PERFORMANCE OF STRUCTURES IN THE JANUARY 2010 Mw 7.0 HAITI EARTHQUAKE

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ABSTRACT

The earthquake that shook the island of Hispaniola on January 12, 2010 devastated Haiti. The resulting damage was widespread due to the construction methods, poor material quality and lack of rigorous design procedures. Post-event reconnaissance has brought to light deficiencies in all these areas. Construction, especially residential, is typically completed by the building owner who may or may not have the necessary skills to design or build safe structures. Very few structures are designed by an engineering professional. The two most common construction materials are masonry block and reinforced concrete. Building response to the ground shaking is demonstrated through damage surveys in downtown Port-au-Prince and Leogane and specific case studies generated through reconnaissance efforts which highlight the infrastructure problems which led to the deadly structural performance.

INTRODUCTION

In the late afternoon of January 12, 2010 an earthquake struck the eastern portion of the island of Hispaniola. The epicenter was located at 18.443°N latitude, 72.571°W longitude, 15 miles southwest of the largest population center in Haiti, Port-au-Prince (USGS, 2010). Several other population centers were also severely affected. According to official estimates reported by the USGS, 222,570 were killed, 300,000 injured and 1.3 million displaced (USGS, 2010). The damage to Haitian infrastructure was severe. The primary port, the power grid and the availability of clean water were nearly completely disabled. The effect from the initial shock was compounded by the significant number and magnitude of aftershocks. People were scared to live in homes that were undamaged or lightly damaged due to the aftershocks and the observed collapses of similar homes. The Haitian people were completely unprepared for this natural hazard.

While the citizens and the infrastructure of Haiti were not ready for a major earthquake, Hispaniola has a history of significant seismicity. The island is on the boundary of the Caribbean and North American tectonic plates. On the western half of the island, two faults capable of producing Mw 7 or greater earthquakes have been identified. The southern section of the east-west fault system in eastern Hispaniola responsible for the recent event has not produced a severe event since 1860. Prior to
that, Port-au-Prince was destroyed in 1751 and 1770 by significant earthquakes thought to be generated by the same fault (USGS, 2010). Due to the long period of inactivity, the government and the citizens of Haiti were not aware of the possibility of significant earthquakes. Haitians are accustomed to significant natural disasters in the form of hurricanes. Four major storms hit the island in 2008. Given the known hurricane hazard, it would be expected that some kind of building code would exist for safety. However, this is not the case. Haiti has no building code, no inspection process, and limited engineering practice.

The most prevalent building type in Haiti, particularly in the Port-au-Prince region, consists of non-engineered, lightly reinforced concrete frame structures with concrete masonry block infill. These low rise buildings are used for single family dwellings and small businesses. Large openings for windows and reduced wall area are very common and contributed to numerous floor collapses, both at the ground level and at singular floor levels above. These building are typically one or two stories, though three or four stories is not uncommon. Floors and roofs are reinforced concrete slabs, typically four to eight inches thick with a single layer of bi-directional reinforcement. Concrete blocks are commonly cast into the slab to minimize the use of concrete. Corrugated steel over a sparse wood or steel truss is also common roof system. Many residences are constructed over a long time period, as the homeowner acquires funds or the family’s needs expand. Most are designed and constructed by the owner or a local mason.

When these building types are excited during an earthquake, initially lateral load is resisted by the combination of the reinforced concrete frame and the infill walls. Because the walls are typically not load-bearing their strength capacity is reduced because of a lack of friction development between the masonry units. Due to the lack of reinforcing, the infill walls have no ductility and therefore once cracked become non-structural mass. Following infill cracking, the concrete frame is left as the sole lateral resisting element. Interaction between wall panels and columns results in localized damage, notably in the columns. Lateral capacity of the slender columns was generally insufficient to resist acceleration demands on the structure. P-delta effects ensued, proliferating collapse. Toppling and out of plane failures of wall panels were commonplace and a primary driver many complete structural collapses. Even when they didn’t contribute to collapse, these out-of-plane wall failures caused innumerable injuries and deaths.

