Rubble Stone Walls and Reinforced Concrete Frames:

Heritage Structures Reveal the Hidden Truth about Risk and Resilience during the Haiti Earthquake

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Introduction

This article is about the effects of the 2010 earthquake in Haiti, a subject I have long wished to share with my ISCARSAH colleagues. With it, I also wish to honor the contributions of the other members of the World Monuments Fund/ICOMOS mission to Haiti undertaken after the earthquake to help in the effort to preserve the remarkable collection of 19th and early 20th century houses of traditional construction, almost all of which, although damaged to varying degrees, survived the earthquake. These houses, which had become known by the English term, "Gingerbread Houses" (not "pan-espice" as it would be in French), had previously been listed by the World Monuments Fund on their 'Watch List' of structures at risk.

Three of the members of the WMF mission team: Steve Kelley, Patrick Sparks and I, are members of ICOMOS-ISCARSAH. The two other members included architect Martin Hammer, noted for his international disaster recovery work in Pakistan and particularly for his work with straw-bale construction, and a builder, Kevin Rowell, noted for his work using traditional materials and technologies. All of the team members generously agreed to volunteer for this mission, with only a small stipend for the preparation of the mission report which became a book co-authored by all members of the team and published by the World Monuments Fund. This book can be downloaded in English, French or Spanish for free from the World Monuments Fund Website that can be accessed from this link: **www.haiti-patrimoine.org**

The Gingerbread Houses of Port-au-Prince

This article describes the findings of that mission, as well as the use of the Pictometry aerial survey data that Pictometry International generously donated to ICOMOS for the mission. For the mission, this aerial survey was of immeasurable importance because the oblique views allowed us, together with the Haitian homeowners in meetings at the co-sponsoring organization FOKAL, to identify the location of their Gingerbread Houses better than straight-down aerial and satellite views, by revealing their architecture from the side. Their significance became increasingly clear when I began to use them to survey the earthquake damage across the entire damage district.


Figure 1. Like a scene from Dante's Inferno, central Port-au-Prince, 4 months after the earthquake.

Using Adobe Photoshop to merge the hundreds of Pictometry photographs taken from the belly of an aircraft into large maps where the side views of every building were visible taught me the power of this data to provide an impartial and comprehensive view of the building construction and the extent and nature of the damage over large areas of the damage district – areas when seen from the ground would be only in the best of circumstances a small portion of the scene. Even the most impartial observer on the ground would tend to migrate towards areas where the damage was most pronounced, which then affects the objectivity of the assessments, while the comprehensive aerial views can help to avoid this problem.

When our team arrived in Port-au-Prince in April of 2010, four months after the earthquake, we had seen the imagery in the news and early reconnaissance reports. We were first taken to the Oloffson Hotel where we found ourselves in a 120 year old three story unreinforced brick masonry building in excellent condition that had never closed after the earthquake. The only marks on it left by the earthquake were cracks so small that to show them in slide shows later, arrows and circles were needed to point them out, even though a new 9 story hotel lay completely pancaked behind it. In fact, the largest crack found in the walls of this building turned out to be from a rusty bolt embedded in the brick wall!

Figure 2. Left: April 2010 Exhibition at FOKAL in Haiti of murals if the Gingerbread District made from Pictometry images. Right: View showing the Gingerbread houses picked out of the aerial images by their distinctive architecture. The National Palace, which collapsed, is visible in the upper left.

We then began to survey the historic late nineteenth century houses, almost all of which had suffered through a half-century of neglect, some of which were constructed of rubble stone masonry laid in earth mortar, confined only by piers of fired brick in deteriorated lime mortar. Almost all of these houses - even those of rubble stone - were still standing. Some were heavily damaged, but almost all were still standing after an earthquake which was by then reported to have killed as many as a quarter-of-a-million people!

To put this in perspective, a quarter-of-a-million fatalities places this earthquake side-by-side with the Tangshan earthquake of 1976, which caused more fatalities than any other in the 20th century – by an order of magnitude, and more than all but one in all recorded history. With the poverty and bad construction known to exist in Haiti this seemed plausible, especially since it was initially reported by the USGS that this earthquake was calibrated in their initial 'shakemaps' as a Modified Mercalli Intensity (MMI) of IX in Port-au-Prince – a statistic that would later change, as is reported below.[1]

Figure 3. The unreinforced brick masonry Hotel Oloffson, Port-au-Prince after the earthquake.

