Paper N° 1104

Registration Code: S-X1463150354

MITIGATING SEISMIC RISK IN THE DEVELOPING WORLD: LESSONS LEARNED IN HAITI AND PROMOTION OF ALTERNATIVE SOLUTIONS

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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 six years after the earthquake, despite the millions of dollars pledged and the (initial) 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, earthquake resistant housing. While many agreed that sustainable redevelopment and self-reliance was essential for Haiti, international goodwill 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 in the face of seismic hazards, especially resulting from residential construction practices among low income families.

This paper reviews the experiences of the authors in Léogâne, Haiti, during the 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. Emphasis is placed on the challenges created by the financial realities families in these countries face as well as the hurdles created by the absence of quality control systems. It then proceeds to discuss technical aspects of a solution promoted by the research team for residential construction in Haiti. The main novelty for this solution is the replacement of the concrete masonry units (CMU) used in Haiti for wall construction by lightly reinforced, pre-cast concrete panels. The panels are simply used as a cladding element and facilitate a considerable reduction of the construction cost and mass of the walls (when compared to the traditional CMU-based solution). With the walls acting completely as a non-structural element, a special moment resisting reinforced concrete (RC) frame is used as the structural system. The design iterations for the panels, as well as the quality control mechanisms developed for the RC frame, established through the construction of prototypes at Notre Dame and in Léogâne, are discussed. The panel's interaction with the RC frame is also examined though a nonlinear static analysis, utilizing an equivalent strut model to incorporate the panels into the analysis. Comparisons between the proposed solution and the common, pre-quake CMU-based construction demonstrate the benefits of the alternate system.

Keywords: Haiti, developing world, residential housing, concrete panel, CMU

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 lives lost 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 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]. Other developing nations, with construction practices that resemble Haiti's, have also experienced disproportionate losses during seismic events over the past year [4, 5]. These comparisons illustrate the challenges in translating the knowledge within the global structural engineering community regarding earthquake-resilient construction, to environments with heavy political, resource, and economic constraints [6].

This reality has created significant vulnerabilities, primarily in the urban residential sector, where poverty and a lack of access to resources have established unsafe construction practices that dominate the market [6, 7] (Fig. 1). Densely packed, informal settlements , often referred to as urban slums, are growing throughout the developing world [8] due to an overwhelming trend of populations shifting from rural settings to urban centers. With this steady stream of new inhabitants, these slums continue to grow, and in many cases so does their exposure to seismic hazards [9]. The aforementioned vulnerabilities created by flawed residential construction practices are destined to have tremendous consequences for these populations. This creates an even more pressing need to address seismic vulnerabilities and risks in the developing world. This paper reviews the authors' experiences as they worked over the past five years in response to this problem, starting with an assessment of the rebuilding efforts in Haiti. The paper offers insights on the development of affordable, sustainable solutions and implementation mechanisms that enhance seismic resilience of underdeveloped communities. It also discusses technical aspects of a proposed solution for residential construction in Haiti.

Fig. 1. Typical home in Léogâne, Haiti: (a) built with poorly confined CMU (concrete masonry unit) walls(b) typically failing in shear and bearing striking resemblance to (c) a typical CMU home in Quito, Ecuador.

2. Challenges in reconstruction efforts in Haiti

Haiti offers deep insights for better understanding the challenges in providing sustainable solutions in resource-constrained environments in the developing world. In the immediate aftermath of the 2010 earthquake and over the past six years, this catastrophe has attracted the attention of the global engineering community and many aid organizations [10, 11]. 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-intentioned 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 [12, 13].

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 to financing for homes [7]. Most homes can be classified as non-engineered construction [7, 11], 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, slender 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 and heavy rains/flooding common in the Caribbean but prove to be extremely vulnerable under seismic events, failing through brittle collapse mechanisms [7].

Fig. 2. Time lapse of heavily partitioned home with CMU load-bearing walls that experienced (a) pancake collapse in Léogâne, [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 many of the same principles that created the original vulnerabilities [documented December 2011].

