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REHABILITATION OF THE MAISON DU FORT: ADOPTING TRADITIONAL TECHNIQUES FOR SEISMIC RETROFITTING

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Abstract. *In the historic center of Port-au-Prince, Haiti, more than two hundred historic gingerbread houses experienced ground shaking during the 2010 Magnitude 7.0 Haiti earthquake. Melding French architectural cues to the tropics, the gingerbread houses, dating from 1890-1925, combined colombage with ornate carved wood facades, masonry piers and sprawling porches. Colombage is a vernacular style having capacity to resist earthquake forces, but other aspects of the gingerbread style, including unreinforced masonry, are susceptible to ground shaking. Horizontal metal tie rods embedded in the upper reaches of the ground floor walls and anchored at wall ends by decorative iron plates, helped stabilize orthogonal wall elements during the earthquake. In accordance with the design of the authors, the ground floor masonry walls have been reconstructed using traditional lime mortars and remain nominally unreinforced. However thee addition of a series of horizontal and vertical embedded rods will encourage the walls to remain connected above wall openings, and to promote rocking. All work is being performed with the collaboration of the Institut du patrimoine wallon who are teaching masonry techniques using lime mortars and carpentry skills to the local construction work force.*

1 INTRODUCTION

In a neighborhood to the east of downtown Port-Au-Prince, more than two hundred historic gingerbread houses were constructed in the late 19th and early 20th centuries. With ornate lattice work, bold colors, and sweeping porches, these houses were constructed in a style well suited to the tropics, and designed mainly by French-trained Haitian architects [1]. An airy design with large windows and doorways and steep roofs to handle tropical downpours, the houses are still generally used as single family homes with several used for offices and schools. The style is best exemplified by the Hotel Oloffson, commissioned as a residence in 1887 and the setting for Graham Greene's novel The Comedians. The houses exist in a compact historically upscale neighborhood with an area of around 1/2 square mile. The style lasted until 1925, when, after a series of devastating urban fires, the mayor proclaimed that all new buildings be "fireproof" and constructed of masonry, reinforced concrete or steel. The age of the wood-framed and colombage house in Port-Au-Prince drew to a close.

In addition to their sometimes complicated geometry of steep pitched roofs and steeples, the buildings have various construction types including clay-brick masonry and stone rubble bearing walls, braced timber frames, and colombage: wood framed walls with vertical and diagonal elements infilled with stone or brick rubble. All of the masonry bearing walls can be considered to be unreinforced based on modern seismic definitions, yet most of the building contain European-fabricated metal elements, everything from balcony columns and metalwork, to horizontal ties, end-plates and "government anchors".

Three months prior to the 2010 earthquake, the gingerbread houses were included on the World Monuments Fund Watch to raise awareness of the buildings [2]. Their inclusion was a testament to the poor condition of the many of the buildings prior to being subjected to ground shaking. Many of the buildings have suffered from years of deferred maintenance, particularly important in a tropical environment where even minimal neglect can lead to insect and fungal infestations. Nearly all of the gingerbread houses suffer from some form of termite damage, and many of the better maintained houses have had large repairs in the past to remedy damage including repairs with concrete block and reinforced concrete. Without proper maintenance of the building envelope, the development of wood rot can also accelerate the deterioration of the building, particularly in wood members of the colombage frame critical to good performance in an earthquake such as the sill plate.

The Maison Dufort, designed by Haitian architect Léon Mathon and constructed circa 1910, is a hybrid structure consisting of all three types of typical gingerbread house techniques having plan dimensions of approximately 55 feet by 40 feet (Figure 1). Exterior walls and most interior walls on the ground level are constructed of clay-brick masonry piers and arches infilled with limestone rubble (Figure 2). These walls are supported on a foundation of uncut stone. The exterior walls on the second floor are constructed of colombage, while the partition walls on the second floor and the construction of the attic consists of wood framing with horizontal sheathing. The diaphragms of the Maison Dufort are flexible and constructed primarily of wooden joists and wooden floor planking at the second and ceiling planks below the attic with no viable load path to the masonry walls. The roof is sheathed in thin corrugated steel. Embedded near the top of the exterior and major interior walls are wrought iron "chains" made up of several rod links connected together over the full length of each wall. At the end of the chain, where it intersects another wall, a square steel rod is linked to the end of the chain and embedded into the masonry.

