URBAN EARTHQUAKE DAMAGE ASSESSMENT AND RECONSTRUCTION: 2010 HAITI EARTHQUAKE

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SUMMARY
The Mw 7.0 20101 Haiti Earthquake caused extensive damage. In its aftermath, the authors, working with the Haitian Ministry of Public Works developed a comprehensive damage assessment and reconstruction program. The first phase of this project has been completed and over 400,000 structures in the greater Port-au-Prince area were surveyed for. Of these buildings, approximately 50%, 30%, and 20% have been tagged as green (safe), yellow (limited occupancy), and 20% red (unsafe), respectively. As a result, over 500,000 displaced people have left the temporary camps. The second phase of the effort involves repair and reconstruction of damaged buildings. Repair strategies have been developed and are being implemented and are intended to provide structures that are more robust and can withstand earthquake shaking without collapse. The first batch of 10,000 buildings has been repaired successfully. The repair of damaged buildings will allow many more people to return to their buildings.

Keywords: Haiti earthquake, damage assessment, damage classification, reconstruction,

1 INTRODUCTION

The catastrophic 2010 Haiti Earthquake has had a tragic effect on the lives of more than 3 million people. This paper describes the work performed by The Haitian Ministry of Public Works, Transport, and Communications (MTPTC) to assess the safety of much of the affected building inventory in Port-au-Prince and other affected communities.

In light of the enormity of the damage caused by the earthquake, the MTPTC created the Bureau d'Évaluation Technique des Bâtiments (BETB), a dedicated agency charged with the task of assessing damage to all buildings in earthquake-affected areas, developing criteria for repair and reconstruction, and providing quality control (QC) reconstruction. With funding provided by the World Bank (WB), and U.S. Agency for International Development (USAID), field logistics provided by United Nations Office of Project Services (UNOPS), and Pan American Development Foundation (PADF), and technical expertise provided by the authors, BETB embarked on an ambitious program to organize and train a cadre of approximately 250 Haitian national engineers to perform rapid evaluation of all affected buildings using the internationally accepted ATC-20 (ATC 2005) and FEMA 310 (FEMA 1998) methodology.

The authors (Miyamoto and Gilani 2011) led a four-day intensive classroom session on the fundamentals of earthquake engineering and assessment for more than 600 applicants. Course work was followed by a written examination, from which approximately 250 candidates were selected as evaluators. Among these, 10 of the most qualified were selected as division leaders. Division leaders were given additional field training before commencing work with their division members. Each of the divisions consisted of a division leader, four team leaders, and eight to ten evaluators, all taken from the ranks of the 250 trainees

2 2010 HAITI EARTHQUAKE

2.1 Overview

The magnitude 7.0 Haiti earthquake occurred at 16:53 local time on Tuesday, 12 January 2010, with an epicenter approximately 25 km west-southwest of the densely populated capital city of Port-au-Prince. The main event induced shaking based on the Modified Mercalli Intensity (MMI) VIII in the city. In the two weeks following the main event, 52 aftershocks in the magnitude range of 4.2 to 5.9 were recorded.

Haiti has experienced previous large (but infrequent) earthquakes. The last major earthquake to strike Port-au-Prince was the 1770 event that leveled the city. In 1842, an earthquake destroyed the city of Cap-Haïtien in northern Haiti. Another large earthquake occurred in 1860 which resulted in a tsunami. It should be noted that the last major earthquake to occur in Haiti dates back over 150 years. This lack of significant seismic activity for a long duration prior to the 2010 event contributed to reduced importance being assigned to proper seismic design which contributed to the level of damage.

The 2010 earthquake caused significant damage to Port-au-Prince and other cities in the region. More than 200,000 structures were damaged or had collapsed, including many essential buildings, such as the Presidential Palace (see Figure 1), and the headquarters of the United Nations Stabilization Mission in Haiti (MINUSTAH) also collapsed (see Figure 2), killing many, including the mission's chief.

