EARTHQUAKE HAZARD CENTRE NEWSLETTER

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Contents

EDITORIAL: ENCOURAGING NEWS FROM HAITI

This newsletter features new information that has emerged from the rubble of the January 2010 Haiti Earthquake. Earthquake Spectra has just published a special issue which covers many different aspects of the quake, and the two articles summarized herein report on observations of damage to buildings, mainly houses. This material, which is very relevant to many developing countries as the vulnerability of construction in Haiti is mirrored world-wide, contains one main message that is in fact very encouraging. A simple change in construction technique alone, without any additional materials, can greatly improve the seismic resistance of low-rise construction.

The first article begins by reporting on the state of building materials present in Haitian buildings. There are no surprises for we read that the materials are generally sub-standard. Unwashed beach sand has caused corrosion of reinforcement, aggregates are either too weak or too smooth as in rounded river gravel for the cement paste to adhere to, and too much water is used in the concrete mixes leading to low concrete strengths. The reinforcing steel is also problematic in that it is mainly undeformed, is bent multiple times and has a low ductility. To make matters worse it is often poorly placed. Many of these deficiencies in reinforced concrete are still commonly observed. Those sections of the articles summarised in this newsletter concentrate on low-rise building construction methods.

As in many countries, typical construction practice involves the construction of RC frames that are then infilled with hollow concrete blocks. The columns and beams of these frames have small dimensions so as to fit within the thickness of the blockwork walls, and the blockwork itself is generally of poor quality and is not grouted and reinforced. As explained in the article, this type of construction was very prone to collapse during the earthquake with most infill walls failing under face-loading and once that source of in-plane bracing was lost, complete collapse followed.

However, what is very encouraging is that where the blockwork walls were laid *before* casting the concrete columns, the bonding between the cast-in-place columns and blockwork was sufficient to almost prevent face-load collapse. And this improved performance was observed even if the beam was not cast directly on top of the block walls. This improved construction is a move towards “confined masonry construction” which is currently being promoted by the World Housing Encyclopedia and other organisations. The experience in Haiti certainly suggests that even its partially confined masonry is a far superior method of construction than infilled reinforced concrete frames.

So here is more evidence of the importance of us adopting confined masonry construction. There is plenty of educational material on this approach, which is almost unknown in some parts of the world, from the World Housing Encyclopedia website. Free downloads are available. The really good news about confined masonry construction is that it doesn't require more materials. Basically, it's just about changing the sequence of construction, and that change, as illustrated in Haiti, makes all the difference in the world.

Virtual Site Visit No. 26: Low-rise RC infill frame construction, India

One of the key observations from the articles in this newsletter is the poor seismic performance of moment frames infilled with unreinforced masonry. The main reason is the lack of bond between smooth reinforced concrete columns and the infill. The authors who analysed the devastation in Haiti note that if infills are placed first, and then the columns and beams cast, the seismic performance is greatly improved. This type of construction is "Confined Masonry"

The four sites shown below are located in India. In every case the buildings are of RC infill frame construction. In those buildings under construction masonry infill is placed against smooth RC columns (Figs. 1-4). The bond between masonry and columns will be poor, and between masonry and the underside of beams, even weaker.

Most of these buildings, because they are low-rise could be constructed in confined masonry. At least in the longitudinal directions confined masonry is entirely feasible as there are many unpenetrated wall panels to act as bracing panels. However in the transverse direction additional bracing walls would probably need to be inserted to provide sufficient lateral strength. If that were not possible, then transverse loads would have to be resisted by RC moment frames.

Fig. 1. Masonry infills under construction within the RC frames.

Fig. 2. Infill walls are about to be laid between frame members.

Fig. 3. If constructed of confined masonry, the longitudinal walls would provide excellent seismic resistance.

Fig. 4. The seismic performance of these houses would be much improved if constructed using confined masonry.

SUMMARY OF "DEVIL IN THE DETAILS: SUCCESS AND FAILURE OF HAITI'S NON-ENGINEERED STRUCTURES" by Lang, A and Marshal, J. From Earthquake Spectra, Vol. 27, No. S1.