Determining earthquake intensity in the absence of instrumentation

At the time of the earthquake, it was the widespread collapse of the more formally constructed buildings in Port-au-Prince that undoubtedly fed the perception that a classification of the intensity as an MMI-IX and even an MMI-X (as is still reported in Wikipedia) was correct – not just in the epicentral area near Léogâne, but also extending through Port-au-Prince, 34 km to the east, and even including Pétionville, an additional 8 km further east. At that time it was thought that the fault rupture extended under Port-au-Prince, but this was later determined by USGS to be incorrect.

Two buildings that may have influenced the setting of a high MMI were the pancake collapses of the five star Hotel Montana, and the former five star hotel used by the UN to house its staff in Haiti (Figures 4 & 5). The Hotel Montana had been heavily used by visiting US governmental officials. These two collapses alone killed the head of the UN mission together with much of its staff, as well as a number of US and European dignitaries. Knowledge of these events spread fast, including to the US Geological Survey (USGS) which within hours of the earthquake began publishing their famous shakemaps that, in addition to instrument data where it existed, included subjective data based on analysis of the initial news reports and over the phone interviews.

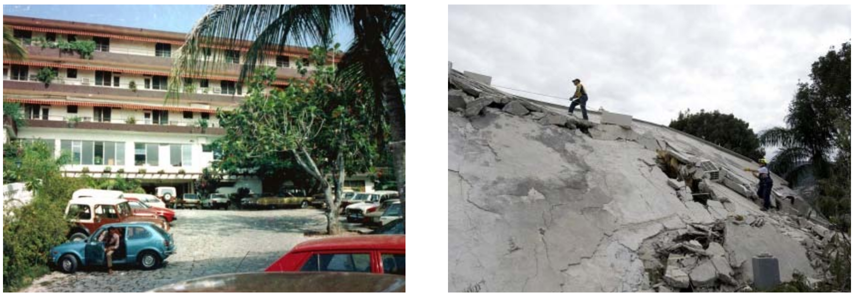

Figure 4. Five star collapses in Petionville: left: Hotel Montana before, and center after the earthquake (Google images).

Figure 5. UN Headquarters after the earthquake (Google images).

Unfortunately, there were at that time no seismographs in or near Haiti, and so the use of the Modified Mercalli Scale criteria to classify the damage became particularly important as a measure of the ground shaking in this earthquake. Since it must have seemed inconceivable to USGS that these hotels would be less structurally sound than the shanty-town houses that surrounded Port-au-Prince by the hundreds of thousands, the estimation of a high death toll seemed reasonable.

But then, how does one reconcile the still-standing houses with walls of rubble stone, or the practically undamaged Oloffson Hotel with an MMI-IX or X? The reaction of many when told of this is to say that the sites may have experienced less shaking than those areas that were devastated – a not unreasonable response. In fact, a detailed geological study was conducted by a team from the University of Texas, Austin shows the soil strata under the downtown area to be more responsive to seismic vibrations. However, just up the slope behind the Oloffson a modern nine-story reinforced concrete hotel building pancaked. The chances of a difference in seismic shaking in such close proximity being the reason for such a difference in building performance seems very remote, although the difference in height and stiffness of the buildings may have contributed to the difference in performance. Similarly, throughout the Gingerbread district, which is to the east of the area identified by UT as being the most vulnerable to seismic resonance, the intermingling of the surviving Gingerbread houses with many buildings of more recent construction – usually of RC or concrete block with RC floors, many of which collapsed – made it unconvincing to explain differences in the extent of damages and collapse by underlying soil differences alone.

The Gingerbread houses were of three main construction types: (1) brick and rubble stone masonry, (2) braced wood frame with brick or rubble stone infill, known there by its French name colombage, and (3) 100% braced wood frame of traditional timber framing and/or American balloon framing with wood board cladding. One important feature of those of masonry is that most, if not all, had an iron band imbedded in the walls at the floor and roof levels – which did help to restrain the walls from spreading. Such probably exists in the Hotel Oloffson, but because the building remained intact, and surface hardware, if it exists, is hidden by the wood verandas. Neither this, nor any existence of rubble masonry in its walls could be confirmed, but the existence of a tie and the absence of rubble stonework are both likely, considering the building's good performance.