The common engineering approach for addressing similar vulnerabilities in the residential housing sector 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 for implementing this customary approach, something that was not realized by the many actors operating in this domain immediately after the earthquake [14]. The inability to fully comprehend the constraints facing Haitian families have contributed to the naïve assumption that seismic resilience could be achieved by simply “importing” and enforcing US or International Building Codes [15]. 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” [16]. Based on this concept the simplest remedy was found to be the formal introduction of confined masonry construction to Haiti, which, given the severely limited availability of alternate construction-grade materials and the functional requirements of Haitian urban housing, surfaces indeed as an immediately implementable solution [17]. As such, confined masonry has received the most attention from multiple groups operating in Haiti, 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 greatly increase the price of a home, putting relevant safe construction practices well beyond the economic reach of the majority of Haitians [13]. Relying on substantial subsidies by foreign entities to enhance affordability and support a large-scale implementation poses a legitimate danger of creating perpetual dependence on foreign aid for even the most basic infrastructure needs, while also suggesting to Haitian builders that such housing designs can be made truly resilient (due to the exclusive focus placed on continued use of load bearing masonry systems). The latter 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. 2 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 there is a need to also investigate alternative affordable housing models, employing new structural systems and/or materials. Sadly efforts to do so have been unsuccessful thus far.

It is evident today that the structural engineering community and NGOs interested in this problem have failed to provide sustainable solutions accessible across the income spectrum. Interviews with displaced families [13] 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 or confinement, 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” [18]. 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 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 this can be accomplished?

3. Empowerment approach to evaluating and developing solutions

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 [19] (a goal never reached). However, this is 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, 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 investigation of these complexities, the authors have proposed an empowerment model for developing recommendations in such environments [12]. 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:

1. *Resiliency*: ensures life safety and protection against natural disasters and other environmental factors; requires an understanding of hazards and vulnerabilities.
2. *Feasibility*: ensures practical implementation using locally available technologies, capabilities, and materials; requires an understanding of technical capacity constraints.
3. *Sustainability*: ensures indefinite support using local resources (economic and natural), technologies, and skill sets of the community and can adapt with their evolving needs; requires an understanding of market constraints.
4. *Viability*: ensures the support of local stakeholders as culturally appropriate so that ideas are not just accepted, but embraced and promoted; 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 hopes to have lasting impact. 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 [12]:

1. Resiliency: Solution should provide strength and ductility against both earthquakes and hurricanes (having opposing resiliency-requirements), while accommodating flood and humid conditions and promoting foundations system that account for the weak, and at times, saturated soil conditions. The predominant pre-existing construction models have a heavy reliance on CMU walls (see Fig.1 and Fig.2). These heavy walls behave well under the frequent hurricanes and heavy rains 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 (see Fig. 1b earlier), which led in many instances to the immediate collapse of the structure.
2. Feasibility: Solution should rely primarily on the staple of Haitian construction: concrete, with judicious use of more expensive imported materials such as steel and wood (imported due to the deforestation of Haiti). They should also recognize the lack of proper quality control, created by the absence of formal training of construction crews, oversight, and financial resources. Concrete, for example, is manually mixed 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. 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 themselves 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 proper mortgage system supports 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; a seismically engineered one double that. While Haitians are now aware of the risks associated with established construction methods and are willing to absorb the new "price of safety," lack of steady income and home financing leave 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 many of the 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. This was the case in Haiti; the last significant seismic event the country experienced (prior to the 2010 earthquake) dated more than a century ago, something that contributed to the community's biased risk awareness towards annual tropical cyclone hazards or daily security risks well arrested by heavy CMU walls. Meanwhile, the cultural preferences toward privacy and the need to develop upward in dense urban areas led to the emphasis on heavily partitioning these homes and using concrete slab floor/roof systems. The vulnerabilities created by these practices were, unfortunately, clearly shown in the 2010 event.