More detailed presentations of the damage incurred by the earthquake can be found in the many reports from the different reconnaissance teams (Eberhard et al., 2010; EERI, 2010a; EERI 2010b; Fierro and Perry, 2010). The significant damage that occurred was due to the lack of engineering design, substandard and uncontrolled construction, and poor material quality. The lack of resources applied to civil infrastructure and citizen education to prepare for the eventuality of an earthquake are evident in the post-event response. The damage that occurred will be presented in the form of local damage surveys and four case studies. Local surveys completed on the ground in downtown Port-au-Prince and Leogane provide approximations of the percentage of collapsed structures. The surveys were accomplished using photos taken along a route and pre- and post-event satellite imagery to determine the number
of structures in existence prior to the event. The four case studies highlight the different flaws in Haitian buildings.

**DAMAGE SURVEYS**

The route in downtown Port-au-Prince is shown in Figure 1. The path was rectangular with a long side of 1200 ft and a short side of 350 ft. The Presidential Palace can be seen in the bottom right of Figure 1. The total number of structures along the path was estimated to be 107. Of those structures, 30 were classified as collapsed or severely damaged. The red pushpins show the location of the 30 structures.

![Figure 1 – Damage Survey Route in Downtown Port-au-Prince](image)

A similar survey was completed in Leogane which is 7 miles from the epicenter having a population of approximately 80,000 (CityPopulation, 2010). Due to the epicenter proximity, the percentage of collapsed structures is higher. There could also be differences due to soil conditions which has not been accurately determined. The survey route in Leogane is shown in Figure 2. The route was L-shaped with a long
side of approximately 1200 ft and a short side of 360 ft. The total number of structures was more difficult to estimate due to the amount of damage. Fifty-two total structures were estimated from the photos and overhead imagery. Only four were classified as undamaged. These are shown with green pushpins in Figure 2. The number of collapsed or partially collapsed structures was approximated at 32 which results in a collapse ratio of 68%. This high collapse percentage may be an anomaly. However, compared with reconnaissance in other areas, Leogane was more severely impacted. A residential neighborhood about 4 miles from downtown Leogane experienced significant damage. Although the collapse rate was not as high, a very high percentage of structures were severely damaged.

![Figure 2 – Damage Survey Route in Leogane](image)

**CASE STUDIES**

A series of case studies is presented here to highlight the causes and effects of Haiti’s fragile infrastructure. Each case study emphasizes a different flaw in the materials, planning, construction or engineering which resulted in failure.

**UNIH UNIVERSITY BUILDING**

The UNIH University Building sits alone along Highway 2 about 3.75 miles east of the center of Leogane. This building had not been completed at the time of the earthquake. Prior to the event it was three stories tall with column reinforcing steel protruding from the top deck in preparation for a fourth floor. There did not appear to be any signs of recent construction activity at the site indicating that the project may have stalled. While the concrete frames in each direction of this building were completed for the first three floors, it still suffered catastrophic total collapse. The building was relatively simple and repetitive in plan measuring approximately 61 ft
wide (three 16.5 ft bays with a 5.75 ft cantilever at each end) x 158 ft long (nine 16.25 ft bays with a 5.75 ft cantilever at each end). Measurements were taken of both the concrete and reinforcing steel elements to try to determine the design of the building. The damage was severe enough to expose both the column and beam steel at the lowest level of the building.