In almost all cases, the timber framing elements were compromised by termite damage and/or fungal decay – which was in a few cases very extensive. Despite the almost universal lack of maintenance and commonly found decay, it was rare to find even a partial collapse at any of these houses, regardless of construction type. In the buildings with rubble stone, in quite a few instances, the rubble stone sections of the walls showed different gradations of damage from the shedding of exterior stucco to the partial or total falling out of a stone panel – leaving the building still standing on the brick piers which surrounded the rubble sections of the walls.

This damage survey of the Gingerbread houses turns out to be particularly significant when one considers that Giuseppe Mercalli largely used masonry buildings to calibrate the scale above the level of VI when, in the late 19th

Figure 6. Brick and empanelled round-rock rubble stone construction, as is typically found in many of the Port-au-Prince "Gingerbread" Houses from the late 19th century, showing different levels of damage from onset, to collapse of the rubble panels. Center: The 2 ½ story Villa Castel Fleuri Mansion was of rubble stone between brick piers and window surrounds, and only the staircase projection collapsed. The onset of inelastic deformation of the rubble stone panels is visible where the surface stucco has come off. Right: The Dufort House still standing on its brick piers after the collapse of the rubble stone panels. This house is now being restored by FOKAL. Many reinforced concrete buildings nearby collapsed.

century, he developed the scale that bears his name. An earthquake classified as a IX on the MMI scale would be expected to cause "*Damage to masonry buildings… from collapse to serious damage*" whereas what was found in the WMF survey seems closer to the description for an MMI-IV: "…*damage to some poorly built unreinforced masonry buildings [and] some cracks even in better built masonry buildings if not reinforced*." Thus the Oloffson Hotel would qualify as a "*better built masonry buildings*," while the brick and rubble stone mixed construction houses, because of the existence of the rubble stone in clay mortar, inarguably can serve as examples of "*poorly built masonry buildings*." So, using these examples, it would seem that this earthquake is more accurately classified as an MMI-VII, rather than an MMI-IX or X, as has been often cited.

A 'Desktop' Damage Assessment

In the months following the WMF mission, Pictometry generously agreed to extend my access after their invitation to give an address at their annual conference in Orlando, Florida. With this opportunity and the Orlando address in mind, I began to survey the entire damage district in what I call a 'desktop' damage assessment. The WMF mission had already made us all aware of what seemed to be a counter-intuitive discrepancy between the performance of the more than century-old Gingerbread houses of brick, rubble stone, and timber construction that we had come to survey and the rest of the building stock in which the reported quarter-of-a-million people died. However, earthquakes often show anomalies where even seemingly identical buildings constructed next to each other at the same time can show radically different damages, with one collapsed and the other showing minimal damage. Although a century or more old, these were constructed as upper class houses in what is now largely a world of urban poverty in Port-au-Prince.

Figure 7. Left: Pancake collapse of a reinforced concrete building that was located in the Gingerbread District of Port-au-Prince. Right: As a remarkable example of the inherent strength and resilience of a well-constructed reinforced concrete building, this one in Rikuzentakata, Japan was swept onto its side and carried upstream by the March 10, 2011 earthquake and tsunami without being crushed or collapsed (AFP/Getty).

The first step in my desktop survey was to take the results of a World Bank sponsored post-earthquake desktop survey and compare it with the visual information provided by the four directions of oblique views in the Pictometry data. The World Bank had asked members of EERI and the earthquake engineering community to access a special layer in Google Earth which had high-resolution straight-down imagery from a flown survey rather than satellite imagery, and from this imagery mark those buildings showing evidence of partial or total collapse.[2] Since straight down photography shows the roofs rather than the sides of buildings, this required judgment based on the debris field around buildings and the distortion of the roofs.

This allowed me to look first at those areas with evidence of concentrated areas of damage – where the red marks from that survey were densely packed. Following that, I looked at increasingly large areas – mainly over the informal settlements known as "*bidonvilles*" or "tin-can-cities" – where the largest concentrations of the population are located. The results of this were revealing. In summary, despite the fact that there were significant areas of concentrations of building collapses, area after area in the heart of the damage district were revealed as having remarkably little visible evidence of even partial collapses.

