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SEISMIC RETROFIT OF CONFINED MASONRY HOUSES IN HAITI: LESSONS FROM IMPLEMENTATION

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Abstract

After the January 2010 earthquake, over 300,000 damaged houses were significantly affected by the earthquake according to the Post-Disaster Needs Assessment issued by the Government of Haiti. The damaged homes from the earthquake resulted in over 1,000,000 individuals left without housing. In response to the earthquake, Build Change, in collaboration with Degenkolb Engineers, developed a Seismic Evaluation and Retrofit Manual for small masonry houses in Haiti in order to facilitate the repair and strengthening of damaged homes. The aim of the manual was to provide a rapid, explicit and systematic seismic evaluation and retrofit procedure which could be implemented during post-earthquake reconstruction to not only speed the return of the displaced population to safe housing, but also create a permanent improvement in construction practices and mitigate future risk to the homes at a lower cost than building replacement.

The manual procedures are based on the methodology of the U.S. standards, ASCE 31 and ASCE 41 and adapted for the applicable building types and materials used in Haiti. The most common construction type for housing in Haiti is unreinforced or partially confined concrete block masonry, the latter of which is not explicitly addressed in the ASCE standards. The performance criteria of the manual is to achieve life-safety performance in the design basis earthquake, based on the seismic hazard defined in the *Code National du Bâtiments d'Haïti*. The procedures identify key potential seismic deficiencies through a checklist format and require basic analysis, and then outline the corresponding retrofit techniques that can be used to address these deficiencies when applicable. For example, a simplified check is done on the lateral strength of the building shear walls versus the demand. If found deficient, options are outlined to either increase the building ductility through confinement of the masonry and thus reduce the demands on the walls, or to augment the wall strength to increase the capacity.

The Haitian Ministère des Travaux Publics, Transports at Communications (MTPTC) adopted the manual procedures as the technical annex to their Guide for Building Retrofit (*Guide de Renforcement Parasismique et Paracyclonique des Bâtiments*). As of mid-2015, Build Change, working with partners, has provided technical assistance to engineers, homeowners and builders to evaluate and retrofit more than 1,400 homes and in addition, at least 10 other organizations have also implemented housing retrofit programs during reconstruction in Haiti based on the seismic evaluation and retrofit procedures and manual developed.

This paper outlines the key challenges and solutions identified in implementing the evaluation and retrofit of confined and unreinforced masonry houses in Haiti following the January 2010 earthquake. These challenges relate to the development of applicable and feasible evaluation and design criteria as well as viable retrofit techniques, to the training of engineers, builders and homeowners, to creating accountability in the construction management process and to maintaining quality control of the construction works.

Keywords: Retrofit, Housing, Confined Masonry, Haiti

1. Introduction

In the urbanized metropolitan area of Port-au-Prince, Haiti the preferred structural typology for residential construction is concrete hollow block masonry. The informal areas of the city are densely populated with this housing type, see Fig. 1. It is widely accepted because of the durability compared to lightweight materials. A solid masonry wall is associated with modernity to many homeowners and provides a secure place to live in. The great majority of houses built in informal neighborhoods are not designed by an engineer or an architect. It is usually the builder who decides with the homeowner the layout of the house and then constructs it, often without having received formal training. The result is that existing houses typically have some confining elements but often key elements are missing, under designed or poorly connected.

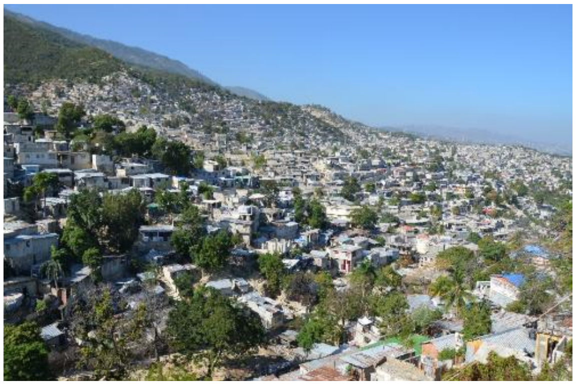

Fig. 1 - Picture of an informal settlement on the hills of Carrefour Feuilles, Port-au-Prince, Haiti

Observations of existing informal house constructions indicate that the vertical load path is generally well understood by builders and homeowners. For example, the use of columns at wall intersections is a common practice. However, the upper ring beams, which brace the top of wall out-of-plane, or vertical confinement of the openings, that confine the wall piers at either side of the opening, are typically missing, indicating that the behavior of the structure when subjected to lateral loads was not well understood by the builders and homeowners.