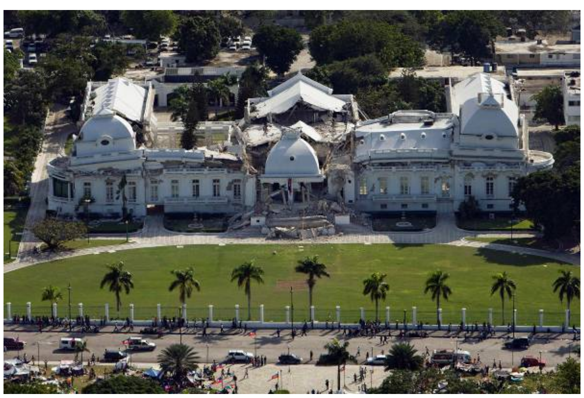


Figure 1. Damaged Presidential Palace in Port-au-Prince (UNDP Global 2010).

Figure 2. Collapsed UN building in Port-au-Prince (UNDP Global 2010).

As listed in Table 1, the human and financial consequences of this even were staggering.

Table 1. Human and financial cost of the earthquake

Human and financial metric	Estimated cost
People affected	3,000,000
Fatalities	230,000
Injured	300,000
Made homeless	1,000,000 to 1,800,000
Residences collapsed/damaged	250,000
Commercial building collapsed/damaged	30,000
Economic cost	US $14B
Cost percentage of GDP	~ 15%
Recovery time	years

2.2 Main Causes of Damage

This earthquake caused devastation disproportional to its magnitude. If any form of standard of seismic design and construction had been used in Haiti, many lives and much of the economic loss could have been avoided.

Many of the structures in Haiti are composed of a particular building type that is seismically vulnerable and poses a life-safety hazard. These buildings use a variation of confined masonry construction comprising weak hollow concrete blocks (HCBs) with lightly reinforced and nonductile beams and columns. Although properly designed confined masonry buildings can withstand large earthquakes, the construction in Haiti did not have proper design, detailing, and construction.

In such structures, the concrete floor and roof slabs are supported by lightly reinforced concrete columns, sometimes as small as 150 mm in size. Floor and roof framing consists in some cases of a grid of concrete joists framing between the beams, and voids between the joists are created using HCBs as stay-in-place forms. Exterior wall cladding and interior partition walls universally consisted of HCBs joined with cement mortar. These infill wall panels effectively serve as the seismic-force-resisting system; however, there has typically been no evidence of any system intentionally designed for that purpose. These buildings typically lacked a seismic load path. In seismic zones, this load path commonly comprises of diaphragms, collector elements such as chord and drag reinforcing, special vertical reinforcing at shear wall corners, and doweling between the walls and surrounding elements. None of these was present in the vast majority of buildings observed.

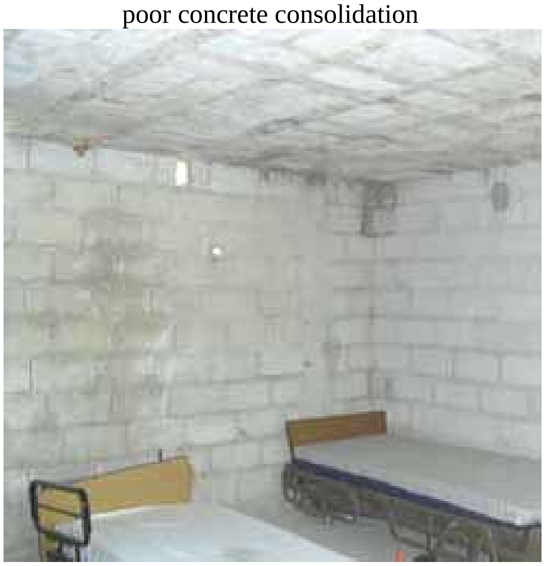
Concrete gravity frames display numerous design and construction practices that would be considered defective. Figure 3 shows some of the common seismic deficiencies. Design defects include the following: a) inadequate column size, b) insufficient amount of longitudinal reinforcement, c) use of smooth reinforcing bars, d) lack of column confinement reinforcing, and e) inadequate lap splices and rebar development length. Construction defects consist of the following: a)segregation, voids, and rock pockets evident in finished concrete, particularly in columns and at construction joints, b) exposed rebar and poor aggregate shape and grading, c) poorly located construction joints, and paper and other debris left in joints; formwork embedded in finished concrete, and d) out-of-plumb columns