INTRODUCTION

On 12 January 2010, a Mw 7.0 earthquake struck the southern region of Haiti, 16 km from the populous capital, Port-au-Prince. The number of reported fatalities varies widely: the government of Haiti estimated 316,000 were killed while an unpublished 2011 report commissioned by the U.S. Agency for International Development estimated the death toll was much lower, between 46,000 and 85,000. A year after the earthquake 810,000 remained displaced. Damage assessment studies reveal that 20% of structures in the Port-au-Prince region were severely damaged or destroyed and another 27% require major repairs. Total damages and losses are estimated to be 7.8 billion USD, equivalent to 120% of Haiti's 2009 GDP. In 35 seconds of shaking, this modest seismic event became one of the deadliest and costliest natural disasters in modern history.

According to damage survey results, over half of residential homes remained unscathed, yet the quality of building materials and construction techniques for these buildings did not vary significantly from those that had collapsed. The authors' observations confirm these data. Undamaged houses were constructed immediately adjacent to others of nearly identical construction that were completely destroyed. This manuscript attempts to explain how these drastically different outcomes resulted.

Historically, traditionally assembled confined masonry has performed well in global earthquakes with little documentation of collapse. Thus, capturing failure mechanisms of these systems was a prime motivation for reconnaissance. Field observations revealed that buildings assembled similar to confined masonry, with the masonry wall erected prior to the frame, did not have load bearing walls. This is an important characteristic of confined masonry which affects the load transfer mechanism. Nonetheless, these systems still performed well. The staggering of masonry units within the column cavity and concrete adhesion resulted in increased bond and continuity between the wall panels and adjacent columns. Construction materials and craftsmanship were of such poor quality, however, that small deviations from this assembly technique resulted in structural failure similar to infilled frame structures. Traditional infilled frame systems lack a bond between the masonry walls and frame elements. These systems performed poorly in the earthquake and account for the majority of structural collapses and fatalities.

PRE-EARTHQUAKE HOUSING SITUATION

The predominant structure type seen in Haiti is a low-rise, nonengineered building constructed of unreinforced masonry walls framed by slender concrete columns. Hollow concrete block is the primary masonry unit used; other types, including fired clay brick were not observed. Heavy concrete slabs are used for floors and roofs. Other roofing methods include sparse wood frames overlaid with lightweight corrugated metal and concrete blocks cast within the slab. The latter exploits the voids of concrete block, reducing the volume of concrete used.

Most buildings are one to three stories and are used for single family dwellings or small businesses. Apartment buildings did not appear prevalent; most families reside alone in one house regardless of income. Most homes are designed and constructed by the owner or a local mason. Because residences are commonly constructed over time as funds are acquired, construction is inconsistent and haphazard. Load paths are frequently discontinuous and member sizes insufficient, particularly columns when additional floors are later added. For these reasons, Haiti's archetypical construction is referred to as "non-engineered."

BUILDING MATERIALS

CONCRETE MATERIALS

Cement:

Based on the authors' observations of active construction sites and interviews with builders and suppliers, Type I Portland cement is used exclusively for all concrete elements, including hollow concrete blocks, columns, beams, roof and floor slabs, and mortar for foundations and wall panels. All cement is imported into Haiti; in-country production ceased following the privatization of the public cement company, Cimint d'Haiti in 1997.

Sand:

Unwashed beach sand was regularly used in concrete mixes in the past. The high salt content facilitates corrosion of steel reinforcement and can lead to complete loss of tensile strength. A past campaign by the government to discourage the use of beach sand appears to have been successful. Residents are aware it is an objectionable building material and its use appears to have ceased and been replaced with river sand. Unfortunately, most buildings subjected to the January 2010 earthquake had been constructed with beach sand. Among other reasons, corroded reinforcement contributed to structural failures because of a loss of tensile capacity of the reinforcement. While river sand is a good alternative to beach sand, aggressive mining of it comes with environmental consequences. Its removal reduces the amount of sediments transported to river mouths and beach estuaries, diminishing natural coastal barriers.