In informal housing construction in Haiti, the existing material quality is often poor due to lack of enforcement or regulation, lack of knowledge and training in the work force, as well as lack of funds to purchase improved materials, implement additional reinforcing elements or hire more skilled builders. Masonry blocks for construction are primarily bought in the informal market without quality control, often in the same neighborhood where the house is constructed. The compressive strength can vary significantly from one local block producer to another. Build Change collected and tested block samples from 170 block producers in the Port-au-Prince area over the past several years as part of the "Building the Capacity and Increasing Demand for High-Quality Blocks in Haiti" project. Six blocks were tested from each producer prior to quality production training; the *lowest* resulting net area compressive strength for a single block of the six varied from 0.3MPa to 7.0 MPa across all producers, with an average of 3.1 MPa (for the lowest strength sample of each producer) [1]. The low quality of blocks can be partially attributed to the poor curing techniques used by producers as they try to speed up production and thus sales to stimulate their often inadequate cash flow.

The insufficient quality and control of materials, the lack of formal skill in the construction sector, and the poor understanding of earthquake-resistant construction concepts, compounded by reduced cash access for incremental improvements to construction practices, contributed to the vulnerability of informal housing and high incidence of damage and collapse of buildings in the January 2010 earthquake. Within this context following the 2010 earthquake, Build Change, a non-profit social enterprise, in collaboration with Degenkolb Engineers, a U.S.-based seismic engineering firm, developed a *Seismic Evaluation and Retrofit Manual* for small masonry houses in Haiti [2] (Manual) in order to facilitate the repair and strengthening of damaged homes, to stimulate a permanent improvement in construction practices and to help mitigate future risk to the homes at a lower cost than building replacement.

2. Development of Evaluation and Retrofit Design Criteria and Procedures

It was critical that the procedures for evaluation and retrofit design be simple in order to be applied broadly with less time and expertise investment in the post-disaster setting, as well as be easily applied to the local existing building types and practices. To address the need for simplicity, the Manual procedures are based on the U.S. standards, ASCE 31 [3] and ASCE 41 [4], using a tier-1 checklist type approach combined with simple calculations for evaluation and a deficiency-only retrofit approach. However, these standards do not explicitly address the confined masonry building typology in Haiti. The performance-based approach was adapted to confined masonry; the masonry walls were identified as the deformation-controlled elements of the system and the confining ties as the force-controlled elements.

The Haitian Building Code (*Code National du Bâtiment d'Haiti* in French, or CNBH) [5] does not yet address existing structures. However, the Interim Rules for Calculating Buildings in Haiti (*Règles de Calcul Intérimaires pour les Bâtiments en Haïti* in French) [6] issued by the Ministère des Travaux Publics, Transports et Communications (MTPTC) applies for structures in Haiti not yet addressed by the CNBH. These Interim Rules reference the 2009 International Building Code (IBC) [7] as one of the acceptable codes to use for design, and ASCE 31 and 41 are applicable for existing buildings under the IBC.

The performance criteria in the Manual is structural life-safety in the design-basis earthquake. Structural life-safety performance, as defined in ASCE 41, is the post-earthquake performance state in which the structure has damaged components but retains a margin against onset of partial or total collapse. The design basis earthquake is taken as two-thirds of the acceleration for the earthquake hazard with a 2% probability of exceedance in 50 years, modified by the applicable site factor. The acceleration parameters for the 2% in 50 year earthquake are outlined in the CNBH for Haiti, and for the house structures applicable in the Manual, the short period (0.2 second) acceleration parameter is used. For Port-au-Prince, the resulting design acceleration, S_a, is equal to 1.05g, for Soil Type D.

2.1 Applicability of the Methodology

The Manual is applicable for existing, typical low-rise masonry concrete block houses found in Haiti, described generally as:

- Foundations: Stone masonry, continuous.
- Walls: Unreinforced concrete masonry bearing walls with or without reinforced concrete confining elements.
- Suspended floor slabs and roofs: Reinforced concrete slabs and joists with masonry void-forms. Roof systems may also be constructed of lightweight metal and wood framing systems.

The Manual was developed to address confined masonry houses from 1 to 3-stories tall in any seismic zone, and unreinforced masonry houses up to 2-stories tall in areas of low to moderate seismicity and only 1-story tall in areas of high seismicity. It is intended for use by qualified engineers.

2.2 Deficiency Identification Checklist

A checklist was developed based on the ASCE 31 tier 1 checklists and adapted to the local context to enable identification of potential seismic deficiencies in a home during a single site visit and with simple calculations. For each item, the engineer can select conform, non-conform or not applicable. A house without a non-conform for each of the checklist items is considered to meet the life safety performance goal. Table 1 lists the twenty nine deficiency identification checklist items, divided in six categories.

