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Procedia Engineering 14 (2011) 23–31

Procedia Engineering

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The Twelfth East Asia-Pacific Conference on Structural Engineering and Construction

Behavior of Engineer Constructed Facilities in the Haitian Earthquake of January 12, 2010

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Abstract

The earthquake in Haiti was rated as M_w = 7.0 resulting in a reported 230,000 deaths and over one million in shelters while a comparable U.S earthquake Loma Prieta M_w = 7.1 caused 63 deaths and left about 1000 homeless. Many reports have attributed this disparity to the great economic, social and cultural differences between a third world and a leading country. Nevertheless there are lessons that can be drawn for the Haitian earthquake that are applicable to more advanced countries.

The paper considers several examples of constructed facilities in the commercial, industrial and institutional sectors that were built with varying degrees of engineering technology, both domestic and imported, and were visited about three months after the event. While detailed engineering information was not available to the authors, physical examinations, published formal reconnaissance reports and comments by on-site personnel provide the basis for these observations. In addition to structural damage, the behavior of non-structural components, particularly mechanical and electrical equipment, was of particular interest.

Keywords: Earthquake Behavior; Structural Response; Structural Failures; Nonstructural Damage

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1. Introduction

The Republic of Haiti is located in the NE Caribbean between Puerto Rico to the east and Cuba and Jamaica to the west. It shares the island of Hispaniola with the Dominican Republic. The country has a population of about 9 million people with almost 3 million in the capital Port-au-Prince. Haiti is the poorest country in the western hemisphere with perhaps 80% of the population living below the poverty line. The country has experienced natural disasters, primarily from hurricanes and political instability for decades, and was ill-prepared for the effects of a strong earthquake. On January 12, 2010, a M_w 7.0

doi:10.1016/j.proeng.2011.07.003

earthquake resulted in a reported 230,000 deaths and another 300,000 injuries. Hundreds of thousands are still living in temporary shelters and both governmental and non- governmental relief organizations continue to be challenged by the enormity of the destruction.

During the authors' site visit approximately 3 months after the earthquake, many of the damaged structures and facilities remained largely undisturbed due to a lack of heavy equipment to clear the wreckage and a road system to remove it. It was possible to examine portions of partially damaged engineered structures to document and evaluate the performance of key structural components and non-structural equipment. The complete list of structures visited and the estimated damage levels will be presented in a future paper. While the construction practices of Haiti have been widely criticized in comparison to western standards, there are interesting and valuable lessons to be learned from the performance of the engineered constructed facilities that are not necessarily unique to the location. Critical structural damage was attributed to inadequate detailing in the structural elements, poor quality concrete, soft or weak stories and smooth reinforcing bars and other inadequacies that have been identified numerous times in other earthquakes around the world (Eberhard, et.al, 2010).

The purpose of this paper is to examine some of the damaged and failed components in surviving engineered facilities, to identify the contributing design deficiencies, and also to point out some cases where proper practices were used with satisfactory results. Because much of the damage to structural members has been attributed to shear failure, it is helpful to briefly note the basic principles of shear design in reinforced concrete. This is done as the cases arise. Also some comments are made regarding the performance of non-structural items such as electrical equipment.

2. Reinforced concrete buildings

2.1. CDTI hospital

This building is a modern reinforced concrete frame structure with masonry infills. The overall damage was evaluated as moderate. The masonry walls were supposed to be separated from the adjacent columns but this was not always the case. Partial height walls under windows restrained the adjacent columns, which resulted in columns with an effective unrestrained height of the windows, the classical short or captive column effect. This is best understood by the following short derivation.