Aggregate:

Haiti has large natural deposits of limestone throughout the country. Because of its abundance, limestone is commonly used for both small and large aggregate. It is quarried from the hills above Port-au-Prince, the largest of which, "La Boule," produces a light colored weak chalky limestone. According to past USGS investigations, limestone from this area contains rudists, tubular mollusks from the Cretaceous. The shells of these organisms are composed of calcite and aragonite, forms of calcium carbonate that compose limestone. A USGS cement specialist hypothesized that if these shells are fragile, then they are the likely cause of the weak chalky characteristics. Alternatively, the sedimentary environment in which the limestone formed may have prevented natural cementing of the material. Haitian builders take advantage of limestone's natural cementing properties by using less cement in concrete mixes in place of more limestone aggregate. This practice is particularly common in concrete block manufacturing. The combined decreased quantity of cement and increased quantity of limestone, which has a lower compressive strength than rock, reduces the overall compressive strength of typical concrete in Haiti. A month after the earthquake, Haiti's public works ministry prohibited the use of La Boule material for construction. They instead recommended using sand and rocks from river beds. Despite this decree, piles of limestone aggregate were frequently seen at construction sites during reconnaissance

Proportions and Placement:
Along with poor quality aggregates and insufficient cement, concrete mix proportions were frequently observed to have high water content in order to ease workability and generate more concrete volume, thus lowering costs. As was commonly observed, the concrete bond strength was incapable of fracturing through large rock aggregate
As was frequently observed, concrete is commonly mixed on the ground at construction sites resulting in heterogeneous batches and inconsistencies between batches. The concrete is shoveled directly into formwork or block molds with no vibration or consolidation effort to remove air voids. Large voids were commonly seen as big as a softball in finished construction. In larger or higher-end projects, a small mixer or concrete truck was observed with a bucket brigade transferring the concrete for placement. Again, no observed effort was made to consolidate.
Concrete blocks are commonly produced at or near construction sites. The blocks are formed, extracted, and dried rather than cured. The drying process generally occurs in a large open area with no cover, resulting in limited hydration of the concrete. Typical block dimensions are 15.75 inches x 7.0 inches x 6.0 inches. Shell thickness is approximately 1 inch. Grouting of concrete blocks was never observed.

STEEL REINFORCEMENT

Steel reinforcement in Haiti is imported in large, tightly bound coils approximately 3 feet in diameter. The coils are straightened and sold in lengths of 30 feet; these pieces are then bent in half for transportation. Once on site, the reinforcement is cut and re-bent into workable geometries. All told, steel reinforcement may undergo three large deformations before placement. Most of the reinforcement is sold as "ungraded," although Grade 60 rebar can be specially ordered. According to interviews with builders, when the price of steel increased globally in 2008, diameters of 1/2 inch and 3/8 inch bar decreased. Although called "1/2inch," the actual diameter is less than 7/16 inch.

Historically, many of Haiti's low-rise structures were assembled with smooth reinforcement. The availability of smooth bar for purchase ended in 2000. Although deformed rebar is the only option for new purchase today, reinforcement of any kind, including smooth, was seen meticulously extracted from destroyed buildings to be used for rebuilding following the January 2010 earthquake.

These testing results suggest that the problem of structural performance is not attributable to the strength of available steel reinforcement. Instead, strain capacity, insufficient area ratios, use of nondeformed bars, and poor detailing were the primary contributors to structural failures.

OVERVIEW OF INFILLED FRAME AND CONFINED MASONRY SYSTEMS

Traditional infilled frame construction consists of reinforced concrete frames with masonry infill walls. The frame elements—columns, beams, and slabs—are poured and finished before masonry is placed. This construction type is identifiable by a clean delineation between masonry walls and columns. Under well engineered circumstances the frame is moment resisting, designed to carry all vertical and lateral forces. The masonry wall panels are normally considered non-structural elements and are not included in capacity analysis, despite well documented evidence of their influence on structural response. Infilled frame construction results in a lateral force resisting mechanism composed of two independent systems: a shearwall and a moment resisting frame. Dissimilar stiffnesses of the two systems commonly results in localized damage to the columns and wall during in-plane action (see Figure 5). Out-of-plane, toppling of the wall panel is common.