2.3 Wall Area Percentage Check

As part of the deficiency identification checklist, a simplified analysis of lateral resistance of the structure is performed using the wall area percentage check (Item 4.4). The wall area percentage is the ratio of the cross-sectional wall area divided by the area of the floor or roof above. The existing wall area percentage, WAP_{ex}, should be greater than the calculated wall area percentage required, WAP_{req}, to ensure enough lateral resistance, Eq. 1. The check is performed individually for each primary direction, at each level. If any case (any direction or level) does not meet the requirement, this checklist item is considered non-conform.

$$\text{Required Wall Area Percentage } (WAP_{req}) < \text{Existing Wall Area Percentage } (WAP_{ex}) \tag{1}$$

Table 1 - Deficiency Identification Checklist Items

CATEGORY		ITEM	CATEGORY		ITEM
SITE	1.1	Liquefaction	BUILDING SYSTEM (CONTINUED)	3.7	Walls
	1.2	Slope Failure		3.8	Cantilever Upper Level
	1.3	Site Retaining Walls		3.9	Damage
	1.4	Surface Fault Rupture	MASONRY WALLS	4.1	Masonry Confinement
FOUNDATION	2.1	Foundation Wall		4.2	Openings
	2.2	Foundation Performance		4.3	Top Ring Beam
	2.3	Overturning		4.4	Wall Area Percentage
	2.4	Ties Between Foundation Elements	BUILDING CONFIGURATION	5.1	Torsion
	2.5	Deterioration		5.2	Adjacent Buildings
BUILDING SYSTEM	3.1	Materials		5.3	Vertical Discontinuities
	3.2	Load Path	BUILDING COMPONENTS	6.1	Freestanding/Discontinuous Columns
	3.3	Number of Stories		6.2	Slab Openings at Shear Walls
	3.4	Story Heights		6.3	Parapets
	3.5	Mass		6.4	Stairs
	3.6	Floor and Roof System			

2.3.1 Calculation of the Required Wall Area Percentage

The Required Wall Area Percentage (WAP_{req}) depends on the seismicity of the zone and other characteristics of the building. To simplify the calculation, a Basic Wall Area Percentage, bWAP, is first established for a general default case, and then modified by C-factors according to the characteristics of the building under evaluation, per Eq. 2, for each direction and story being evaluated to determine the corresponding WAP_{req}.

$$WAP_{req} = bWAP_{req} * C_B * C_Q * C_R * C_L * C_N \tag{2}$$

Where C_B is the block strength factor, C_Q is the construction quality factor, C_R is the retrofit factor, C_L is the level factor, and C_N is the net area factor. The $bWAP_{req}$ is established, by assuming default values and checking the acceptance criteria. The acceptance criteria for shear in the masonry walls per Eq. 3, as a displacement-controlled action, is taken as:

$$V_{ne} \geq \frac{V_{uD}}{m} \tag{3}$$

The capacity, V_{ne}, must be great than the demand reduced by the system modification factor, m. The demand, V_{uD}, is calculated using the pseudo lateral force as per Eq. 4.

$$V_{uD} = C * S_a * W = 1.5 * 1.4 * S_{ds} * A_b * N * 7.2kPa \tag{4}$$

C is a modification factor to relate expected maximum inelastic displacements to displacements calculated for the linear response and is taken as 1.4 as a default. The seismic weight, W, is the product of the area of the building, A_b, multiplied by the number of stories, N, and an average seismic weight per story, w, taken as 7.2kPa. The spectral acceleration is S_{ds}, in accordance with the CNBH. Additionally, even though the checklist includes a simplified check of torsional regularity, a factor of 1.5 is included to take into account torsional effects.

The lateral capacity of the block masonry wall in a given direction, V_{ne}, is given in Eq. 5, where v_{me} is the expected shear resistance of the block and A_w is the gross cross-sectional area of the wall. The default expected shear resistance of blocks was taken as 0.43MPa, based on an expected unit net area compressive strength of 4.8 MPa and corresponding expected masonry compressive strength of 3.9 MPa. This expected unit compressive strength was estimated from samples collected and tested in compression to represent average-to-good quality blocks found in the locally available markets. When existing houses are observed to use slightly lower quality blocks, indicated by color or aggregate type, the evaluating engineer will use the block strength factor to adjust the required wall area percentage up to account for the strength reduction (the next tabulated value in the Manual corresponds to an existing block strength of 2.8MPa). In cases where the block is found to be of poor quality or unsound (corresponding to very low strength masonry), the wall is reconstructed in better quality blocks as part of the retrofit. Typical concrete blocks in Haiti are approximately 55% solid, and this value was taken.

$$V_{ne} = v_{me} * A_w * \%\ \text{solid} \tag{5}$$

Through applying Eq. 4 and Eq. 5 to the acceptance criteria with the default values noted, $bWAP_{req}$, can be determined by solving for the ratio A_w/A_b as in Eq. 6. The component modification factor, m, is 2.5 for confined masonry walls and 1.25 for the unreinforced masonry walls.

$$bWAP_{req} = \frac{A_w}{A_b} \geq 6.4\% * N * \frac{S_{ds}}{m} \tag{6}$$

Supplemental information on the C factors used to adjust the WAP_{req} in evaluating individual buildings is included in the Manual and discussed briefly here. The block strength factor, C_B, is used to adjust the WAP_{req} where strength of existing masonry varies from the default strength. The construction quality factor, C_Q, is used to adjust the WAP_{req} based on the quality of construction. The retrofit factor, C_R, is taken as 0.75 for the evaluation of the existing building and as 1.0 for the evaluation of the retrofit design. The level factor, C_L, is used to adjust the WAP_{req} depending on which particular story is being analyzed in a multi-story building. C_L varies based on the number of stories in the building, the story being analyzed and the roof type according to the vertical distribution of forces and adjustment to the appropriate ASCE 31 modification factor, C. The net area factor, C_N, is used to adjust the WAP_{req} when the net area of the existing blocks varies from the default percentage (55%).