The shear from the lateral loading in a structural member ab with length L_{ab} can be evaluated from the simple equation:

$$V_{ab} = (M_a + M_b) / L_{ab} \qquad (1)$$

Many modern design procedures are based on the shear evaluated from taking M_a and M_b equal to the member capacity provided by the design, rather than the values determined by an analysis under specified loading conditions. The shear is essentially constant along the length of the member while the moments are maximum at the ends and much smaller near the mid-point if the member is bent in double curvature. If the member is a beam rather than a column, the effects of gravity loading may be added but the behavior and design procedures are similar. If the design is based on the moments determined from the analysis, then the design shear and the reinforcement provided might well be less than that corresponding to the ultimate end moments.

The column shown in Figure 1 may have developed up to the moment capacities M_a and $M_b = M_u$ at both ends. However, the restraint of the walls forces the bending with a reduced length $L < L_{ab}$, moving the hinge into a region that was perhaps not detailed for this action. The magnification of the shear force based on the full length L_{ab} in Equation (1), apparently caused the column to fail due to inadequate shear reinforcement. The captive columns are being retrofit with steel jackets.

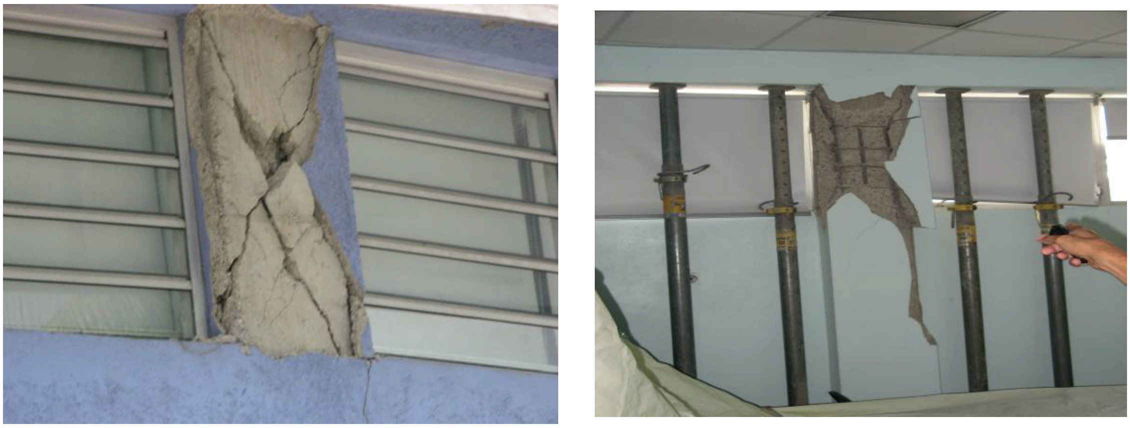

Figure 1: Failure of Captive Column, Exterior and Interior

2.2 Digicel buildings

The Digicel tower, on the right in Figure 2, is a 12 story RC dual wall-frame system and is the tallest engineered building in Port-au-Prince. The company provides mobile phone communication, which has been extremely important during the recovery.

Figure 2: Digicel Buildings

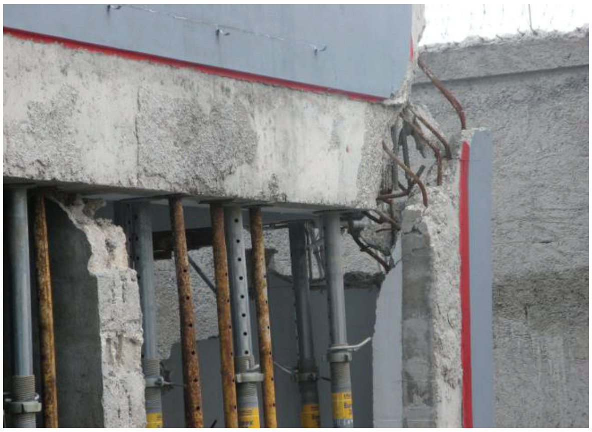

Figure 3: Beam-Column Joint Failure

The adjacent data center on the left in the photo is a RC moment resistant frame. While the damage was regarded as moderate in the tower, the data center was severely damaged. Moreover, a reinforced concrete frame hospital building with masonry infills directly across the street essentially collapsed (EERI, April, 2010) so the region likely experienced moderate to strong motion. Because of their different heights, the periods of the two Digicel structures and the resulting seismic demands are likely quite different but each of the structures has deficiencies in the details that are revealed in the remaining damage.