In fact, a good number of the buildings in the *bidonvilles* identified in the World Bank survey as collapsed turned out to be misidentified only because they were constructed with roofs that were uneven and discolored – the kind of thing impossible to be able to see from straight-down images alone. Interestingly, the World Bank survey proved to be far more accurate for the downtown commercial buildings than for the *bidonvilles* because there the collapses were more easily discerned.

Figure 8. View of 4 Carrefour Feuilles area bidonville, close to the city center, Port-au-Prince (© Pictometry).

Figure 9. View of 4 Carrefour Feuilles area bidonville, close to the city center, Port-au-Prince showing the unsophisticated rough construction of informal settlement dwellings, with incomplete frames, round-rock rubble stone retaining walls, and unreinforced concrete block construction – that nevertheless did not collapse (Source: Carlos Barria-Reuters).

There were areas – as confirmed by the news and reconnaissance photography on the ground – which did show extensive or complete devastation, and for these, the Pictometry images also have proved to be a remarkable diagnostic resource.[3] Unlike with Google Maps or Google Earth, working directly with the Pictometry website allowed me to download the actual original photographic images as jpgs. This then enabled me to be able to import them into Photoshop, and align two sequentially shot images so that the area of overlap could be excised. This then allowed the export of the images as stereo pairs.

One may ask why this would provide scientific data beyond the possible entertainment value of looking at ruins in 3D, but it proved to be invaluable. It showed that every surveyed area in the bidonville settlements where the damage was widespread or total to be located on a steep slope, and those areas where there were few or no collapses, the slopes were less. Looking at these intact areas more carefully, the damage that one could see in the areas where the damage visible from the air consisted only of isolated wall collapses (often of walls that were under construction at the time of the earthquake and thus without roof or top plates), while in the steep areas, total collapses could often be seen where buildings had cascaded down the hillside, with one perhaps falling on one below, or a foundation being undermined in a mini-landslide. If one considers that poor people will probably not bother to build retaining walls, or if they have, perhaps they have done so without the engineering know-how or access to the proper materials to assure that they will resist earthquake vibrations, this difference between the sites is logical. In fact, many of the retaining walls in Haiti, where they did exist, were of dry laid round river stones between widely spaced concrete columns.

When I embarked on this desktop survey, I did not have a particular idea of what I would find, as my access to sites during the short visit to Haiti for the Gingerbread mission was focused on that one particular area. I had the opportunity to make only a single trip to the city center – which was forced by circumstance to be particularly short when we helped a mother find medical help to save the life of her baby burned badly from a campsite fire. In fact, I expected to find in the desktop survey what the news reports had described – almost total devastation within the informal settlements. The vast encampments of displaced people seemed to reinforce this impression, but many of these people, I later learned, were displaced from buildings that were still sound, but which they were afraid to return to.[4]

As I moved systematically in Pictometry over the landscape of Port-au-Prince, scene after scene came into view showing intact buildings, and I began to realize that this was potentially a significant finding. This was especially the case when a similar survey over the city center revealed the kind of almost total devastation that one expected to find throughout the *bidonvilles*, but which turned out to be concentrated only on particularly steep sites.

There were three areas that were particularly representative of these findings: informal settlements (1) on the hillside above Pétionville a short distance from where the Hotel Montana and the UN residential hotel had stood, (2) on the hillside nearest the city center, the National Palace and the Gingerbread district, and (3) the area known as *Cite Eternal* located on an alluvial fan closer to the epicenter than almost all of the rest of Port-au-Prince. In the case of (1) no collapses could be found, and the damage was thus limited to repairable damage to the dwellings. Colleagues of mine, architects Christopher Andrews and Seth Wachtel of the San Francisco Bay Area, visited this settlement subsequent to the earthquake and confirmed the finding that little damage and displacement of the occupants occurred at this site. At (2), a hillside area showed pockets of heavy damage, but the vast preponder-

Figure 10. City Eternal an informal settlement on an alluvial fan next to downtown Port-au-Prince, with insets (left) showing 2, 3, and 4 story buildings still standing without visible damage, and only evidence of one collapsed building in the view, and (right) evidence of the collapse of RC frame structures, including an open air market structure among other buildings.

ance of the tightly packed cluster of homes that spread over the hills showed little damage visible from the air within the high resolution of the Pictometry images (Figures 8 & 9).