2.3.2 Existing Wall Area Percentage

The existing wall area percentage, WAP_{ex}, is calculated for a given level and direction by adding the areas of all the walls in the corresponding direction and level per Eq. 7. Only wall lengths that are at least 1.0m long (excluding openings) are considered to contribute to the lateral resistance.

$$WAP_{ex} = {\sum t_{mi} L_{mi}}/{A_b} \tag{7}$$

Where, t_{mi} = thickness of wall i, l_{mi} = length of wall i, and A_b = Area of the building plan. If the WAP_{ex} is found to be below that required, WAP_{req}, the building does not conform and corrective action is required for the level and direction found to be non-confirming as part of the retrofit scheme.

2.4 Retrofit Design

In developing the retrofit techniques, methods using local practices were prioritized in order to help ensure labor and materials would be readily available. However, small changes were made in common practices to increase the suitability for areas of seismic hazards, such as ensuring proper laps and detailing of reinforcing.

After the deficiencies are identified, a suitable retrofit scheme may be developed directly from the checklist evaluation process, such that for each non-conforming item in the checklist, a strategy to convert it to a conforming condition is developed. Site category deficiencies are difficult and costly to correct and might prevent a full retrofit to life safety performance. Foundation category deficiencies are critical because if they are found to be non-compliant, the structure might need to be rebuilt from the foundation up, eliminating the option for retrofit. Building system deficiencies can be corrected by demolishing and rebuilding the non-compliant element. For example, demolishing a cantilever wall and lining up a new one with the wall below. Masonry wall seismic deficiencies can be addressed by adding the required confining elements. See an example retrofit detail in Fig. 2. In some cases, replacement of the wall or infill of an opening may be required. When the existing wall area percentage does not meet that required, the wall area can be supplemented as described below. Building configuration deficiencies can be corrected by balancing the shear wall layout to reduce torsion, or providing vertical elements for continuity (or removing discontinuous ones above). Adjacent building deficiencies may require an intervention in the adjacent building, or the creation of a separation joint. Building component deficiencies such as parapets and stairs can be simply corrected by removal and replacement of the element, or by supplemental support or reinforcement. Once the retrofit scheme is developed, the checklist is applied to the design to confirm that there are no longer non-conforming items in the building and therefore that the house meets the desired life-safety performance goal.

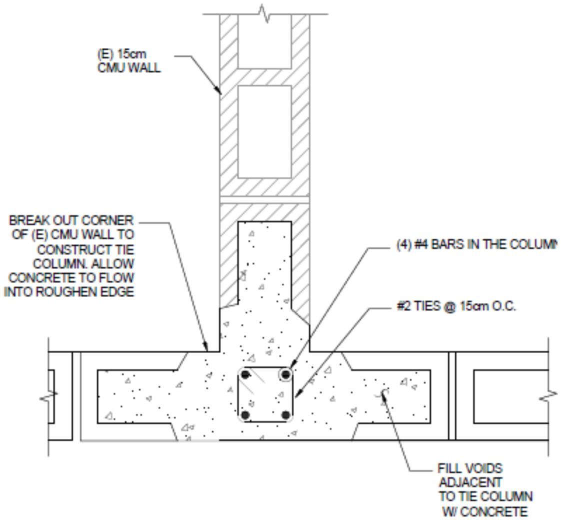

Fig. 2 - Retrofit detail to install a new vertical confining tie at the intersection of two existing walls

2.4.1 Effective Wall Area Percentage

When the existing wall area percentage is found to be insufficient, there are two primary options for the retrofit scheme – to add supplemental wall area or to reduce the amount of wall are required. To increase the actual shear wall percentage, the Manual identifies several options: add new masonry shear walls, or increase the length of walls that are less than 1m long, double the thickness of existing shear walls, infill doors and/or windows to increase the length of solid shear wall panels, or increase the effective area of the existing walls by an exterior-applied cement mortar layer or by adding a reinforced concrete overlay to one face.

Alternatively, to reduce the required wall area percentage, the Manual identifies several options: introduce reinforced concrete confining elements to permit an increase in the m-factor, improve the quality of existing walls by repairing them, or if the block is low strength, replace them with new walls to effectively decrease the C_Q factor, or decrease the seismic mass of the building (for example, demolish an upper story).