In the low-rise structure, another type of shear failure was observed in a beam-column joint, as shown in Figure 3. Such a joint needs to transfer the forces from the top reinforcement of the beams that frame into the joint through the joint and into the columns. While the shear strength of such joints is enhanced by the vertical compression from gravity loading and the confinement provided by perpendicular beams framing into the joint, there may still be a need for special horizontal reinforcement through the joint for seismic loading. Such reinforcement is uncommon in conventional construction and is absent from the joint shown in Figure 3. Closely related is the failure shown in Figure 4, where the opening is close to the edge of a shear wall with an inadequately reinforced boundary element.

A classical failure observed in this structure is the damage produced by the adjacent low-rise impacting the lower floors of the high-rise. This is known as pounding, as shown in Figure 5.

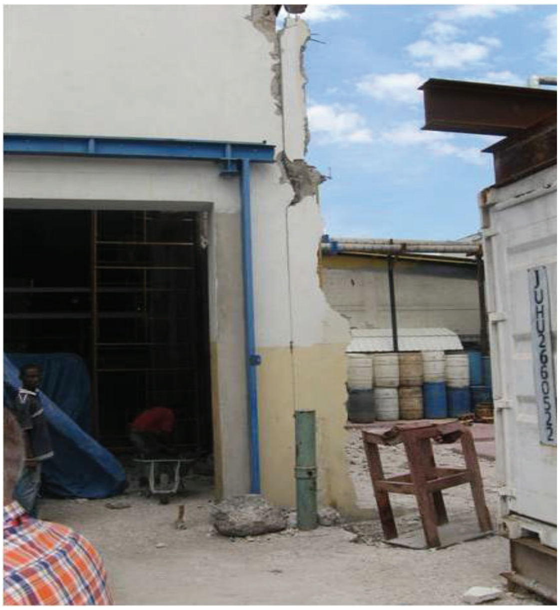

Figure 4: Interrupted Shear Wall

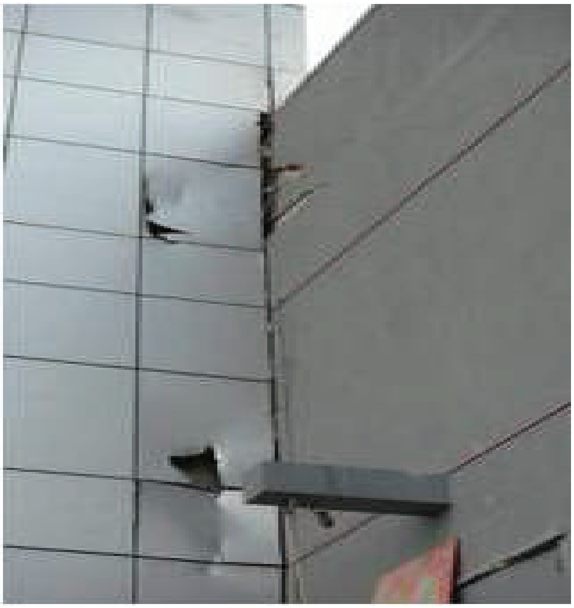

Figure 5: Pounding Failure

2.3. Union School

The Union School consists of two three-story reinforced concrete frames that were reportedly designed in conformance with ACI 318-99. The damage is regarded as severe and little repair was evident at the time of the inspection.

In this building, there is also short column damage as previously described for the CDTI Hospital. Also there are a number of wall failures due to shear-induced diagonal tension, as shown in Figure 6.