Number (3), known as *Cite Eternal*, was even more remarkable for a number of reasons in addition to being closer to the epicenter (Figure 10). One would normally expect that an alluvial soil site like this would be particularly vulnerable – especially for taller buildings, but three and four story structures appeared in the imagery to not show visible damage, although there may be damage invisible from the air. Also interesting was to find that several buildings around a large central market structure that were of more formal construction of reinforced concrete frame with infill walls collapsed. The rest of the settlement consisted of construction that was more common to informal buildings, which could only be loosely described as confined masonry or simply concrete block construction.

This particular observation was consistent with the larger issue that defines what has happened to the building stock in this earthquake. If the buildings in the informal settlements not on steep sites proved to be more earthquake-resistant than expected, one must then ask the question *why*. As has been documented by the University of Texas – Austin geologists, the soil strata differences can account for some of the excess of damage in the city center, but it is not enough to simply turn to the geological reports to explain all of the difference that one finds. If so, then what about *Cite Eternal* which, at best, is on similar, but more recent, alluvial strata to that under the downtown area where the concentration of the collapses of formal multi-story buildings of recent origin occurred – including many government buildings.

Does this defy the improbability that poor people without training on land they do not own would use higher quality materials, better engineering, and better construction quality control than that found in the formal, contractor-built, and even sometimes engineered structures downtown and in Pétionville? The answer to this question is *no*. The quality of the design, construction and even the materials used in the informal settlements was in fact quite poor as one would expect – they just did not often collapse (Figure 9).

The clue that I believe helps to explain this is the performance of the brick and rubble stone Gingerbread houses. This provides some evidence that the earthquake shaking in most of Port-au-Prince was no greater than an MMI-VII. Only an understanding of this explains the survival of the rubble stone houses and the informal settlement houses – the earthquake, although big, was simply not as strong as had been thought. In fact, the USGS did report that the earthquake was only an MMI-VII in Port-au-Prince in their last and most accurate shakemap published on March 4, 2010 after all of their scientific data had been reported and analyzed and this was also the same as was reported by the UN/European Commission. If this is all true, then the most challenging question is *why did the formal construction – most of which was of reinforced concrete – fail so catastrophically?*

It would be easy here to list all of the reasons why a reinforced concrete moment frame with infill building constructed in Haiti would have defects, such that could cause a collapse in an earthquake, but my ISCARSAH colleagues would already know these reasons. In fact, one colleague from Ove Arup Engineers in Haiti for OXFAM prepared a list of reasons which he shared with me of what he observed were faults he frequently found in the construction of RC buildings. The list came to 20 items, any one of which could have caused the onset of a collapse.[5] However, what is interesting to explore here in relationship to the Pictometry data is why the slum housing – much of which was made of concrete and which, as I have mentioned above, *even of lower construction quality than that of the downtown RC frame buildings* – did better.

At this point in the analysis two facts have been determined: (1) It appears that a reasonable calibration of the shaking using the criteria set by the Modified Mercalli Scale that shows that the earthquake over much of Port-au-Prince, including the city center area, was in the range of an MMI-VII rather than higher. (2) Except for the steep sloped areas, the informal housing of a mixture of concrete block and partial concrete frame and slab elements with site-mixed concrete, salvaged rebar and other materials constructed with little or no training, even if manifesting damage, almost entirely remained standing.

Thus, what still needs to be determined is why a greater share of these poorly made houses – many of which were of more than one story – survived than of the downtown buildings. The conclusion that I have come to is that, no matter how rough the construction was in the *bidonvilles*, the houses were primarily constructed with solid walls, and the reinforced concrete framing elements did not constitute the primary lateral-resisting structural system.