Confined masonry structures resemble infilled frames but with a

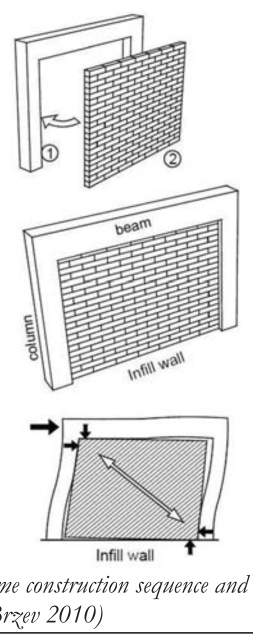

Fig. 5. Infilled frame construction sequence and lateral force resisting force mechanism (Brzev 2010)

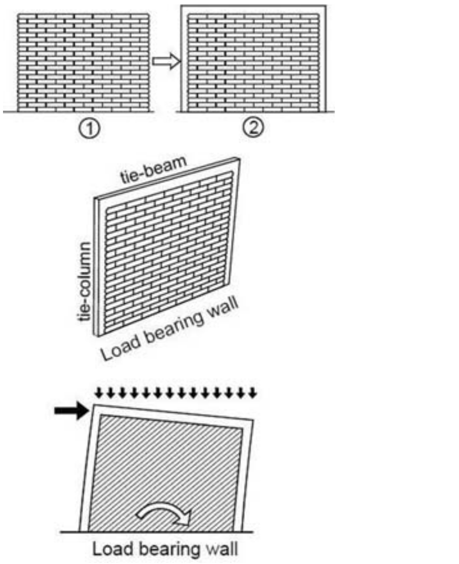

Fig. 6. Confined masonry construction sequence and in-plane lateral force resisting mechanism (Brzev 2010).

reversed construction sequence, resulting in a significantly different structural response. The masonry walls are first assembled then used as formwork for the surrounding frame elements, including columns, beams, and slabs. This seemingly minor construction difference from infilled frame systems results in vertical load bearing on the wall and larger friction force development among the masonry units. Unlike infilled frame construction, confined masonry resists inplane lateral loads with the combined mechanism of a moment frame and shearwall. Inplane loads are transferred to the masonry wall by frictional contact at the column-wall and beam-wall interfaces (see Figure 6). Regarding the former, the staggering of masonry units in a saw-tooth manner within the column cavity produces a mechanical connection similar to multiple shear keys. Because the masonry wall is used as formwork, the column boundary is prescribed by the saw-toothed pattern. A research effort is underway by the primary author to quantify the effect of this interface on lateral load transfer.

Confined masonry also performs well in out-of-plane loading particularly in comparison with infilled frame construction. Vertical load bearing on the walls improves force transfer across the beam-wall and column-wall interfaces. The increased compressive stress reduces tensile stress and strain across the wall panel and facilitates two-way bending (see Figure 7). Arching action is achieved because of the mechanical saw-toothed connection at the column-wall interface.

INFILLED FRAME AND CONFINED MASONRY SYSTEMS IN HAITI

As highlighted in previous sections, Haitian construction practices are haphazard and of poor quality. Builders often use different column and reinforcement sizes and construction techniques on the same building, unaware of any subsequent effects on performance. Specifically, erecting the masonry wall first or building the frame first does not result in a significant change in appearance. The two techniques use the same materials and in similar quantities; to an untrained individual, there's little discernible difference.