When options to supplement the existing wall area are chosen, the *effective* wall area percentage (WAP_{eff}) is calculated by accounting for the addition of structural elements to the WAP_{ex}. To simplify the retrofit design, the additional resistance provided by new structural elements is accounted for using K-factors, which relate the strength of the added element to the strength of the block masonry walls in the development of $bWAP_{req}$. K-factors for new masonry, thin cement plaster overlays and thicker reinforced concrete overlays are included in the Manual. The WAP_{eff} accounting for the retrofit elements is calculated by Eq. 9.

$$\mathrm{WAP_{eff}} = \frac{\mathrm{A_m}}{\mathrm{A_b}} + \frac{\sum \mathrm{K_i L_i t_i}}{\mathrm{A_b}} \tag{9}$$

Where, A_m = sum of existing wall areas in the level and direction under consideration that will remain in the retrofitted state, A_b = the plan area of the building, K_i = adjustment factor for new element i, L_i = length of new element i in the level and direction under consideration, and t_i = thickness of the new element i.

3. Application of the Evaluation and Retrofit Procedures

In practice, the Manual workflow starts with the engineer performing a site visit to observe and document the existing condition of the house and fill out the deficiency identification checklist. The measurements of the house are taken and sketches of the site plan and each existing floor plan are made. The evaluator takes pictures of the identified seismic deficiencies and the exterior façades of the house. By following the evaluation checklist and performing the wall area percentage check, the engineer evaluates the building and then designs directly a retrofit solution as needed. The engineer then develops the retrofit plans for each level and a roof plan, as needed, to indicate the required interventions. See an example existing and retrofit design plans in Fig. 3.

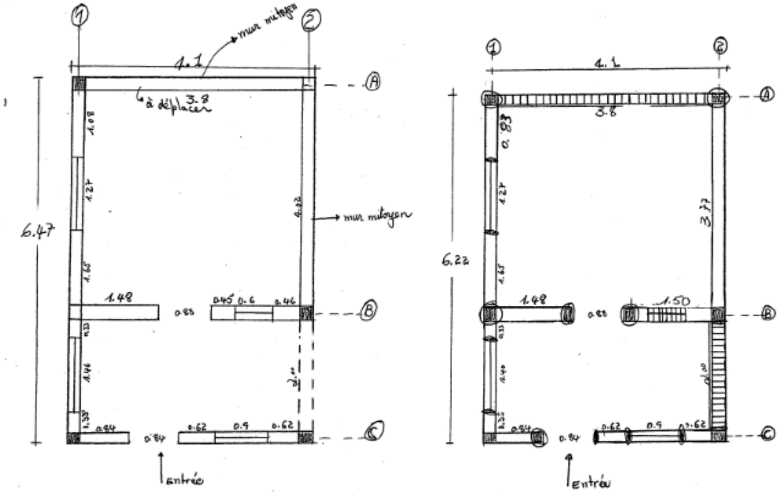

Fig. 3 - Existing (left) and retrofit (right) plans of an unreinforced masonry house retrofit to a confined masonry house (circled columns indicate new vertical ties and hatched walls indicate new walls)

3.1 Homeowner Driven Retrofit Projects

Several homeowner driven retrofit projects have implemented the Manual procedures since 2010 and at least 1,400 homes have been retrofitted with technical assistance from Build Change in various neighborhoods in the Port-au-Prince area. Homeowner driven construction puts the homeowner at the center of decision making and responsibility for the project so that they are actively participating from design through construction.

Retrofitting is particularly suited to the homeowner driven approach because the technical solutions for the retrofit can be varied to suit the needs of the homeowner. For example, in cases where a homeowner would like to add a new story to the house in the future, the retrofit can be designed so that the existing home can safely resist the additional earthquake demands from the future level when it is constructed. Homeowner satisfaction is further increased because often retrofitted houses are improved, safer versions of the houses that the same families lived in before the earthquake [8]. See Fig. 4 for an example of a retrofitted house.

Fig. 4: A home in Port-au-Prince before (left) and after (right) a seismic retrofit

3.1.1 Example Project Scope

One example retrofit program used the Manual to improve houses in Carrefour Feuilles, an area with a large density of informal housing construction in Port-au-Prince. Following a rapid assessment of approximately 1,100 houses and a geotechnical investigation in the area, technical criteria for eligibility of homeowners to participate in the program was established. The resulting intervention of the project is illustrated in Fig. 5, where 224 houses for 508 families were retrofitted and in some cases expanded vertically or horizontally. Orange and red hatched buildings were retrofit, while the purple buildings indicate those that were confined masonry (CM) or unreinforced masonry, but did not participate in the program.

