulnerabilities in Quito

Field research was conducted in Quito, Ecuador, to assess the vulnerabilities of the predominant housing models in the city's poor communities against the four pillars of the empowerment model [23]. Quito has the same exposure to seismic hazards as Haiti and has similarly not experienced a significant seismic event since the mid-nineteenth century. The absence of a major earthquake in the region has contributed to low-income construction without a formal consideration of seismic resilience. However, Quito does not face hurricane hazards or deforestation problems, thus opening the possibility for use of lightweight materials, such as wood and bamboo. The current predominant housing model in Quito, however, reveals the same dependence on concrete and CMU block as observed in Haiti; the majority of homes possess load bearing, CMU walls that are confined by corner columns and topped by corrugated metal roofs supported by wood framing (see Fig. 1c). This typology closely resembles confined masonry construction, but lacks crucial elements that are essential to providing sufficient strength and seismic resilience: the absence of longitudinal and transverse reinforcing steel in the walls, under-sized and under-reinforced columns, and the absence of any type of beams that sufficiently confine the masonry walls. This results in structural system that, much like the situation in Haiti, cannot efficiently engage all its lateral force-resisting elements. Quito's inclusion in the Rockefeller Foundation's 100 Resilient Cities Network has provided an important platform to draw attention to these vulnerabilities: "The poor are also most at risk in the event of a high-magnitude earthquake, which would devastate the city's irregular, unplanned settlements in steep-slope areas" [24]. Thus Quito faces many of the same resiliency challenges.

Evaluation of these construction practices under the remaining tenets of the empowerment model revealed other important factors that need to be taken into account before considering mitigative measures. Construction models in Quito follow similar characteristics as the ones existing Haiti, a master builder operating with heavy reliance on manual processes and working directly with the community to build homes. Similarly, security and safety concerns also exist -- theft is a frequent problem within the city limits. Poor soil conditions, financial constraints for low-income families, concerns for providing insulation against colder weather conditions, and a very strong cultural preference towards homes that have the modern appearance of concrete also need to be accounted for. Thus even though lightweight materials such as wood and bamboo provide viable options based on solely engineering (resiliency) considerations, and even have been widely applied in other (rural) parts of the country, they ultimately are inappropriate for low-income families living in the city. Proper construction with these materials in this environment requires a very different skill set than the one offered by master builders in the city, in order to provide a finishing that has the appearance of a concrete home and satisfies security and insulation demands, while still guaranteeing seismic resilience. Formal introduction of confined masonry construction also faces challenges since proper implementation will have to rely on skilled labor, something that does not, at least under the current conditions, seem like a viable plan.

This discussion demonstrates the potential of the empowerment model for identifying and even formally accounting for financial, cultural or capacity challenges, facilitating a solution process that can achieve meaningful impact. The process relies ultimately on uncovering, acknowledging and accommodating the non-engineering dimensions of the problem through an integrated approach. This can be especially challenging for engineers, as the non-engineering dimensions of the problem are not always easy to discover and are rooted deep within a country's history, transcending any one sector such as shelters and settlements.

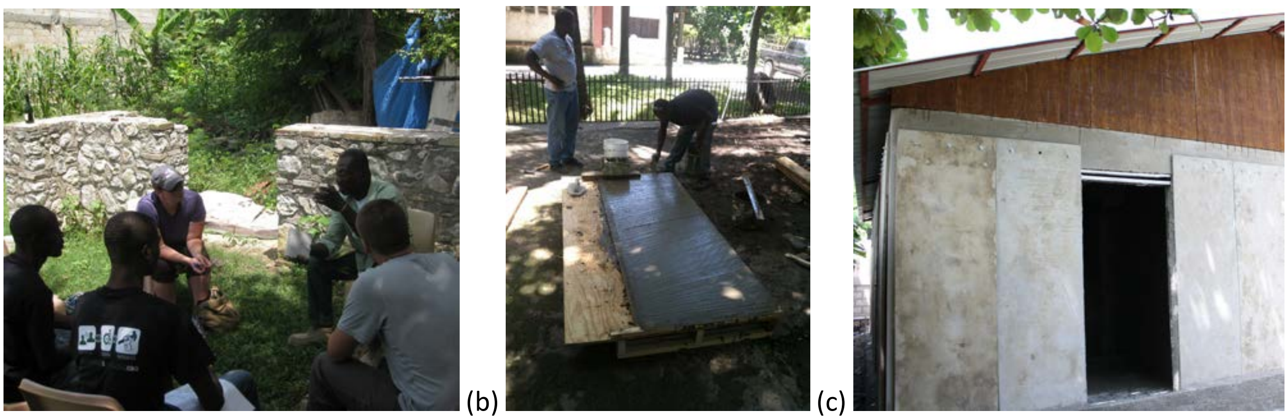
5 Shifting the paradigm through innovation: the engineer's responsibility

Despite the tremendous progress of seismic design practices in the last half-century, vulnerabilities in residential housing construction in the developing world keep increasing, primarily dictated by urbanization trends that have maximized exposure and encouraged informal practices. As concluded above, providing solutions to these vulnerabilities is not an easy task; it not only involves a holistic understanding based on the tenets of the empowerment model but additionally requires innovative practices and research for establishing context-appropriate recommendations. Small tweaks in existing practice, or introduction of new codes and standards, though well-intentioned, can actually perpetuate vulnerabilities, as the failure of relevant efforts in Haiti has proven. "First world solutions" are often inaccessible without complete reliance on foreign aid, and thus "first world approaches" do not deliver sustainable recommendations.