The empowerment model can be further used to evaluate (or guide the development of) proposed solutions. Evaluations of the solutions that were implemented in the aftermath of the 2010 earthquake against the model reveals immediately the failure to satisfy one or more of the model's tenets (see [12] for more details). 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. Such focus on only the engineering dimensions of the problem leads to contextually-inappropriate solutions. Thus, the empowerment model presented in this section establishes an alternate, rational approach for arriving at solutions that can have long-lasting impact.

4. Shifting the paradigm through innovation

The aforementioned discussions make clear that mitigating the vulnerabilities in residential housing construction in the developing world 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, 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 prototypes already completed (Fig. 3). The main technology innovation for this system is the introduction of a lightweight partitioning element: precast concrete panels, reinforced in the first iteration of the solution with wire mesh. This innovation 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 [17]. The precast panels can be 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 with more targeted quality assurance than masonry construction), 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 same standard frame can be customized (in its cladding, partitioning and finishes) without needing to re-engineer the design. That same flexibility also 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 and facilitate the required quality control have been further established and will be detailed in the next section. Development of these processes was facilitated by the parallel construction of prototypes at the University of Notre Dame, USA and Léogâne, Haiti. This parallel construction promoted the exchange of ideas and technology innovations, with the Notre Dame site, led by undergraduate students, serving as the research lab and the Léogâne site, led by Haitian construction crews with the guidance of an American structural engineer, serving as the implementation lab.

Fig. 3. (a) Concrete panel tilt-up process at the prototype built in the University of Notre Dame campus; (b) concrete panel production in Haiti and (c) first prototype structure built with concrete frame and panel system in Haiti.

5. Residential housing solution promoted in Léogâne

As discussed previously, the proposed solution, shown also in Fig. 3 (c), consists to a RC frame with concrete precast panels and a corrugated metal roof. It is standardized and relies heavily upon prefabrication to deliver a higher level of quality control than pre-quake construction standards. To accommodate regional incremental construction practices and the needs of families with different financial capacities, as well as to facilitate the use of communal resources like formwork (critical issue in a deforested nation), a modular solution is promoted. The standard room has dimensions 4 m by 4 m, with a height of 2.5 m and foundation corresponding to individual footings connected with grade beams at a depth of 43 cm. Different configurations of this standard room can produce different floor plans. In Fig. 4 the basic plan with 4 rooms is shown, targeted at a larger family with higher income. The frame design, discussed in detail next, was performed for this configuration.

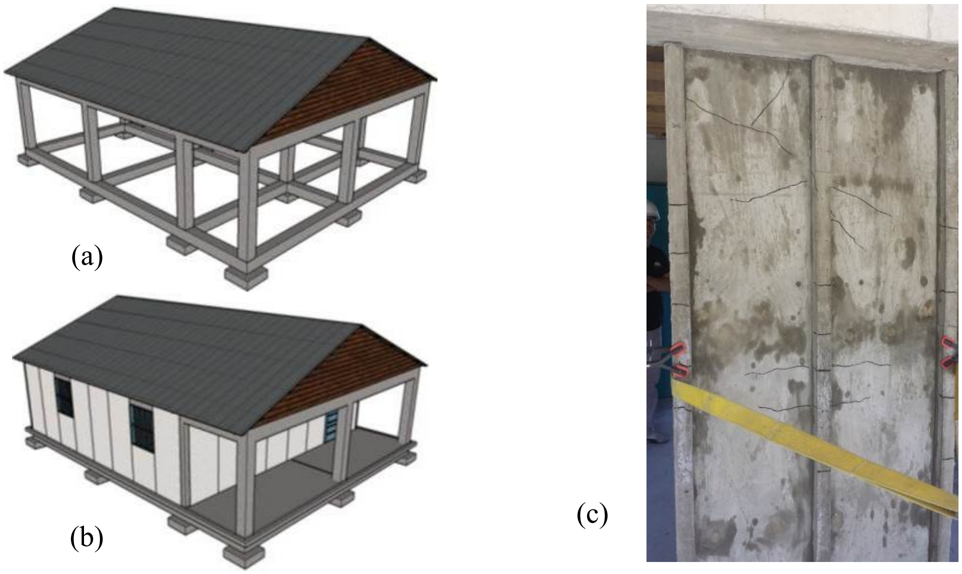

Fig. 4. (a) Structural system (with roof) for house configuration with 4 rooms and covered porch and (b) house clad with prefabricated panels; (c) ribbed panel, shown while testing out of plane strength