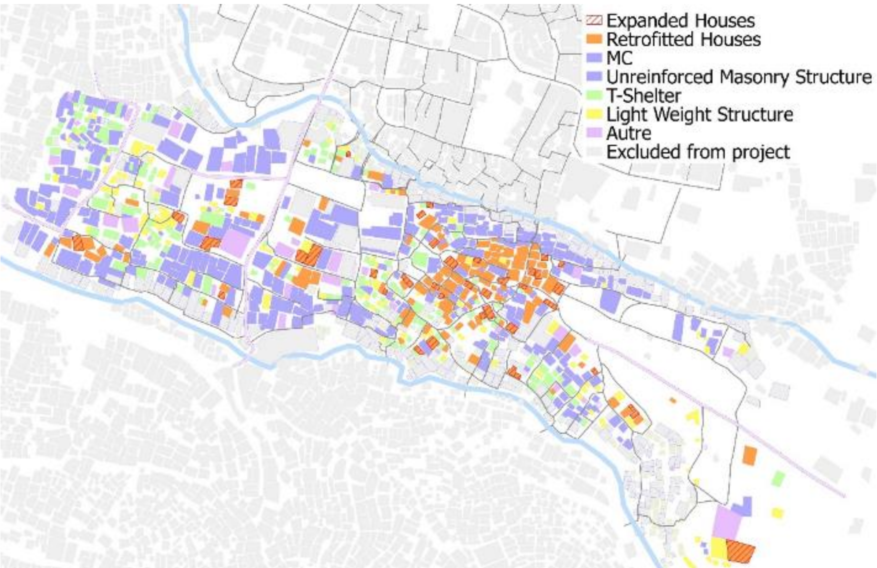

Fig. 5: Map of house structure typology and intervention in Carrefour Feuilles, Port-au-Prince

3.1.2 Example Project Costs

The resulting cost of retrofit in this example project was \$130/m^2 but the price varied from as low as \$30/m^2 to as high as \$300/m^2 depending on the intervention required. Total final retrofit costs per building were on average \$6,422. However, the number of housing units in each building (defined as private, exterior accessible spaces) varied from 1 to 9, with and average per building of 2.5. The least-cost retrofit was \$1680, for a single housing unit building, and the most expensive retrofit was \$16,040, for a 6-housing unit building [9]. Some of the higher cost retrofits were so because the work included not only seismic retrofit activities, but also layout reconfiguration due to adjacent infrastructure projects. The costs noted include the costs of building materials with transportation to the site, all labor including demolition and debris removal, and the rental of formwork and shoring for construction.

Compared to new construction and transitional shelters (t-shelters) used following the 2010 earthquake, retrofit is a competitive option. The average price per square meter for a new confined masonry house in Port-au-Prince or for a T-shelter is approximately \$250/m^2 [10].

Prior to the start of construction, the allocated budget for each house in the example project also included a contingency of 12% of the total construction cost. Among the structures retrofit, half of them had unforeseen costs that required budget above the planned contingency. The additional budget required per house varied from as low as \$25 to as high as \$4000, depending on the extent of unforeseen work and the willingness or capacity of the homeowner to contribute more money. Some of the most costly unforeseen conditions were due to replacement of existing walls and existing suspended slabs. Of the houses with unforeseen costs, 70% of the adjustments were less than \$1000, and the overall budget envelope for all houses increased by 7% due to unforeseen work [9].

3.2 Decision Making in Evaluation and Design

The lack of enforced construction standards and the diversity of foremen knowledge in good construction practices made existing building evaluation challenging in some cases. However, with experience, engineers developed good judgement and improved the evaluation and retrofit process. Based on the projects performed in Port-au-Prince, common issues in evaluation that can impact the retrofit design are discussed below.

3.2.1 Walls

Existing walls are generally not plastered or painted and therefore it is easier to analyze the load path and the quality of blocks, but it also increases deterioration of the walls due to weather exposure. When evaluating a wall, the condition of the materials, the layout of the blocks and damage state of the wall should be considered in order to determine if replacement or repair is required in the retrofit.

The quality of the mortar can be evaluated to see if the color of the mortar indicates it is made from unwashed sand, or if there are signs of erosion in the joint, or if the joints are too thin or too thick. Walls in which the mortar can be scraped away by a nail should not be considered shear walls and should be replaced as needed.

The layout of the blocks is also an indicator of the quality of the wall construction. It is not unusual to see pieces of block in an existing wall or a joint layout not staggered. If the construction quality is so poor, or the deterioration so great, that there is risk of collapse, the engineer should recommend replacing the wall. If there is not an apparent collapse risk and the blocks simply have a non-optimal layout or insufficient toothing at the column, wall replacement may not be required and the evaluating engineer can consider increasing the construction quality factor to account for these issues.

Cracks in existing walls can be superficial and concern only the cement plaster covering; in that case the plaster can be removed around the crack and repaired. If the masonry is cracked on only one side of the wall, repair during the retrofit should be made. In the cases where the crack is visible on both sides of the masonry, it is recommend to replace the damaged portion of wall. In Fig. 6, the crack in the wall was previously repaired: first filled with unwashed sand mortar and pieces of rubble, and then plastered over. This condition would require a larger, more significant repair with adequate construction materials, and potentially replacement of the wall.