The structural floor framing included a grid of 10 in. x 14 in. beams in each direction supporting a 5 in. thick slab. The in. beams were reinforced with three #5 bars top and bottom and #2 stirrups at 9 in. on center. The #5 bars were hooked at the ends of the beam with 90 degree bends and only a 3 in. hook length, substantially shorter than the 10 in. required by ACI. The typical columns were only 10 in. x 10 in. in plan and were estimated to be approximately 12 ft tall. Typical interior column reinforcement included four #5 vertical bars and #2 column ties at 9 in. on center. Typical corner column reinforcement included four #4 vertical bars and #2 column ties at 8 in. on center. In some of the columns, both the vertical and tie reinforcement consisted of smooth bars. Typical column ties had non-seismic 90 degree hooks in lieu of 135 degree hooks required by ACI in seismic regions. The reinforcing steel for both the columns and beams was fairly minimal. The only concrete masonry wall debris observed was on the back (north side) of the building and may have still been a work in progress. An ETABS (CSI, 2007) analysis model of the building indicated that the structural frame would work for gravity loads but would be highly overstressed for lateral seismic loads. The demand-to-capacity ratios assuming 3,000 psi concrete under gravity load only range from 0.64 at the corners to 1.03 at the interior columns. Under lateral loads, the same ratios range from 4.5 at the corners up to 7.3 at the exterior columns on the short side indicating a complete lack of design for lateral loads. Figures 3 and 4 show photos taken during the reconnaissance showing the collapsed structure and the exposed construction details. This case study highlights the fact that for a structure as important as a university building, rigorous design procedures including potential seismic loads was not utilized to ensure safety.

![Figure 3 – Pancake Collapse of UNIH Building](image-url)
There were examples of buildings engineered to U.S. building codes, most noticeably the U.S. Embassy compound which received no permanent damage. The only damage seen in the embassy itself was displaced ceiling tiles and popped rubber seals on a few windows. This would be an example of a building designed and constructed in accordance with the most current and highest level of seismic requirements. Another example of a seismically resistant design is a three-story reinforced concrete frame school building with construction drawings indicating design in accordance with ACI Standard 318-89. The drawings included well detailed frame elevations indicating seismic detailing. The details included tight tie spacing in hinge zones, continuity of beam reinforcing (both top and bottom steel), and code compliant column vertical reinforcing. The drawings also indicated details for isolating CMU partition walls from the concrete frames to ensure ductile behavior and limit masonry cracking. There was however damage in the columns, typically in the middle third, and throughout much of the CMU partition walls. A majority of this damage appeared to be the result of poor quality control in the concrete and masonry materials and lack of inspection needed to ensure conformance to the details specified in the construction documents. Two notable discrepancies were column ties that did not match the seismic ties indicated in the drawings (90 degree versus 135 degree hooks) and CMU partition walls that were not isolated from the frames. Figure 5 shows the damage that occurred which highlights the lack of attention to the details during construction. This study illustrates the need for building officials to ensure the as-built structure conforms to the well-detailed design documents.

Figure 4 – Exposed Connection Details of UNIH Building

“ENGINEERED” SCHOOL BUILDING
HANDS TOGETHER SCHOOLS

Many buildings in Haiti are combinations of multiple structures of different shapes, roof heights and number of stories. This results from the economic necessity to use existing structures as support for or components of new buildings. This method can be effective and efficient if the appropriate construction details and structural designs are implemented to account for the additional forces on the existing structural elements and dynamic differences between building sections. This could be accomplished through strengthening or by providing seismic expansion joints to allow the two sections to respond at the individual fundamental frequencies. The typical practice in Haiti is to use the wall of an existing structure as a wall for a new structure thereby reducing construction costs. This practice was commonly observed during reconnaissance missions. The post-event detailed structural inspection of eight school sites and one medical clinic run by Hands Together, a nonprofit organization based in the United States, provided multiple examples of this behavior. All of the Hands Together sites are in Cite Soleil.

The St Francois compound, located at 18.5871° north 72.3276° west, is a high school complex. It consists of six buildings, many of which are connected to one or more adjacent structures. A high resolution Google Earth image of the compound is shown in Figure 6. The letters shown in the figure are used to reference the different structures. All the campus buildings are constructed of reinforced concrete frames with masonry infill. Building A is a two-story classroom structure. It experienced very limited damage during the earthquake in the form of masonry wall cracking and damage to the stairway leading to the second story. It is the only structure that is not connected to any other building. Building B is a classroom building. The first two
stories are enclosed while the third floor is a covered patio supported by reinforced concrete columns and a half-height masonry wall. Building B itself experienced some wall cracking. The most significant damage occurred in the stairwell which connects buildings B and D at the second and third story. The damage to the second floor slab is visible from above in Figure 6. Due to the difference in orientation of buildings B and D, the stairwell became the fuse element between the two structures and was severely damaged during the ground motion (See Figure 7).