5.1 Structural design

The design of the RC frame and the lightweight concrete cladding elements was guided by load demands calculated according to the provisions of ASCE 7-10 [21]. For gravity loads, the self-weight of the panels was distributed along the beams supporting them. Live loads equal to 0.48 kN/m^2 were considered for the roof. For the wind hazard, wind maps for the Caribbean were used [22], leading to a wind speed of 150 mph for a mean recurrence interval of 700 years for Risk Category II structure in the city of Léogâne. Exposure Category B was used, under the assumption that the structure will be located in an inland, suburban area. Seismic loads were calculated utilizing the equivalent lateral force procedure and flexible diaphragm assumption (due to lightweight roof). Seismic excitation was considered simultaneously in both horizontal directions as well as in the vertical direction according to ASCE 7-10 provisions. The fundamental period of the structure is approximated as 0.1 sec, whereas spectral acceleration values were taken from USGS [23] with short period spectral acceleration (dictating demand) corresponding to S_s=1.89 *g*. Site class was taken as D (soft soil), with seismic design category corresponding to E. The latter imposes a requirement of special moment frame classification, which allows a response modification factor equal to *R*=8. A conservative value of *R*=3 was utilized for estimating the seismic demand. These characteristics lead to displacement demand equal to 0.4 cm.

Design of the RC frame follows the ACI 318-11 provisions [24]. Steel yield strength was taken as 420 MPa (60 ksi) and concrete peak compressive strength as 20 MPa (3.0 ksi). Both these correspond to standard values utilized for Haiti that were independently verified though material testing performed by the research team. To address concerns raised during the external peer review process about potential substandard concrete supplies, validation of the design using a reduced peak compressive strength of 14 MPa (2.0 ksi) was also performed, showing that the frame design achieves sufficient capacity even when poor quality concrete is used. Beams were sized at 25 cm wide and 30 cm deep, and columns at 25 cm square. All longitudinal and transverse reinforcement details in the beams and columns were governed by ACI 318-11 minimum reinforcement requirements; this corresponds to 6 #3 bars for beams, 4 #4 and 4#3 bars for columns (note the small diameters chosen based on local market availability), and transverse reinforcement of #3 bars at 12 cm and 10 cm spacing for beams and columns, respectively. In accordance with special moment frame requirements in ACI 318-11, transverse spacing near joints and within lap splices were reduced to 6 cm for beams and 5 cm for columns. Joints were analyzed for shear capacity using the procedures prescribed in ACI 352R-02 [25], assuming Type 2 connections with sufficient strength to withstand significant inelastic deformation. Anchorage and development lengths were governed by ACI 318-11. In general, the strength of the RC members exceeded demand by at least 20%, with the joint shear capacity dictating the capacity of the design. Ductility demands follow the ACI 318-11 [24] guidelines for special moment resisting frames, supplemented by Eurocode 8 [26] provisions. This supplement was deemed necessary since ACI 318-11 is not intended for small (one-story, two-bay) structures, but rather for larger, multi-story buildings [27]. In that regard Eurocode 8 was deemed more appropriate for satisfying ductility demands associated with low-rise concrete residential structures (which are much more common in European countries), such as capacity design checks for avoiding soft-stories. This decision was made not for reducing cost or simplifying construction procedures, but rather to uphold the primary goals and responsibilities of the research team, in accordance with the unique settings Haiti provides, to create efficient and code-compliant systems that provide maximum value to lower income families.