Fig. 6 – Poorly repaired wall crack

3.2.2 Confining Columns

The evaluation of existing confining columns is facilitated by the fact that most column reinforcing extends vertically and is exposed above the structure. This visual accessibility provides useful information that cannot be easily observed otherwise. Existing reinforcing encountered includes both smooth and deformed bars. The diameter and the number of reinforcing can vary from a column to another and within the same column. For example, in order to save money, a builder may have used a four-bar column with three #4 bars and one #3 bar. The quality and the spacing of the stirrups can sometimes also be evaluated from the extension of the column reinforcing, particularly to understand whether the stirrups are properly hooked at both ends.

The quality of the confining column concrete can be evaluated visually, looking for signs of deterioration, aggregate segregation, or thin concrete cover. The quality of the concrete can also be evaluated looking at and tapping on exposed rough concrete. In Haiti, use of poor quality sand and a lack of sufficient cement in the concrete mix is a common issue.

Very few existing confining columns are built to standards for new construction, see Fig. 7; nevertheless the Manual procedures do not aim to replace all the columns of a house. Engineering judgement is needed to evaluate the adequacy of an existing column depending on the role of the column in the structure. For example, a confining column in a deteriorated state, particularly with corroded reinforcing, or very poorly built should be replaced. A confining column that does not meet all of the new construction standards, but is in decent state may be kept and still serve to adequately confine an existing wall.

Following the capacity based approach, an existing masonry wall, with lower shear strength than that which would be used for new construction, would sustain lower shear forces than a new stronger wall. Thus the demands on the confining elements are proportionally lower and an existing column, although not compliant with new construction standards, can still be sufficient to resist the axial tension demands, and ensure the confinement of the masonry of an existing wall. When a new wall is added with good quality blocks and mortar, a new column is built to maintain an appropriate balance between the strength of the confining element and the masonry elements.

Fig. 7 – Left – Existing column extension with (3) #4 and (1) #3 bars
Right – Existing column extension with smooth rebar and stirrups already placed

3.2.3 Slabs

The suspended slabs are a critical element during the evaluation, because a house retrofit without slab replacement is relatively inexpensive, but if slab is replaced, the price increases much more.

During the example project in Carrefour Feuille, retrofits of 35 houses with existing suspended slabs were performed. In the evaluation phase, nine of the houses (approximately one quarter) were identified to need slab replacement due to the poor condition of the existing slab, see Fig. 8. However, during the construction phase, an additional four houses were added to the number of houses needing slab replacement [9]. This represents a total of about 40% of the existing slabs requiring replacement (foreseen and unforeseen), a 15% increase due to unforeseen conditions.

Fig. 8 - Existing slab in poor condition

It is common for the ceiling plaster below the slab to appear to be in good condition, but when construction starts and the slab vibrates more than usual, the plaster can collapse and expose corroded reinforcing (Fig. 8). The high rate of slab replacement required (40%) can be attributed to the poor construction techniques used during the original slab pour – primarily lack of adequate concrete cover below the reinforcing.

Several techniques can be used to correctly evaluate the existing slab condition: 1. A visual assessment to understand if water can stagnate on the roof above (accelerating corrosion) and to assess below if there are signs of delaminating plaster or exposed rebar. 2. Information on past ceiling repairs can be requested from the homeowner to know if the slab was previously repaired to hide corroded reinforcing. 3. Finally, destructive investigation, such as chipping or removal of plaster, gives a clear understanding of the state of the slab.

3.3 Construction Quality Control

It is important that the design is implemented well during construction so that the performance of the house can meet the design goals. Systems for accountability with each of the actors in the construction process improved the quality. Engineers used standard quality control forms to document their observations, recommendations and the ongoing quality of work. Builders were held accountable through payment and future work opportunities to follow the retrofit design and specifications. Homeowners were held accountable to purchase the correct materials and manage the construction well through conditional subsidy disbursements, as they received funding for the work in phases and only after the prior phase was managed properly.

Quality control tools help to maintain a high level of quality, particularly when multiple house retrofits are active in a project at a given time. Quality control checklists were developed to be used by supervising engineers to maintain quality on the construction site and to keep record of the work.

The construction quality checklist outlines each step in the construction process for a particular structural element, such as foundations, new columns, new walls, reinforced concrete overlays, wall opening reinforcement, wall opening infill, and concrete roof and light weight roof construction. The checklist also includes specific detail requirements, such as the size, quantity and detailing of reinforcement, the concrete mix proportions, etc. Guidance on documenting each step is provided as well as a method for rechecking work that was originally identified to be non-conforming and required correction.

Even though the builder and the homeowner are trained to select and purchase good quality material, the engineer is also responsible to check the quality and proper storage of materials on site. The main issues for material quality encountered in implementation were poor quality sand and blocks. When poor quality materials are found on site, the homeowner is instructed to discard or return the poor quality materials and replace them with adequate ones before authorizing the builder to proceed with work.