In recent years, 'confined masonry,' in which infill walls are constructed before the reinforced concrete frames, has increasingly been found to be quite resilient. The problem with even applying such terms-of-art in the *bidonville* areas is that many of the houses had incomplete frames, misplaced rebars, large rock pockets, and other faults, but all needed walls to serve as buildings – and for poor people room sizes are small, and thus a level of redundancy is inevitable, as well as the fact that walls go to the ground without an open ground level story (Figures 9 & 10). Because this earthquake was an MMI-VII rather than a IX masonry buildings, by definition, of poor construction are expected to survive with significant damage – so their survival is to be expected, as it is consistent with the survival with damage of the rubble stone buildings.

That then is what is significant about the findings of this Pictometry study – the multi-story RC moment frame buildings with infill masonry that collapsed did so at a level of shaking that did not collapse 19th century buildings constructed of brick and rubble stone, the only reinforcing in which was an iron tie at the second floor level. These RC collapses happened over a wide enough area to buildings of varying height with enough difference to make it difficult to attribute this phenomenon to building-ground resonance alone, as, for example, was a very important phenomenon in the 1985 Mexico City Earthquake.

After arriving at these findings from the Pictometry desktop-survey, I have found that two scholars on the EERI reconnaissance team, Anna Lang and Justin Marshall, came to similar conclusions based on their inspection of buildings on the ground in the *bidonvilles*, as well as in the city center.[6] In their paper, they agree that Haitian RC construction is generally so haphazard that even the use of the term "confined masonry" gives credit for confinement that is incomplete – so they used the terms "column-first" and "wall-first" to distinguish these two types by the order in which the walls and framing elements were constructed. They reported that they observed that "*Infilled frame systems ['column-first'] performed poorly and account for the majority of structural collapses [whereas] buildings assembled in a manner similar to confined masonry ['wall-first'], however, performed well and experienced little damage*." They found this to be the case even though they found that the construction of the 'wall-first' buildings were usually seriously flawed and deficient, which they describe in detail.

How can one fix this in the future? This is a subject for another article, but one place to begin is to explore a recommendation that all construction – except that meeting certain engineering oversight and peer review, with on-site supervision and quality control – be of construction which does not in any way depend on the beam/column intersections of frames for lateral resistance. Such can be of confined masonry, as is already popular in many developing countries, ideally with published and widely circulated guidelines. Consistent with Lang and Marshall's observations, and also with the experiences in India where the government has included "Rules of Thumb" and simple to use guidelines for non-engineered buildings which serve in lieu of formal codes, a requirement that non-engineered RC construction be 'wall-first" would be a manageable first step towards improved life-safety conditions for such construction. For more formal and taller buildings, shearwalls, or the 'Armature Crosswalls' I have proposed for a more economical alternative, are more dependable than moment frames alone.[7] Exploring how to implement such provisions in Haiti and other places similarly at risk, both for existing buildings and for future new construction, is an important subject to explore further than is possible in this article.

Casualties under Pancakes

After undertaking this study, one is forced to ask: "*Where did the oft-reported quarter-of-a-million people die?*" The corollary to this question is: "*Where did this large casualty estimate come from?*" Early in this research, I came across a report that may have served as an early stimulus for such a large figure. It published by RMS (Risk Management Solutions) Corp only 10 days after the earthquake. This report predicted that the casualties could be as high as 250,000 people[8]. This conclusion was based on a USGS shakemap published four days after the earthquake that showed the fault rupture extending under central Port-au-Prince, and an estimated intensity of MMI-IX. In the weeks following the earthquake, the Red Cross reported casualties in the range of 40,000 to 50,000, but the much larger number has seemed to stick, being consistently cited within fifty thousand either way for the past four years. This has been particularly interesting since the data to back up such high numbers was so weak, and because Haiti lacked census data to be able to establish the pre-earthquake population of the area with any certainty and getting an accurate count in the chaos of the post-earthquake environment was impossible.

It is interesting also to see why RMS did come up with this casualty estimate of 250,000 fatalities. On page 7 of the report, it says:

The building vulnerability was assumed to map on average to unreinforced masonry construction, which is extremely susceptible to collapses and heavy enough to cause significant casualties to occupants. This is consistent with the prevalent construction type in the urban regions of Haiti (i.e., blocks/concrete), but actual construction practices vary and include reinforced concrete, reinforced masonry, and unreinforced self-constructed buildings.