Typical masonry construction also has numerous defects, including irregular coursing, missing or inadequate vertical mortar joints, inadequate horizontal joints, poor material quality, and extensive use of broken block. These conditions were commonly found in nearly all the buildings, regardless of age, size, or number of stories. These design and construction practices led to a combination of heavy buildings with little lateral strength and essentially no post-yielding capacity, and were key factors in the vast majority of failures observed.

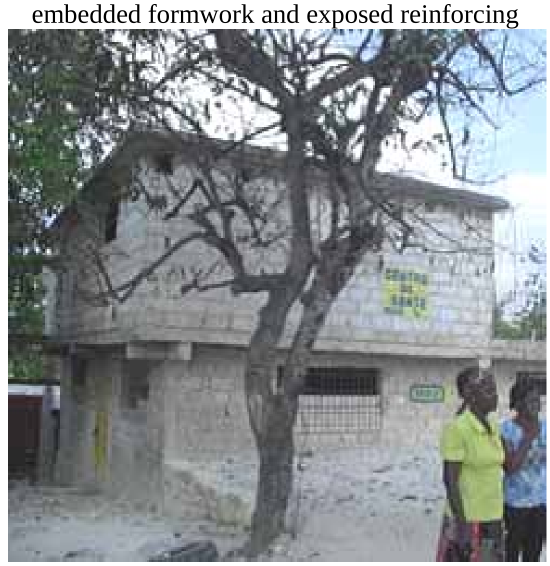
Although no comprehensive material testing was conducted, both the masonry and concrete elements for residential construction appeared to have quite low material strength. For commercial buildings, the quality of material appeared to be better.

poor concrete consolidation

embedded formwork and exposed reinforcing



poor workmanship in unreinforced HCB wall



building with overhanging upper floor.

Figure 3. Typical Haitian construction practices showing common inadequacies

3 DAMAGE ASSESSMENT PROGRAM

3.1 Damage Assessment Methodology

The evaluation methodology chosen for this program was the ATC-20 (ATC 1987) rapid assessment, with modifications made to adapt to Haitian construction practices and to provide information that is more useful to the MTPTC. This methodology, which was first developed in California in the 1980s, has been used successfully for evaluation after many major earthquakes in the United States. The rapid assessment form allowed evaluators to characterize buildings in one of three ways:

- “Inspected” (also known as “green-tagged”), meaning that the building is structurally undamaged and may be occupied full-time.
- “Restricted Entry” (or “yellow-tagged”), meaning that the building should not be occupied for extended periods and that parts of the building might be considered off-limits.

- "Unsafe" (or "red-tagged"), meaning that the building cannot be safely inhabited.

The form was modified to provide evaluators with a checklist of earthquake vulnerability factors per FEMA 310 (FEMA 1998), which allowed evaluators to list the features of each structure that would make it more prone to earthquake damage.

One important consideration that was stressed to the evaluators is that while the three-color evaluation system provides an understanding of the hazard associated with a building at the time of evaluation, it does not state whether a building must be demolished. Some buildings given "unsafe" ratings are considered repairable, but the nature of the damage has rendered them unsafe to occupy until repairs can be completed. In the same way, the "inspected" rating does not guarantee that a building will not be seriously damaged in the event of future earthquakes. For example, if another major event of equal or greater magnitude were to take place along a section of the Enriquillo-Plantain Garden fault zone closer to the city of Port-au-Prince, in all likelihood, damage would be much more widespread. In general, the nature of local design and construction in Haiti is such that nearly all buildings can be considered vulnerable to damage from earthquakes.