4. Training the Actors in the Construction Value Chain

4.1 Builder Training

Construction quality and foremen skills were often found to be unsatisfactory due to lack of training and capacity and so training of builders before and during retrofit work was required. When the training of builders included the following key aspects, it was most successful in improving the quality of construction: 1. Initial verification of the builder's knowledge prior to the start of training to understand if the builder has the minimum construction experience necessary to successfully complete the training. 2. Self-assessment by the builder in order to identify which skills require supplemental formal training. 3. Theoretical training about earthquake engineering, material quality, load path, etc. 4. Practical training in the required skills identified, mimicking the site conditions as closely as possible through training stations. 5. Verification through testing that the builder can demonstrate all of the skill required. 6. Certification of the builder for all portions of the required work, based on successful verification. 7. On-the-job training as the builder implements new skills in a house retrofit project.

4.2 Homeowner Education

As the manager of the retrofit work on their house, it is important for the homeowner to be knowledgeable in: understanding the basics of building behavior in an earthquake, how to purchase good quality materials, and how to identify generally good and bad construction practices the builder may be using on site. Training for the homeowners participating in the retrofit program included these topics, using materials that were highly visual with videos, models and drawings to make the technical concepts more accessible.

4.3 Local Engineer Training

Engineer training in the use and application of the evaluation and retrofit methodology, both through theoretical and on-site scenarios, was critical to project implementation. The engineer must understand how to properly evaluate a house, develop the retrofit design and provide construction quality supervision. He or she must be able to compile the elements of the retrofit design package, including drawings such as the site plan, plans of the existing structure, retrofit plans and roof plan, the evaluation checklist of the seismic deficiencies, the calculations of the wall area percentage, the scope of the retrofit work to explain to the homeowner, and the bill of quantities and cost estimate of material, labor, and rental costs.

4.4 Block Producer Training

Due to the very low quality of the existing blocks available in the informal market in the Port-au-Prince area, block producer training and certification was performed. After training, producers following the recommendations given, produced block with an average net area compressive strength of 7.9 MPa, up significantly from the lowest existing block compressive strength average of 3.1MPa [1]. Homeowners were trained in how to identify and avoid poor quality blocks, and were required to purchase better quality, stronger blocks for the retrofit work.

5. External Risk Factors

Outside of technical challenges, implementation of a retrofit program in an informal zone can have non-trivial external risk factors. These are not addressed at length here, but need to accounted for in project development and can include items such as community acceptance or prioritization of the retrofit work and engagement or education of the community, political instability (national, regional or communal), lack of infrastructure such as electricity, roads, water, or other, violence and insecurity, and availability of funding and distribution mechanisms or systems.

6. Conclusions

The experiences in Haiti gained through several retrofit programs since 2010 indicate that a post-earthquake housing retrofit program, implementing simplified evaluations and retrofit procedures is feasible and can be more economical than new construction while still improving the safety and resiliency of the affected areas. It is important for variations in the existing structure quality and condition to be identified during evaluation, and addressed as needed in the retrofit plans, to reduce cost increases during construction. However, due to infinite variations and inevitable unforeseen conditions in existing buildings, cost contingencies and flexibility should be accounted for in the retrofit project funding set up. For effective implementation of a retrofit program, it is important for there to be accountability mechanisms for each actor in the project and for the technical capacity of all actors to be at the required proficiency for their role. Non-technical external factors, including some particular to informal construction, require consideration in the overall project planning.

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8. References

[1] *Building the Capacity and Increasing Demand for High-Quality Blocks in Haiti, Project Database*. Build Change, 2016.

[2] Build Change and Degenkolb Engineers. *Seismic Evaluation and Retrofit Manual*, MTPTC Training, April & May 2011, revised September 2013.

[3] American Society of Engineers. *Seismic Evaluation of Existing Buildings*, *ASCE/SEI 31-03*. Reston, Virgina, 2003.

[4] American Society of Engineers. *Seismic Rehabilitation of Existing Buildings*, *ASCE/SEI 41-06*. Reston, Virgina, 2006.

[5] Ministère des Travaux Publics, Transports et Communications. *Code National du Bâtiment d'Haiti.* Haiti. 2012, 2013 Edition.

[6] Ministère des Travaux Publics, Transports et Communications. *Règles de Calcul Intérimaires pour les Bâtiments en Haïti.* Haiti. February 2011.

[7] International Code Council. *2009 International Building Code*. Country Club Hills, IL, 2009.

[8] Build Change for Parsons Engineering, USAID. *Seismic Retrofit of Housing in Post-Disaster Situations– Basic Engineering Principles for Development Professional: A Primer*. January 2014, Draft.

[9] *LAMIKA Reconstruction and Retrofitting of Housing and Supporting Infrastructure, Project Database for Retrofit and Expansion*. Build Change, 2016.

[10] Homeowner-Driven Housing Reconstruction and Retrofitting in Haiti: Lessons Learned, 4 Years After the Earthquake, Build Change Report, January 9, 2014.