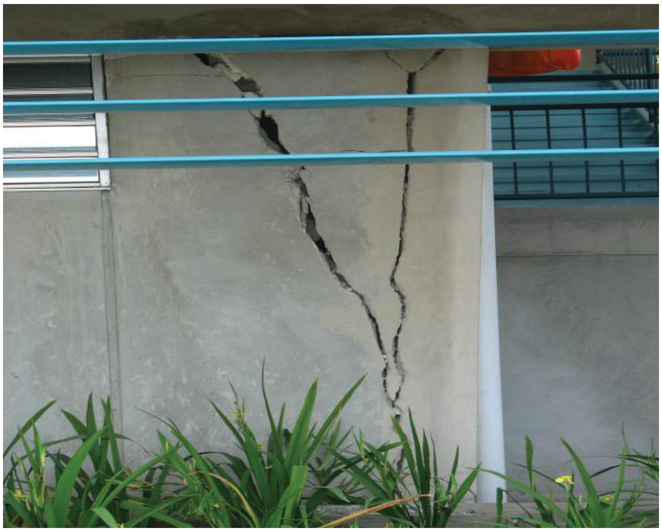

Figure 6: Wall failure due to Diagonal Tension

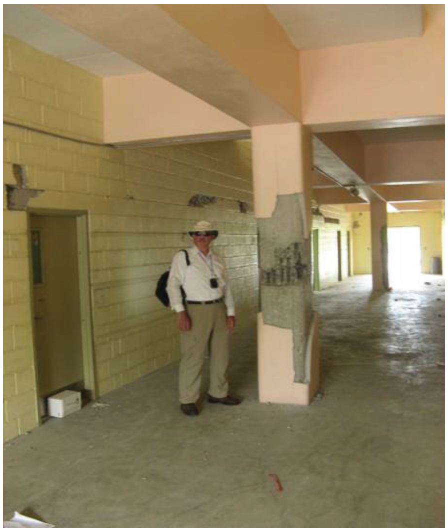

Figure 7: Column Failure at Mid-Height

Figure 8: Close-up of failure zone

Figure 9: Confined core

An interesting column failure is shown in Figure 7. The failure occurred in the mid-height region of the column, apparently because the transverse reinforcement spacing was larger in this region relative to the transverse spacing at the ends of the column (Eberhard, et al, 2010). In addition, it was observed that there was also a lap splice for the vertical reinforcing steel located in this region, as shown on Figure 8.

Another tied column is shown in Figure 9. Despite the spalling, this column joint performed satisfactorily with the tie spacing likely adequate to confine the concrete core and retain the vertical load carrying capacity.

2.4 University Adventiste

Overall, the damage in this complex was regarded as moderate and classes were resuming in selected buildings at the time of the visit.

The large auditorium on this campus was damaged as shown in Figure 10. This damage is attributed to the large stiffness difference between the full height main structure and the structure covering the open plaza, imparting severe loading at the connection. The combined building appears to be highly unsymmetrical, introducing torsional effects at the extremities. Also the dynamic properties of the two parts of the structure are different and they may have responded primarily as individual elements rather than as a combined system, putting large demands on the junction region.