In order to distinguish between construction sequences and subsequent performance, the terms "column-first" and "wall-first" are used herein to describe those construction practices in Haiti which are similar to infilled frame and confined masonry systems, respectively. While the terms "infilled frame" and "column-first" can be used interchangeably, the terms "confined masonry" and "wall-first" cannot. Significant differences exist between traditional confined masonry and the wall-first systems that exist in Haiti. Properly constructed confined masonry results in vertical load bearing on the masonry wall panels. Common building practice in Haiti, however, results in a gap between the top of the wall and the beam or slab above, prohibiting vertical load transfer (see Figure 8). Subsequently, twoway bending cannot develop across the wall. The benefit of erecting the walls before the columns is therefore restricted to arching action alone. For this reason, true confined masonry construction was not observed in Haiti and is instead referred to as "wall-first" construction.

Wall-first and column-first construction appeared to be equally

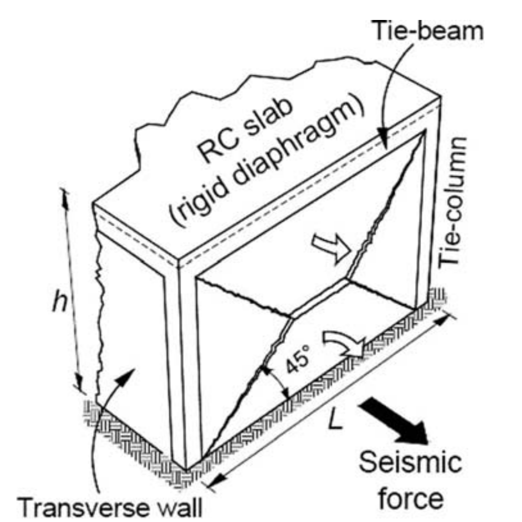

Fig. 7. Two-way bending mechanism of load bearing confined masonry walls subjected to out-of-plane forces (Brzev 2010).

Fig. 8. Masonry walls are built short of the roof slab for all types of masonry construction; block debris is added to fill in the gap.

Fig. 9. Wall-first construction is identifiable by the oozing of the column concrete around the masonry blocks.

prevalent in Haiti. During reconnaissance, column-first construction was easily identifiable because of delineation or even a gap between the wall panel and the adjacent column. Wall-first construction was identifiable by the absence of this division and the presence of concrete oozed around individual masonry units. Evidence such as that shown in Figure 9 strongly indicates that the wall was in-place prior to pouring of the column.

PERFORMANCE OF NON-ENGINEERED STRUCTURES DURING THE JANUARY 2010 EARTHQUAKE

INFILLED FRAME COLUMN-FIRST BUILDINGS

For those structures assembled with a column-first technique, observed performance during the January 2010 earthquake was poor and consistent with the expected behavior of infilled frame systems. Initially, masonry walls contributed to and increased the lateral stiffness of the surrounding frame system. Once the masonry cracked and deformation demands increased, interaction between the wall panel and columns resulted in localized damage to both. Lacking out-of-plane resistance, masonry infill frequently toppled out-of-plane (see Figure 10), leaving the adjacent slender columns unsupported. Ultimately, insufficient beam-column joint detailing led to joint damage and the formation of sway mechanisms. This damage progression and failure mode were likely the most common means of collapse of low-rise, nonengineered buildings in Haiti and were responsible for the majority of fatalities. Inadequate transverse reinforcement of the columns also resulted in frequently observed shear failures, compression failures, and column bar buckling.

WALL-FIRST BUILDINGS

As previously discussed, construction of a masonry wall prior to the frame results in a modest bond or saw-toothed connection between the columns and masonry wall. For this reason, wall-first buildings constructed with a significant column-wall bond experienced little to no damage from the earthquake. The extent of damage observed in this case was limited to minor cracking around window and door openings. However, Haitian construction is of such poor quality, and in fact represents a lower bound condition, that this seemingly minor change of assembly technique defined the difference between adequate force resistance and collapse during the 2010 earthquake.