One feature of the process was the use of Personal Digital Assistants (PDAs) with Global Positioning System (GPS) capability to assist in performing the evaluations. The PDAs were preloaded with the modified ATC-20 damage assessment form, and evaluators filled out the forms electronically during the course of each assessment. At the end of the day, all information from the more than 150 PDAs was uploaded to a main server. Because some of the street layout of Port-au-Prince is unmapped and many residences have no formal addresses, the GPS coordinates of each structure were used as the primary means of identification. The use of GPS has also proved to be an invaluable tool in developing overall damage maps and a strategic reconstruction plan.

Evaluations were performed systematically, with each division given responsibility for evaluating all the structures within a given zone each day. Zones were determined by MTPTC using aerial maps, which were updated daily to show the status (green, yellow, red) of each evaluated structure. As each zone was completed, new ones were assigned.

As the program evolved, and as additional funding became available through USAID and PADF, the ten teams were expanded to 17. With all 17 teams working at capacity, it was possible to assess more than 3,000 structures daily. The initial target of 100,000 structures evaluated was met on 31 May 2010, and by 15 June 2010, 133,000 buildings had been assessed. By the end of August 2010, more than 250,000 structures had been evaluated. All of the structures (approximately 400,000) in the earthquake-affected area were assessed by March 2011.

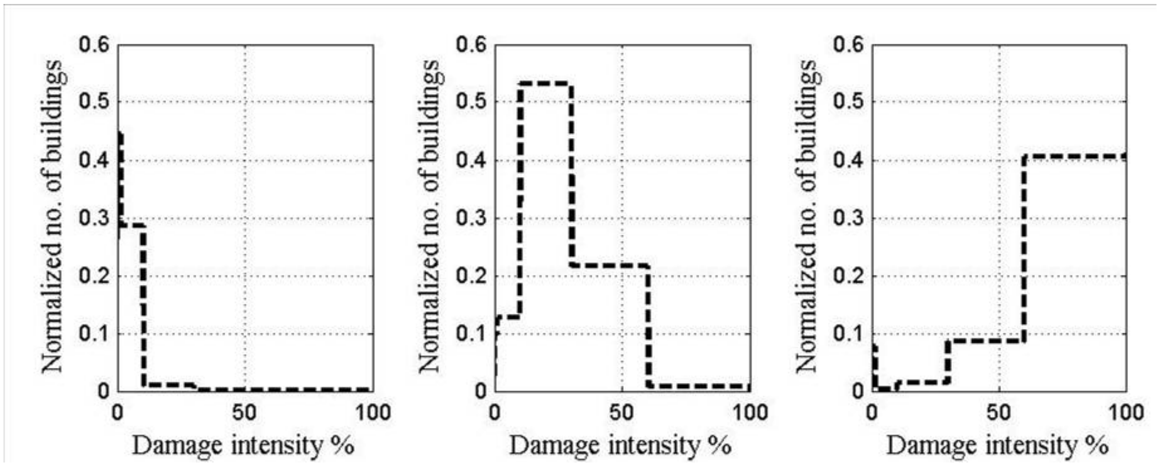
3.2 Building Damage Summary

Table 2 summarizes the number and the median (50^{th} percentile) damage estimate for the 398,829 buildings evaluated. Fifty-three percent is building stock that is undamaged and safe to use. Twenty-six percent has moderate damage and most likely can be repaired. These numbers are significant, because they indicate that approximately 80% of buildings affected by the earthquake can be immediately occupied or repaired with relative ease.

The median damage estimate was computed from the histograms of Figure 4. During the assessment process, the damage for each structure (regardless of the assigned tag) was classified in the following subsets: none (0%), 0.1% to 1%, 1% to 10%, 10% to 30%, 30% to 60%, 60% to 99%, and complete (100%). The data was then normalized for each color-tagged building, and the median damage estimate was computed.

Table 2. Summary data for damage assessment

Category	Green	Yellow	Red	Overall
No. of buildings	213,083	102,147	79,481	398,829
Percentage	53%	26%	20%	100%
Median damage	0%–1%	10%–30%	60%–100%	-



a. Green-tagged b. Yellow-tagged c. Red-tagged

Figure 4. Histograms of damage intensity for all assessed buildings

The majority of the damaged and collapsed buildings were in the low-lying districts west of the airport, which includes downtown Port-au-Prince, Nazon, Turgeau, Canape-Vert, Carrefour, and the lower portion of Delmas. By contrast, more southerly and easterly regions, in particular Juvenat and Pétionville, suffered much lighter damage (see Figure 5).