The design of the concrete panels utilized for cladding and partitioning went through an iterative process, considering (i) constructability issues (curing, transportation, tilt-up efficiency), (ii) displacement demand due to seismic loading, and (iii) strength demand due to wind loading. Strength checks extended to both the panels itself as well as the bolted assembly connecting them to the structural frame. The prototype house built at the University of Notre Dame served as the laboratory for the iterative design process. Different mix designs were examined with initial design corresponding to panels with initial thickness of 1.0”, reinforced with a 4x4 0.035” diameter woven-wire mesh. Testing revealed barely sufficient out-of-plane strength against strong hurricane winds and challenges in tilt-up of the panels (failures could occur due to insufficient stiffness). This led to a modification of the design, adding three, 5 cm by 5 cm longitudinal concrete ribs, as shown in Fig. 4 (c). Each of the ribs is reinforced by a one quarter inch diameter steel bar. The modified design satisfies all strength requirements by a factor of safety over 1.5.

5.2 Impact of walls on seismic behavior

The impact of the walls on the seismic performance (in-plane interaction between panels and structural frame) is further evaluated though a nonlinear static pushover analysis. This analysis is extended to also include pre-quake typologies, specifically a CMU infilled frame with 4 inch concrete slab (instead of a lightweight roof) and with typical dimensions for the region [7]: 16 cm by 16 cm columns with four #4 bar reinforcement and 16 cm by 30 cm beams with six #3 bar reinforcement. The CMU thickness is 16 cm with net thickness taken as 6.35 cm, calculated based on the recommendations in [28].

The equivalent strut method [29] is used to incorporate the panels (or CMU infill walls) into the structural model, utilizing the nonlinear force-displacement relationships proposed in [30]. As shown in Fig 5 eccentric loading is adopted for properly modeling the load transfer mechanism for the CMU walls [28]. This ultimately means that loads are transferred to the surrounding columns (below the beam-column joint). Since panels are bolted directly into the beams eccentricity was not incorporated for the load transfer mechanism for them. To address the lower construction quality for CMU infill, the reduction factor proposed in [28] was utilized, adopting 0.7 and 0.4 reduction values (for stiffness and strength) for moderate and low, respectively, production quality. Effect of openings was accommodated by a similar reduction factor, proportional to the opening area [28]. These reduction factors impact the strength and equivalent width of the strut. For the panels, in order to address potential reduced connectivity to the frame, a connectivity reduction factor γ was introduced. This factor was taken to impact only the equivalent width of the strut. Considering the different factors that impact this connectivity, for example the applied torque of bolt-nut attachment to the frame, the effects of stucco on panel-frame engagement, panel fabrication tolerances, the bearing tolerances of the bolt-panel connection, a range of different values was considered for γ. Strength for the panels is taken as 14 MPa (2 ksi) based on experimental tests, whereas for the CMU infill as 3.4 MPa (0.49 ksi); this value follows the recommendation given in [11] to approximate hand-pressed CMU quality (common practice in Lèogâne). The resultant force-displacement relationships for the struts are shown in Fig. 5 for both a frame with panels and a frame with CMU infill. The panels demonstrate improved ductility behavior due to the presence of the reinforcement. For the structural frame, plastic hinges for flexure and shear were modeled based on FEMA 356 [31] recommendations. To address compromises in construction quality, a strength reduction of 50% was also examined in the definition of these hinges.