Based the authors' observations, the distance that the staggered masonry units extended into the column cavity appeared to directly affect the amount of damage. As the column-wall interface became more flush and more closely resembled infilled frame construction, performance diminished even despite the wall-first construction sequence. Frequently, a completely flush interface with no brick staggering was observed between the masonry wall and column. In this case, only contact adhesion existed between the concrete and the masonry wall; no shear key action could develop. Nonetheless, the authors speculate that even this lower bound interface may have helped mitigate or delay collapse, as numerous undamaged or slightly damaged buildings were observed with this negligible bond.

Several examples of out-of-plane U-shaped wall failures were observed for buildings assembled with a wall-first technique, for which masonry units remained attached to the columns. The presence of these units indicates that the column-wall bond was not

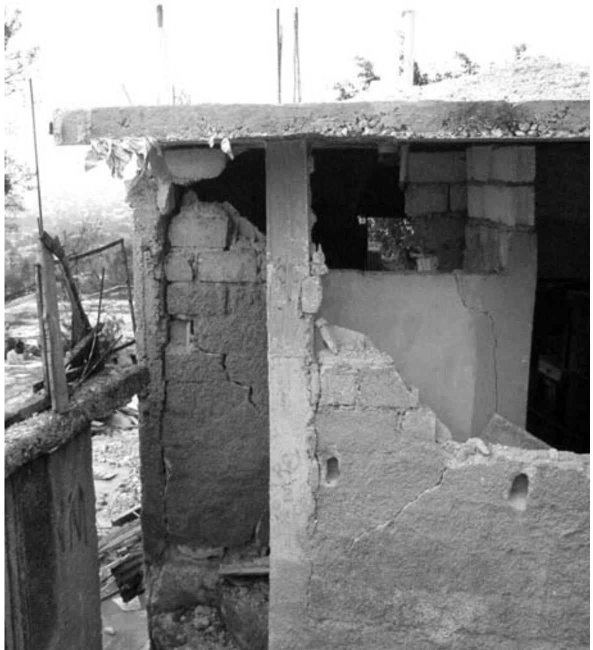

Fig. 10. Infilled frame construction is distinguishable by clean lines between columns and walls. Typical failure is out-of-plane toppling, as shown

the weak link, but that the displacement capacity of the wall was reached.

Despite the successful performance of wall-first construction in Haiti, poor quality design and craftsmanship are pervasive. The use of a wall-first or column-first construction technique is inconsistent; a wall may be bookended by a column at one end and unsupported at the other. This gross lack of redundancy and consistency in the design and assembly of Haitian houses frequently facilitated the rapid escalation from a single component failure to global structural collapse. Residents should not assume that because their house withstood the earthquake that it was built properly and is safe from future seismic events.

CONCLUSION

The January 2010 earthquake revealed the great frailty of Haiti's built environment to the world. The factors that contributed to the devastation had been in place for decades before the event. Haitians have lacked access to quality materials, knowledge of proper building techniques, and an awareness of their seismic risk. The lack of governance, in the form of building codes and enforcement, facilitated these causes.

Considering the realities, it is remarkable that any structure withstood the earthquake, let alone emerged undamaged. Knowledge can still be gained from this lower-bound scenario. What determined success of a structure was oftentimes a minor construction sequence change that resulted in a different load resistance mechanism. Infilled frame or column-first buildings performed poorly during the January 2010 earthquake. Conversely, those buildings for which the walls were assembled before the columns, reminiscent of confined masonry, generally performed well. This wall-first technique resulted in a modest column-wall bond which was generally sufficient to resist lateral demands. Significant differences exist, however, between properly assembled confined masonry and the wall-first technique typical in Haiti, notably the lack of load bearing masonry walls. This results in decreased in-plane shear resistance and prohibition of two-way bending across the panel. Subsequently, the wall-first construction technique in Haiti successfully resisted lateral loads by in-plane shear resistance and out-of-plane arching action alone. This modified behavior has not previously been associated with successful confined masonry performance.

The authors do not advocate that a wall-first construction is sufficient to meet seismic demands. There are numerous and significant deficiencies of Haitian construction that a wall-first technique cannot overcome. It is the intent of presenting our observations to highlight small distinctions which delineated collapse from success. Simply because a structure remained intact or lightly damaged after the January 2010 earthquake does not suggest it is well constructed and can survive another. In fact, another seismic event could reveal with more fervour the brittleness of Haiti's housing stock.