3.3 Damage classification

By far, the most common damage found among the buildings evaluated was cracking or collapse of the HCB walls, which is a natural consequence of both the lack of reinforcement and the poor material quality. Among the buildings evaluated, moderate or serious wall cracking was cited in nearly 160,000 cases, or 40% of the total assessment. Wall collapse was noted in approximately 120,000 cases, or 30% of the total. Cracking was observed to be most widespread in the lower levels of multistory buildings, where shear forces were highest. The next most common damage mode was either cracking or crushing failure of concrete columns, in about 91,000 cases, or about 23%.

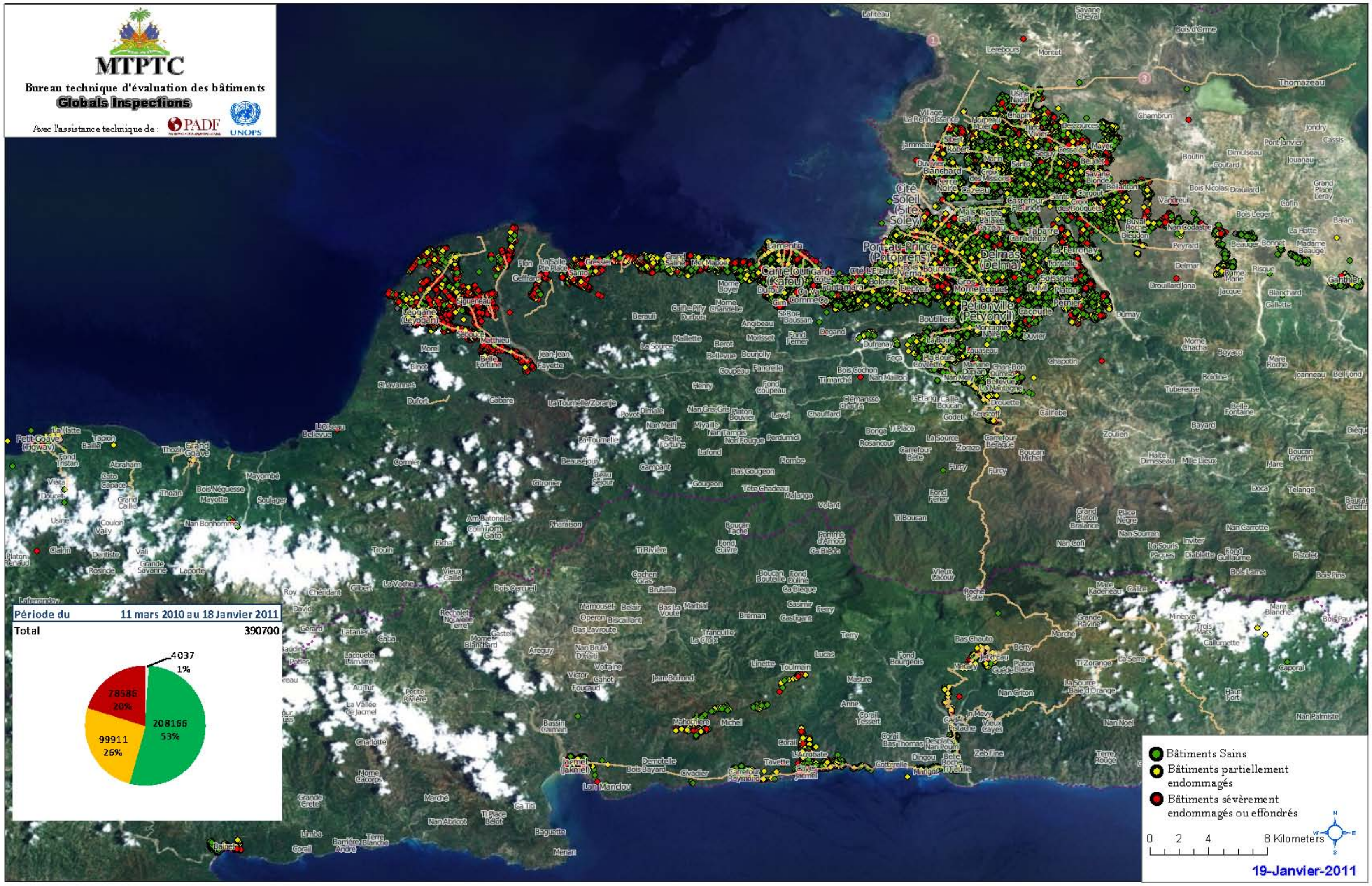


Figure 5. Map of Port-au-Prince showing the location of green-, yellow-, and red-tagged buildings as of March 2011

4 DAMAGE- AND REPAIR-ASSESSMENT PROGRAMS FOR YELLOW-TAGGED BUILDINGS

4.1 Program staff training

The damage and repair assessment program is organized by divisions. Ten engineering divisions (150 local engineers) were deployed as part of the repair assessment program of yellow-tagged buildings. Each division has a leader, and is made up of 10 to 15 assessment teams. Each assessment team consists of two Haitian Engineers. Each engineer is assigned a unique number and will maintain a list of the total number of structures they have evaluated. To ensure consistency and uniformity in evaluation, both classroom and field training are mandated before engineers can survey damaged buildings. Before the engineers can begin assessing yellow-tagged buildings for repair, they are required to spend one full day of classroom training and one full day of training in the field.

4.2 Program procedure

For each yellow-tagged building, the damage and repair assessment was conducted by a team of two engineers. During the repair assessment, one engineer will collect the data on the PDA and the other engineer will create the sketch. Both engineers observe the house from the outside and inside first and work together to indentify the observed damage and repair types, locations, and extent. Once the repairs have been identified, damaged walls and columns have been numbered and marked, one engineer records all of the required data to the PDA and the other engineer completes a sketch of the plan of the structure mapping the damage and repairs required.