After I found this RMS report, I contacted the author of the report, Patricia Grossi, and asked her: "*If at the time you wrote the report, the USGS shakemap had been the one later published on March 4, which reported an MMI VII for Port-au-Prince, would your casualty estimate been different?* Her answer was "*absolutely – it would have been much lower.*" Thus, perhaps an answer to the question of where the quarter-of-a-million people died, may only be that countless numbers of people did die, but not a quarter-of-a-million. The purpose of my research has not been to call into question the body count – and in my experience even the 46,000 to 85,000 people later estimated by anthropologist Timothy Schwartz in a report for USAID that was found and published by the Associated Press on June 2, 2011 is still a vast number of casualties, beyond the scope of wholly accurate counting and of huge impact on the survivors. It is in scale with that experienced in Pakistan in the 2005 Kashmir earthquake and in Iran in the 2003 Bam earthquake, and exceeds the official estimates of even the two catastrophic earthquakes in Turkey in 1999 combined.

My purpose was to try to isolate what can be learned by the Haitian tragedy that may constructively change our thinking about how to influence building construction and maintenance in areas of earthquake risk – by accepting the fact that bad construction of buildings is inevitable. After the earthquake there have been concerted efforts to improve the education of Haitian engineers and builders to raise the standards of reinforced concrete construction, but it is equally important to approach the problem of building construction from a philosophical standpoint – that is to accept the fact that a certain percentage of buildings will be substandard, and thus try to modify the common structural systems in use today such that substandard does not inevitably mean they be so extremely dangerous as they proved to be in Haiti. The difference is what has been demonstrated by the still standing primitive houses in the *bidonvilles* and the pancaked downtown commercial and government buildings. It is not a difference in quality of construction, but a basic difference in typology.

There is a simple reason why RC frames can be so vulnerable if mistakes are made. Design level earthquakes are expected to cause structural damage, even to well-constructed buildings that meet modern codes. With an RC frame structure – the beam/column connections are thus expected to begin to break. Under such circumstances, preventing the building from collapsing, while at the same time allowing its structural frame to yield - that is an engineer's art of the highest order - way beyond the knowledge and capacity of the usual contractors responsible for building these structures. Thus what is needed particularly in developing countries with limited training, enforcement and inspection is the use of construction typologies that are less dependent on good design, and construction quality, than is standard RC infill 'column-first' frame construction.

Conclusion

A report on the Calabria earthquakes of 1905 and 1908 by Italian engineers in the 1932 treatise by John Ripley Freeman described the damage to reinforced concrete dwellings in Melicucca in 1905[9]. Exactly what kind of RC structural system is the subject of the description is not known, but the quotes are interesting nevertheless in light of the vast differences found in the RC buildings in the Haiti earthquake. It says the "*reinforced concrete… dwellings… were nearly all tumbled down in spite of the fact that… the shocks were less violent than elsewhere… because of the poor quality of material used, and lack of proper joints or connections between thevarious members…"* In this description they said these were houses whose builders…classed… as "*reinforced concrete structures* [but] *the subcommittee reported that they had no right to this classification*".

In the next paragraph, they described *"four structures of reinforced concrete in Messina* (where the shaking was much greater) *which remained wholly unharmed… examples of the capabilities of this material when properly used*." These quotes indicate that over a century ago, near the beginning of the modern invention and use of reinforced concrete, it was already being discovered that variations in construction quality resulted in the difference between perfect performance and catastrophe. It is also interesting to see that professional expectations of its potential for good performance should mean that the use of the term "reinforced concrete" should not be allowed. Today, a century later, the same spread from superlative to abysmal performance in earthquakes is still a characteristic of the system.