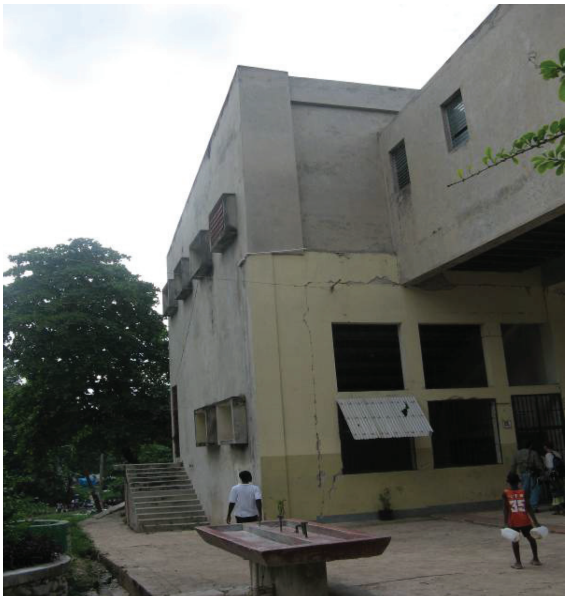

Figure 10(a): Failure of Wall in Auditorium

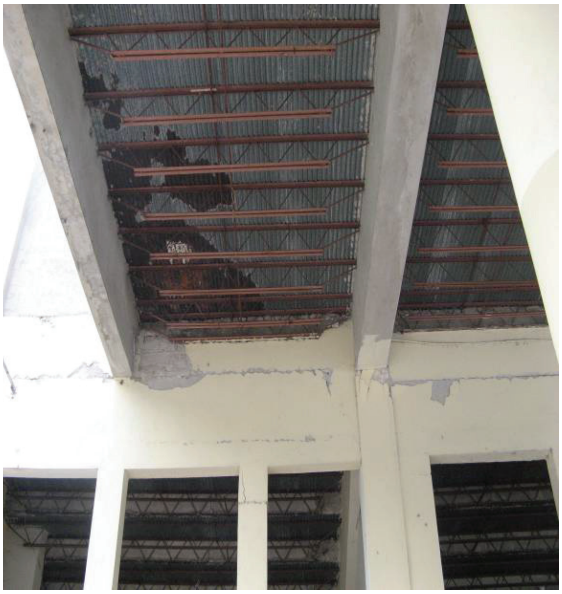

Figure 10(b): Close-up of failure zone

3. Industrial facilities

3.1 Prestige brewery plant

This plant was up and running after having suffered minor but disruptive damage that shut down beer production for eight weeks.

Several large steel fermentation tanks were damaged and repaired as shown in Figure 11. The repair at the base indicated that the tank may have suffered classical elephant's foot buckling but this was not confirmed. There were also failures at the base of some water tanks as shown in Figure 12 and an apparent overstressing of some of the steel moment frames as shown in Figure 13.