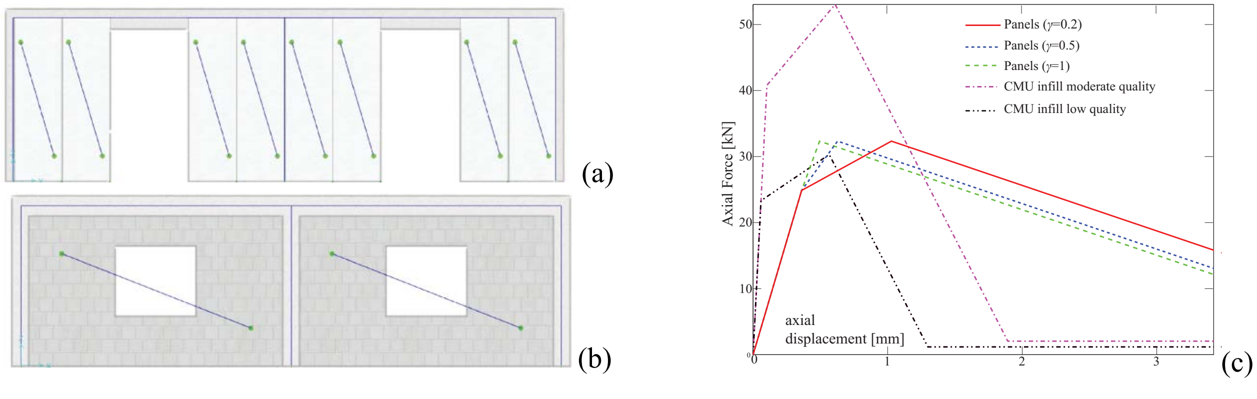

Fig. 5. Strut model configuration for (a) panel assembly and (b) infill wall assembly; (c) Force-displacement relationships for the struts used for the panels and CMU infill walls.

Results of the static nonlinear analysis along the weak frame axis are shown in Fig. 6 for different variations. Figure 6(a) includes the primary RC special moment frame with or without panels, whereas part Fig. 6(b) shows cases that correspond to vulnerable construction practices: frame with reduced strength (due to lower quality construction) and a pre-quake frame (with reduced column/beam dimensions), both employing a concrete slab roof. The displacement design demand is also shown in this figure, calculated based on FEMA 356 [31] utilizing yield and ultimate deformations from each pushover curve. The corresponding ductility demand, denoted as μ_d is then reported next to each curve. For the bare frame [Fig 6a] the ductility demand is close to the assumed response modification factor (R=3), but, as expected, smaller (overstrength effect as minimum requirements dictated many aspects of the frame design). The panels contribute to significant increase of strength and ductility. Lower connectivity values (γ=0.2) result in higher ductility demands but overall more ductile behavior. The panels attract initially a smaller fraction of the seismic forces and therefore do not contribute an immediate increase in stiffness and strength. As the frame displacements increase though, the panels gradually engage more and contribute towards the overall frame response. Even for a frame with a reduced strength [Fig. 6(b)], when considering the contribution of the panels, the ductility demand remains below the response modification factor for ordinary frames (R=3). For the pre-quake frame, the demand greatly exceeds its capacity (value of μ_d over 30). Infill facilitates a significant increase in strength, but its brittle failure still leads to a very large ductility demand (μ_d close to 4). These comparisons show the benefits of the proposed panel system.