The data from the PDAs is then collected at the end of the day and imported into a database. The division leader collects all the hard copies of the plan sketches and they are filed in a folder by the date that the sketch was made for future reference. A Portable Document File (PDF) is created of all of the structures that were assessed that day using an Output Form that displays the input data taken in the field. The PDFs are reviewed and checked for consistency with the information documented on the sketches. The PDAs are then gathered up and placed on the chargers for the following day of assessments. The next morning, before the engineers go out to the field for the repair assessments, the PDAs are checked for GPS functionality and checked out to the engineers, the tool bags are replenished (e.g. flashlight batteries, crayon, blue spray paint) and checked out to the engineers, and maps of the areas being assessed that day are created. The maps show the structures that have been originally evaluated with a color tag (green, yellow, or red). The teams of engineers will use the maps to search out the structures indicated with a yellow tag, or originally tagged with a yellow placard.

The damage assessment program and repair assessment Program were tested with four damaged homes in Delmas 32 in August 2010 as a pilot project. The damage and prescribed repairs were documented for these four structures. Material and costs were estimated and the repairs to these four structures were completed with local masons who were trained per the Repair Guideline.

4.3 Repair procedures

The repair procedures were developed using the information obtained from assessments. During the damage assessment phase, damage types common to the yellow-tagged structures began to emerge. These damage types included diagonal cracking of walls, out-of-plane wall failure, and concrete column damage.

One of the most common damage types was cracking of masonry walls. The cracks can be grouped into two categories: a) minor hairline (cannot easily slide a piece of paper through) cracks, which occur through both the plaster and concrete block, and b) major, wider than hairline (can slide a piece of paper through or see light from outside) cracks, which occur through the plaster and the entire width of the concrete block. The walls with major diagonal cracks require complete replacement of the wall because they have lost much of their lateral load carrying capacity. Their repair falls into three categories: Repair A1 (see Figure 6) for walls without windows For walls with window opening a slightly different repair is used.