Figure 11(a): Repaired Steel Tank

Figure 11(b): Repair at Base

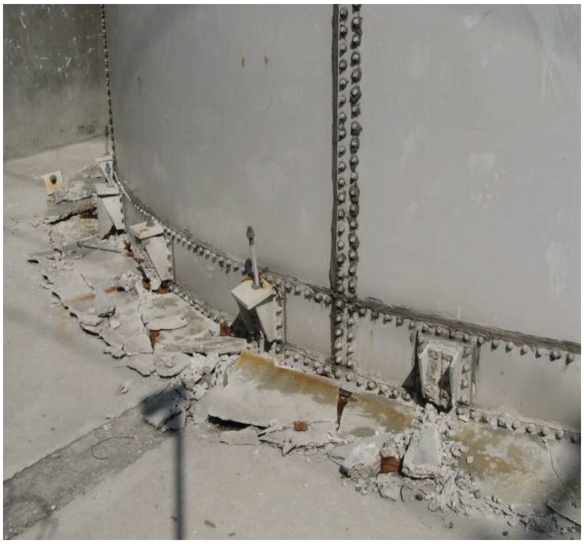

Figure 12: Base Attachment Failure

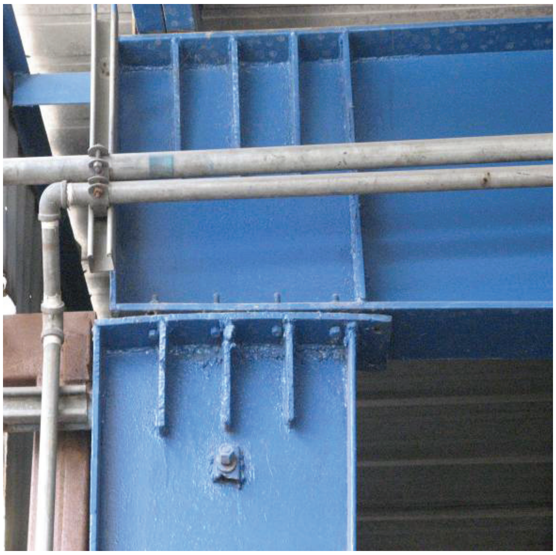

Figure 13: Deformed Joint in Steel Frame

3.2 Central Petion power plant

This modern power generation plant contains a wide variety of mechanical equipment including diesel generators, substation transformers, control cabinets, piping and fuel storage tanks. Overall, this plant fared well in the earthquake because most equipment and piping systems were well anchored and/or laterally restrained, with only minor damage to a circuit breaker, a water tank, and fence wall. The plant was down was down for a minimal period of time with very limited impact on the delivery of the electricity. An adjacent older power plant, which was not accessible to the team, was purported to have sustained significant damage. It was reported that several substations that receive the power from the Central Petion Power Plant were damaged, which limited the amount of power that the plant could send to the grid.

A failure near the end of the somewhat unusual masonry wall that encircles the plant is shown in Figure 14. This type of wall with concrete trees as vertical elements is common in Haiti. An overturned fuel storage tank is shown in Figure 15. Other similar tanks survived the earthquake.

Figure 14: Failure of Masonry Wall

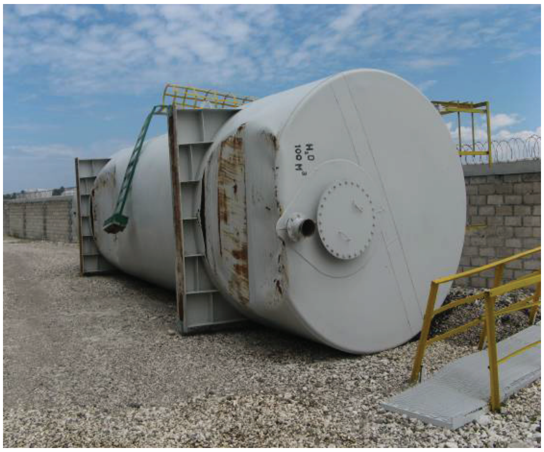

Figure 15: Overturned Fuel Storage Tank

4. Electrical equipment

Facility electrical power distribution and control equipment, as well as system design and installation methods, surveyed at all sites were typical of what would be found in similar facilities in North America. The origin of manufacture was North America for a majority of the power system components (switchgear, transformers, conduit, etc.) at all locations. Some minor equipment damage was noted and a detailed listing will be presented in a future paper. While there were no strong motion records, estimates of the ground accelerations at the sites surveyed from damage data were compiled. Various types of electrical equipment were checked against the fragility curves provided in Porter, et al., 2010. In most cases the probability of failure at the estimate ground acceleration was low.

Uniquely different from North American facility electrical systems was the common use of on-site diesel generators as the normal source of power. While all facilities had provisions for service entrance connection to the public utility power grid, very few used it as a normal source of power, even before the earthquake, due to reliability and cost. As a result the North American paradigm of "emergency generator" does not exist in Haiti since on-site generation is frequently the normal source of power. This heavy reliance for user owned diesel generators had significant implications for post disaster return to operational status for critical facilities due to interruptions in fuel availability and delivery.

5. Conclusions

An examination of several engineered facilities in Port-au-Prince that survived the earthquake revealed structural damage that can be attributed to inadequate design and a lack of seismic detailing. Non-structural damage, especially to electrical equipment, was consistent with the estimated level of ground shaking. Most of the structural failures discussed have been seen many times in past earthquakes in other locations around the world and can be remedied in future structures by adopting current seismic design methodology with adequate construction supervision. Inasmuch as a massive rebuilding of Haiti will be necessary to restore the functionality of the country, it is important to insist on high standards for seismic design and construction in order to avoid a repeat of the disaster.

Acknowledgments

The support of the US National Science Foundation under the RAPID Projects Program, Award Number 1034794, is gratefully acknowledged.

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