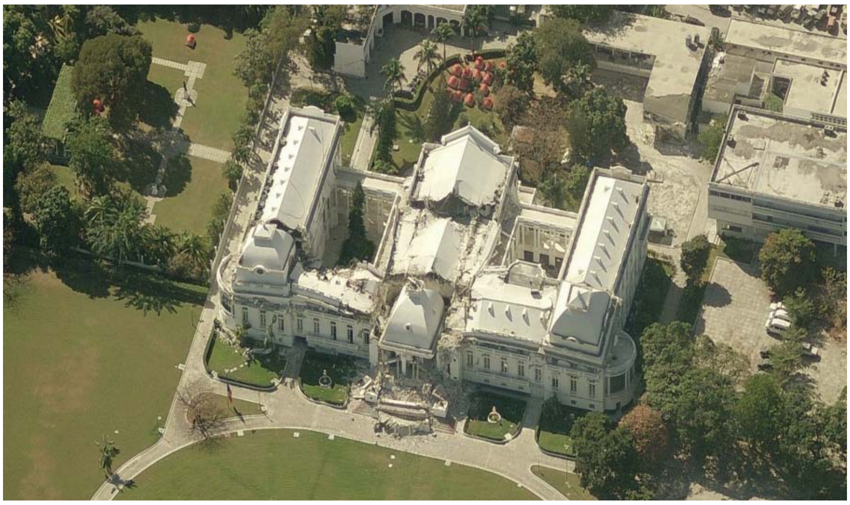

Figure 11. National Palace in Port-au-Prince after the earthquake and partial demolition, revealing the reinforced concrete frame infilled with rubble stone (© Pictometry).

12. Detail view showing the reinforced concrete frame with round rock rubble stone infill of the 1916 structure exposed during the demolition of the ruins of the National Palace.

In Haiti, the two iconic symbols of the destruction wrought by this earthquake were the National Palace (Figure 11, 12) and the National Cathedral. Both were reinforced concrete. The cause of the collapse of these two structures, as well as many other 100+ year old churches, was the corrosion of the rebars after a century of exposure to moisture in the tropical environment. Yet only a few blocks away from both, and resting on the very soil identified as subject to the highest shaking, is another structure that few have seen and which has rarely been in the news, but which stands as a remarkable monument to resilience when almost every building around it collapsed – the Saint Louis de Gonzague Chapel (Figure 13). It was as high and about half the length of the cathedral, and about 20 years older – but little damage was visible on the exterior. The structure was of brick masonry with an iron or steel frame. Not only has it not rusted out, despite its age, it has remained standing, even as all of the school buildings around it, some of concrete, and others of timber, collapsed. Much still needs to be known about this church, but perhaps when we are looking at this structure we are looking at the future, and not just at the past. Embodied in this magnificent survivor may be at least one idea of how we can build durable and safe buildings in earthquake areas that can remain standing after an earthquake a century later.

13. Saint Louis de Gonzague Chapel ca. 1890 in central Port-au-Prince showing external lightweight steel frame on masonry walls.

Footnotes

[1] A more detailed discussion of this research will be published in: Randolph Langenbach (forthcoming) "*Was Haiti in 2010 the next Tangshan in 1976*" ICOMOS Symposium: Tangible Risks, Intangible Opportunities: Long-Term Risk Preparedness and Responses for Threats to Cultural Heritage, Beijing, China, 2012, Proceedings.

[2] **http://www.unitar.org/unosat/node/44/1425**

[3] Further information by scholars in a number of different disciplines can be found in the papers contained in the "2010 Haiti Earthquake Special Issue" of Earthquake Spectra, Volume 27, Number S1, October 2011, published by EERI, Oakland, Ca. USA.

[4] Kubilay Hicyilmaz. 2010. Email correspondence with author dated May 31, 2010. To see the list, go to: **http://www.haiti-patrimoine.org/Haiti-RC.pdf**

[5] Randolph Langenbach. 2008. Learning from the Past to Protect the Future: Armature Crosswalls, *Engineering Structures*, Elsevier. Vol. 30, No. 8, August 2008, pp. 2096-2100 (**www.conservationtech.com/armaturecrosswalls.html**)

[6] **http://www.buffalo.edu/news/releases/2010/01/10872.html**

[7] Anna F. Lang and Justin D. Marshall. 2011. "Devil in the Details: Success and Failure of Haiti's Nonengineered Structures," *Earthquake Spectra*, Vo. 27, No. S1, Earthquake Engineering Research Institute (EERI), Oakland, Ca., USA.

[8] RMS FAQ: 2010 Haiti Earthquake and Caribbean Earthquake Risk: **http://www.rms.com/publications/Haiti_Earthquake_FAQ.pdf**

[9] John Ripley Freeman (1932). *Earthquake Damage and Earthquake Insurance*, McGraw-Hill, New York.

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