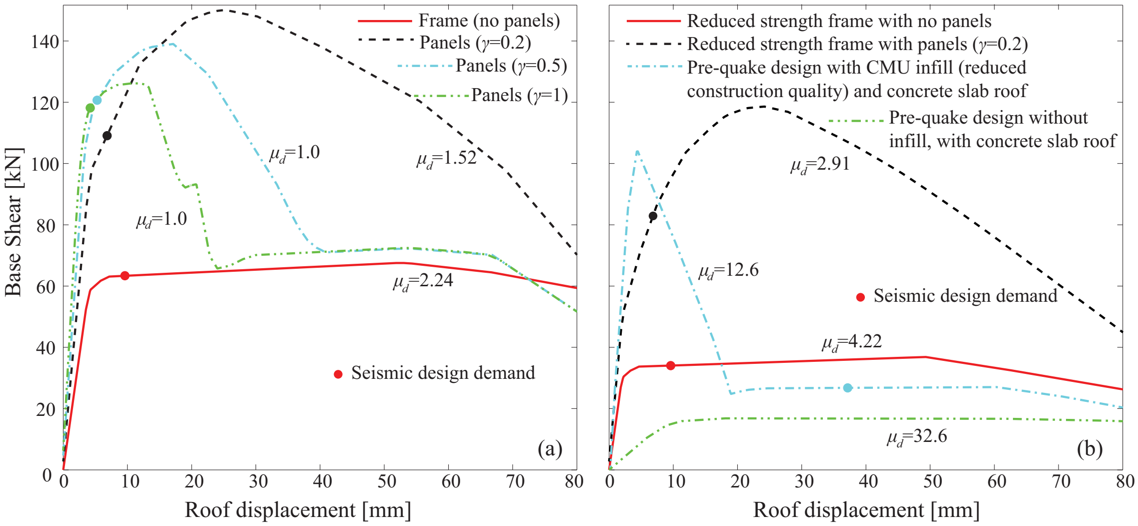

Fig. 6. Pushover curves for (a) special RC moment frame with and without panels (for different γ's) and (b) frames with reduced capacity, employing panels or CMU infill. The ductility demand μ_d under design earthquake is also reported.

5.3 Haiti implementation and quality control mechanisms

Barriers for implementation of the housing model were examined through the pilot construction of full-scale prototypes in Lèogâne, Haiti that allowed the research team to tune quality control strategies. As discussed earlier, the developed construction techniques rely on the core concepts of standardization and pre-fabrication, while the quality control strategies rely on the core requirements of visualization and construction crew buy-in. The strategies for both were intertwined, as standardized components are much easier to inspect from project to project and form crew habits around, and pre-fabrication allowed much of the quality control to happen off-site, granting more control over the process. Examples of standardization and prefabrication in practice are shown in Fig 7. Examples of visualization and construction crew buy-in in practice are shown in Fig 8.

Fig. 7. (a) Standardized and prefabricated column cages being installed, (b) standardized formwork used to ensure proper column and beam sizing and spacing, (c) standardized and prefabricated roof trusses staged on site prior to installation.


(a) (b) (c)

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- Ekri "OK" sou tout semèl ki plase byen

1

Fig. 8. (a) A quality control engineer using a visual checklist for concrete production, (b) concrete samples cast with design concrete mixes to prove increased strength to crews, (c) sample visual quality control form

6. Concluding thoughts

The 2010 Haiti earthquake revealed the immediate and long-term ramifications of failing to identify and eradicate vulnerable infrastructure in regions of the world susceptible to natural disasters, regardless of their economic capacity. Unyielding urbanization trends, fueled by families migrating in search of higher wages and access to better services, have created cities around the world with massive populations living in informal settlements, 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, a reality demonstrated by recent seismic events in Nepal and Ecuador. The global engineering community is therefore faced with an ethical responsibility to develop approaches that holistically assess contemporary construction practices, particularly in the residential sector, and to offer alternative solutions that take into account the economic, political, and cultural context that shapes severe resource-constrained environments. True solutions cannot be born from a focus solely on resiliency aspects and most likely to satisfy other constraints and preferences, must offer technology and process innovations over 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, 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 and commitment, this is the only means to eradicate vulnerable housing practices.

The solution developed by the authors though this lens has been met with enthusiasm and genuine interest by Haitian builders and the local community still living in transitory shelters. This serves as a validation of the potential of the proposed empowerment approach and the engagement of the local community at 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. Whether this can be truly achieved at scale is still a question the authors are actively exploring. Indeed, innovations in the structural concept have delivered a peer-reviewed, code-compliant design for one of the most severe seismic design categories. That design has proven to be consistently executed by local crews as a result of creative quality control strategies that are rooted in local construction practices and the mindset of its workers. Still the increased "price of safety" is inescapable, and the cost of a safe home will continue to outweigh the cost of vulnerable construction. Safety has real value to Haitians who saw too much destruction on January 12, 2010, but desperation to rebuild may erode this commitment to safety as families save for ten years or more to begin reconstruction, all the time still effectively homeless. This of course emphasizes, more than anything, the reason why solutions must be holistic. It will not be just the innovation in design or even in construction quality assurance that gives new hope to the displaced families of Haiti, but innovation in housing finance. For the authors, this represents yet another phase of work that again must listen, again must engage, and again must innovate to deliver a true solution.

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