There is, therefore, a necessity that "first world" good intentions of the structural engineering community translate from reimplementation of familiar systems towards paradigm shifts that empower the bottom of the pyramid. To do so requires innovations in technologies and processes that treat, with *equal* importance, resiliency, feasibility, and most importantly sustainability and cultural viability. The authors' involvement in post-quake Haiti is demonstrating that such pathways to empowerment can indeed be discovered first and foremost by listening to the community being served. This requires the commitment and patience to follow what inevitably is a long and arduous path, requiring continuous feedback from the population being served and frequent re-evaluation of priorities and proposed solutions. These efforts have also demonstrated the great benefits of making the communities themselves part of the solution-generation process, seeding new concepts and offering opportunities for technology incubation [20]. Not only does this approach allow the local population to truly embrace the proposed paradigm shift, but encourages true ownership of the process and the seeding of a local culture of innovation where new solutions can be discovered.

Such an approach has helped the authors, operating under the banner of Engineering2Empower (http://e2e.nd.edu), to introduce a new housing typology in Léogâne, Haiti, with the first prototype already completed (Fig. 4). The main technology innovation for this system is the introduction of a lightweight partitioning element: precast concrete panels using a lightweight mix reinforced with wire mesh. This solution originated from an understanding that most of the identified vulnerabilities in the 2010 earthquake stemmed from the CMU walls and that this is the preferred partitioning option by Haitians only because there is no other legitimate free market competitor [10]. The precast panels are attached to the frames through bolts and as such are isolated from the primary structural system to help reduce the seismic demand on the home while still maintaining adequate strength to bear the pressure of hurricane-force winds and provide basic security from intruders. This innovation satisfies cultural requirements (security, aesthetics), relies on materials and skill sets locally available and thus establishes a sustainable solution (training of local crews has been proven straightforward), while it also significantly reduces production/construction costs (when compared to the intricacies and labor intensity of CMU wall construction). This cost reduction allows families that have limited resources and cannot afford the degree of reinforcement required to aseismically design every wall in a highly partitioned confined masonry home to adopt a reinforced concrete frame system that concentrates the structural resistance and thereby limited financial resources in only select elements. While reinforced concrete frames are already common in Haiti for commercial structures and apartment buildings using block infill, the introduction of the panels fills an important void in alternate feasible partitioning/cladding technologies, thus opening the system to single family residential construction. More importantly, by removing reliance on the walls as load bearing elements, the new system allows the home to be expanded and reconfigured with time, as the owner's financial resources become available – an important capability in a post-quake residential reconstruction space that still lacks access to credit. Process innovations that further support the seeding of this technology in the open market have also been established through the promotion of communal resources such as concrete mixers and reusable formwork, the introduction of prefabrication processes for panels and reinforcing cages used in the frame, and the use of standardized plans that allow flexible layouts of single-family homes. These innovations help to achieve requisite quality control, a much needed innovation in a country that lacks any regulatory processes. The prefabrication also allows components to be purchased progressively, a mode compatible with financial realities of low-income families.

The new housing paradigm has been met with enthusiasm and genuine interest by both Haitian builders and the local community. This serves as a validation of the potential of the proposed empowerment approach and the engagement of the local community in every step of the process. These innovations will not only offer seismic resilience, but have the potential to also break dependence on foreign aid through true local ownership of the solution.



(a) (b) (c)

Fig. 4. (a) Discussion with Haitian architects during the solution incubation process; (b) concrete panel production in Haiti and (c) structure built with concrete frame and panel system.

6 Closing thoughts

The 2010 Haiti earthquake revealed to the structural engineering community the immediate and long-term ramifications of failing to identify and eradicate vulnerable infrastructure in regions of the world susceptible to natural disasters. Unyielding urbanization trends, fueled by poor families migrating in search of higher wages and access to better services, have created cities around the world with massive populations living in sporadically and informally constructed homes, creating similar immensely vulnerable targets for natural disasters such as earthquakes. The populations of numerous developing cities are silently and unknowingly waiting to share Haiti’s fate, and unless swift action is taken to improve the seismic resiliency of low-income housing, the Haitian earthquake will not be the greatest disaster in modern human history for long. The global engineering community is therefore faced with an ethical responsibility to develop approaches that holistically assess contemporary construction practices, particularly in the residential housing sector, and to offer alternative solutions that take into account the economic, political, and cultural context that shapes severe resource-constrained environments. Any solution cannot be born from a focus on only the resiliency aspects and more often must offer technology and process innovations instead of mere re-implementation of existing technologies. Achieving this requires: (i) extensive field research that avoids promoting recommendations ill-suited for the particular economic, social, and cultural context of a region, and (ii) active engagement of the local population throughout the process, creating a culture of innovation that empowers communities to take control of their own fate. Though requiring time, commitment and patience, this is the only means to eradicate vulnerable housing practices worldwide.

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