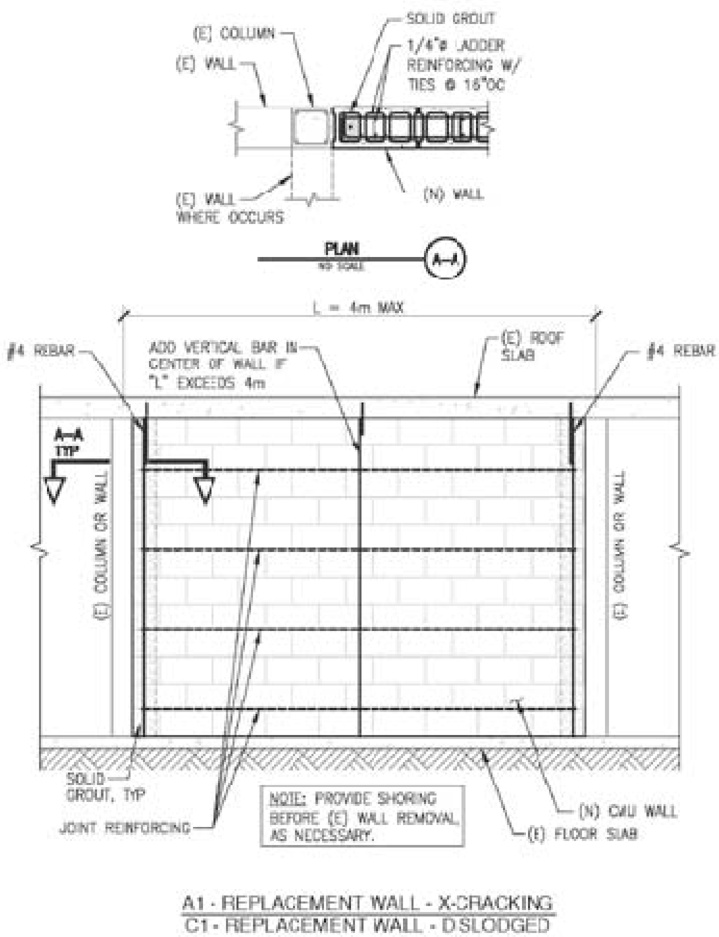


Figure 6. Repair A1, Replace Solid Wall

4.4 Implementation of repair plan and construction quality management

To implement a successful repair program for large number of buildings, a structured but flexible program that can allow good construction quality management was used. One feature of the repair work is that since the contractors are asked to use higher quality materials and new construction techniques, it is difficult for them to estimate the repair cost. Therefore, the management team decided on the repair cost. The initial award was for each contractor to repair 10 houses. Then, as part of an incentive program, the contractors that performed the repairs adequately, were rewarded with additional work, whereas, the ones with questionable quality were dropped from further consideration. It is estimated that a typical repair costs approximately US $1,000 to 2,000.

The repair program emphasizes utilizing local resources including material, contractors, and personnel. This approach serves several purposes: s) provides long-term training and establishes good engineering practices for Haiti, b) stimulates local economy and assists in development of local small businesses, and c) empowers citizens with a sense of ownership. To facilitate train and ensure uniform, low-cost, and consistent repairs, a repair manual has been developed.

CONCLUSIONS

The 2010 Haiti earthquake once again revealed the vulnerability of unreinforced masonry and nonductile concrete construction to earthquake damage. The problem was more severe in Haiti because the country was unprepared for a major earthquake; no seismic event had occurred there for more than 150 years. To address the special circumstances and damage assessment in Haiti, an international and national partnership was formed, and it has focused on inspection and reconstruction. This effort has shown that:

- An innovative assessment approach that relies on the expertise of international engineers to train national engineers in using state-of-the-art technology—such as ATC-20 and FEMA 310 protocols, PDAs, and GPS—is effective for rapid assessment and data collection.
- Such an event provides a unique opportunity to collect field data and to develop fragility functions for various building types, occupancies, and construction.
- Using a rapid assessment program as a database for reconstruction is an effective methodology. The methodology developed in Haiti can also be implemented in other parts of the world as an effective damage assessment and reconstruction method.

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