Building C, the newest in the complex, is a two-story classroom building. Future expansion upwards is expected as reinforcing cages above the roof slab were installed showing the low level of reinforcing in the frame elements. The building was minimally damaged in the form of cracked masonry around the windows and doors. The only severe damage was at the interface with buildings C and D. Building D is the largest building on the complex. The bottom two stories are enclosed classrooms. The top floor is a covered patio with reinforced concrete columns. It is attached at both ends to the adjacent structures. This was the most seriously damaged building in the complex. It was damaged at both interfaces with adjacent structures. The large difference in plan dimensions resulted in full depth slab cracking at the interface between buildings D and E. Building D also experienced significant cracking of masonry walls and serious damage to the reinforced concrete columns and beams supporting the third floor timber trussed roof. Some of this damage was due to the elimination of every other block just below the slab to allow for lighting into the class rooms. This resulted in early fracture of the single blocks which then transferred the load to other internal walls which also had large voids. Buildings E and F experienced...
minimal damage with the exception of the previously mentioned damage at the joint between D and E. Overall, the compound performed well. Had the structures not been linked together or been linked to account for movement, the most significant damage could have been avoided.

This case study as well as many other examples of this type of performance are prevalent in Haiti. A medical clinic located in the same region had a single story addition supported on the walls of an existing two-story structure. The single story separated from the two-story structure during the ground shaking, leaving the roof very close to collapse. Sainte Anne’s elementary school was another case where the common wall of two different buildings experienced severe cracking due to different plan geometries and an offset in roof height. The practice of building onto existing buildings without considering transfer forces or providing a movement joint resulted in a significant amount of damage. In these cases, it was not fatal, however the repair costs are significantly higher due to the added damage and there are likely cases where this type of behavior was fatal.

**PRE-ENGINEERED METAL BUILDINGS**

Most industrial or warehouse buildings in Haiti are constructed of long span steel trusses supported on masonry infilled reinforced concrete frame walls. In the United States many of these buildings would be pre-engineered metal buildings (PEMB). Due to the cost and availability of steel in Haiti, they were the exception. The typical construction of PEMBs in Haiti utilized a masonry façade. During reconnaissance efforts, several PEMBs were encountered and the damage to each of them was similar. The masonry façade failed while the primary structural framework was
undamaged. Photos of this failure are shown in Figures 8, 9 and 10. Figures 8 and 9 are pictures of a retail building located across the street from the U.S. Embassy. All five of the front sections detached from the framing although some of them had not fallen. The building is being repaired and the masonry exterior walls are being replaced by insulated metal sheathing. This upgrade will make this structure much more resilient for future events. This out of plane failure of the masonry on the gable end of PEMBs was common on nearly all metal buildings seen during the reconnaissance. Figure 10 shows wind girts attached to a masonry that were damaged during the event by out of plane wall action. The building shown in Figure 10 also experienced the out of plane wall failure on the gable end wall. PEMBs in Haiti did not experience dramatic structural failure with the exception of the warehouse building at the Port-au-Prince port which failed due to significant lateral spreading between the foundations. The consistent failure mechanism of the masonry façade highlights the fact that even with a pre-designed, resilient structural system, not having an engineering professional design all aspects of a structure and including proper detailing for attachment of non-structural components can result in dramatic failure with the potential for significant fatalities.

Figure 8 – Masonry Wall Failure of Retail Metal Building
CONCLUSION

Haitian infrastructure was completely unprepared for the earthquake which struck on January 12, 2010. With rare exception, buildings are not planned, designed or constructed with the necessary detailing to survive significant seismic events. While some buildings may have been designed, the necessary channels are not in place to verify compliance during construction. The damage surveys and case studies presented here highlight many of these deficiencies. In order to avert a disaster of this magnitude in the future, the people of Haiti need to be instructed in the proper
material quality, planning, design and construction of all infrastructure, especially during recovery and rebuilding from this event.

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REFERENCES