Brzev, S. et al. 2010. Seismic design guide for low-rise confined masonry buildings. World Housing Encyclopedia (www.world-housing.net)

SUMMARY OF "RECIPE FOR DISASTER: CONSTRUCTION METHODS, MATERIALS, AND BUILDING PERFORMANCE IN THE JANUARY 2010 HAITI EARTHQUAKE"

by Marshall, J; Lang, A; Baldridge, S and Popp, D. From Earthquake Spectra, Vol.2 No. S1.

SUMMARY

The earthquake that shook Hispaniola on 12 January 2010 devastated Haiti. The damage was widespread due to uncontrolled construction, poor material quality, and lack of rigorous engineering design. Post-event reconnaissance has brought to light serious deficiencies in these areas. Residential buildings in Haiti are typically constructed by their owners, who may or may not have the skills or resources to build a structure that is earthquake-safe. Few structures are designed by engineering professionals or are inspected for quality of construction. The two most common construction materials are masonry block and reinforced concrete.

Masonry blocks, concrete cylinders, and reinforcing steel were taken from Haiti and tested in the United States. The concrete and masonry were shown to be of low strength and quality. The steel samples show expected strength properties with some specimens having reduced ductility due to bending. Building performance is demonstrated by reconnaissance photographs and case studies of the structures inspected by reconnaissance team members.

PERFORMANCE OF NONENGINEERED STRUCTURES

When Haiti's non-engineered buildings were excited by the earthquake, their concrete floor and roof slabs generated large inertial loads. These loads were transferred through the column-slab or beam-column joints, which typically lacked sufficient detailing and transverse reinforcement. Columns lacking in-plane lateral support from adjacent infill walls due to wall damage or openings regularly experienced damage to the column-beam joint, which often resulted in the formation of a plastic hinge without ductile detailing. The moment resistance of the frames was reduced and a racking failure mode ensued, resulting in collapse or residual drift. Figures 11a and 11b illustrate residual drift and structural instability as a result of this failure mode. Lighter roof systems also experienced damage, but much of it was repairable and fell within the life-safety damage measure.

Because the masonry walls are typically not load bearing, as previously described, their lateral capacity is reduced due to the lack of friction development between the unreinforced masonry blocks. This frequently resulted in brittle X-cracking of the walls, often initiating at the corner of openings (see Figure 11c). Subsequently, wall panels did not significantly contribute to the overall lateral capacity of

Fig. 11a. Typical failures of infill masonry construction: Infill wall failure initiated at openings resulting in large rotational demands at beam-column joint.

Fig. 11b. Damage to reinforced concrete beam-column joints following failure of masonry infill.

Fig. 11c. Common brittle in-plane shear failure (X-cracking) of masonry wall.

Fig. 11d. Complete failure of infill panels followed by partial collapse due to poorly confined columns.

structures once they were damaged. As described above, however, the walls reduced the unsupported length of slender columns, improving the in-plane moment resistance of the frames. Localized damage was often observed as a result of in-plane interactions between wall panels and columns. Column shear failures were common. In some cases the column failure resulted in partial or total collapse, as shown in
Figure 11d. Further, toppling and out-of-plane wall failures were frequently observed and caused the majority of the complete structural collapses. Even when they didn't contribute to building collapse, these out-of-plane wall failures caused innumerable injuries and deaths.

CONCLUSION

Haiti's infrastructure was completely unprepared for the earthquake that struck on 12
January 2010. With rare exceptions, buildings were not planned, designed, or constructed with the necessary detailing to survive seismic events. While some buildings may have been engineered, the necessary channels were not in place to verify compliance during construction.
The material testing results 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 must improve construction material quality, planning, engineering design, and construction of all infrastructure. This lesson is critically important during the recovery and rebuilding phase.

Earthquake Hazard Centre
Promoting Earthquake-Resistant Construction in Developing Countries

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