2 SEISMOLOGICAL SETTING

Having a historical record of over 500 years of frequent seismic activity, the island of Hispaniola lies on the northern boundary of the Caribbean plate. Although the strike-slip Oriente-Septentional fault has recently been considered the source for devastating earthquakes in the region (such as the 1842 Cap-Haitien earthquake), the southern strand of the east-west trending, strike-slip Enriquillo-Plantain Garden Fault has an equally active history with damaging earthquakes in 1701, 1751, again in 1751, and 1770. This fault, which is located just five miles from downtown Port-Au-Prince, has been quiescent for over 240 years until the 7.0 Mw earthquake on January 12, 2010. According to a USGS, the Maison Dufort experienced ground shaking equivalent to either VII or VIII during this earthquake, corresponding to expected damage ranging from “moderate” to “moderate/heavy”. Although geologic deposits underneath Maison Dufort can be classified as being stiffer than soils in downtown Port-Au-Prince, and presumably lead to less severe ground shaking, other mechanisms could have contributed to the high degree of building damage observed in the neighborhood such as topographical effects [5]. Some have hypothesized that the 2010 event could mark the beginning of a cycle of large earthquakes on the fault similar to what occurred in the1770s [4].

Figure 1. Line drawing of Maison Dufort in 1972 by Anghelen Arrington Philips [3].

Figure 2. View of Maison Dufort after 2010 earthquake showing bearing walls constructed of clay-brick masonry and limestone rubble infill. The metal rods now exposed appear to have kept the corner pillar in place during the earthquake.

3 BEHAVIOR OF MAISON DUFORT DURING THE 2010 EARTHQUAKE

Based on historical records, the ground motion during the 2010 earthquake was the largest shaking felt by the Maison Dufort since its construction. Even though the duration of the 2010 earthquake was only 15 seconds, the shaking led to significant degradation of the masonry bearing walls, on some elevations near total loss of infill panels (figure 3).

To describe the behavior of the masonry bearing walls of the Maison Dufort during the earthquake, it becomes important to describe the configuration of the clay-brick masonry and the rubble infill comprising the 20-inch thick masonry bearing walls. At the jambs of each doorway opening, at the corners of the building, and at wall intersections, clay-brick masonry “columns” rise from the uncut stone foundation to the second floor diaphragm. At the top of the 14-foot walls, just below the second floor diaphragm, there is also a horizontal “belt” of clay-brick masonry just below the colombage, and three horizontal “bands” of clay-brick masonry consisting of two courses of brick. Between the four wythe “columns”, arched doorways, “bands” and “belt” the wall is infilled with a limestone rubble. Although wholly inadequate as a wall system to resist large lateral deformations, the system nonetheless is a vernacular confined masonry, where less competent material is encapsulated by stiffer, stronger materials. To even further undermine the continuity of the wall, the collar joint that exists between the two stacks of two wythe masonry on the interior and the exterior is also filled with limestone rubble.

Figure 3. Earthquake damage to Maison Dufort, clockwise from left: 1) Damage to colombage in one corner location, 2) long rear wall of house showing masonry bearing walls, 3) wall intersection showing iron “chains” with square rod anchors.

From a petrographic analysis performed by WJE’s Janney Technical Center in Illinois, the mortar is composed of a crushed limestone, hydrated lime, clay and an organic contaminant. The hydrated lime does not appear to contain any hydraulic components. The aggregate is a mixture of siliceous and calcareous rocks and minerals, clay and organic contaminants. The mortar loosely binding the infill rubble is lime-based, also with clay and organic contaminants. Taken together, in the absence of destructive testing, it is likely that the shear strength of the clay-brick cement-based mortar is significantly greater than the rubble infill mortar.

Although it may seem that bearing walls parallel to the joist direction will receive less dead load than bearing walls perpendicular to the joist direction, the load path at the Maison Dufort is more complicated. The majority of the seismic mass of the building above the second floor is wrapped up in the heavy colombage exterior walls; the light-framed interior partition walls and the third floor attic contributes little to the seismic mass compared with rubble infilled wood-framing. The bottom chord of the heavy colombage walls is a sill plate having an approximate size of 10 cm squared (4x4 inches) which rests directly on the masonry bearing walls. This sill plate also supports the joists of the second floor framing, which do not pocket into the walls, but are notched at the ends and supported by the sill plate. This type of framing configuration provides continuity for the second floor diaphragm, which is more likely to be influenced by the behavior of the colombage rather than the masonry walls below. Therefore, although the walls perpendicular to the joists do receive slightly higher overturning resistance from dead load, it is to a much lower proportion than contemporary wood framing. In addition, the dead load is not distributed equally between the walls, because in many cases the stiff colombage panels and sill plate can easily span between the clay-brick “columns” leaving the infill portions vulnerable. This type of mechanism may be more pronounced at short lengths of colombage walls, which leave the middle portion of the wall below without dead load.

The layout of the masonry bearing walls at the ground floor is shown in Figure 4, along with the joist spanning direction. Many of the bearing walls shown have flanges at wall intersections, which can significantly boost the in-plane and out-of-plane resistance. But it is also clear that the fewer number of walls in the east-west direction will impart higher demands on the walls in this direction. Therefore, in a general sense, the masonry wall piers that performed worse in the earthquake were situated in the east-west direction and also situated parallel to the joists.

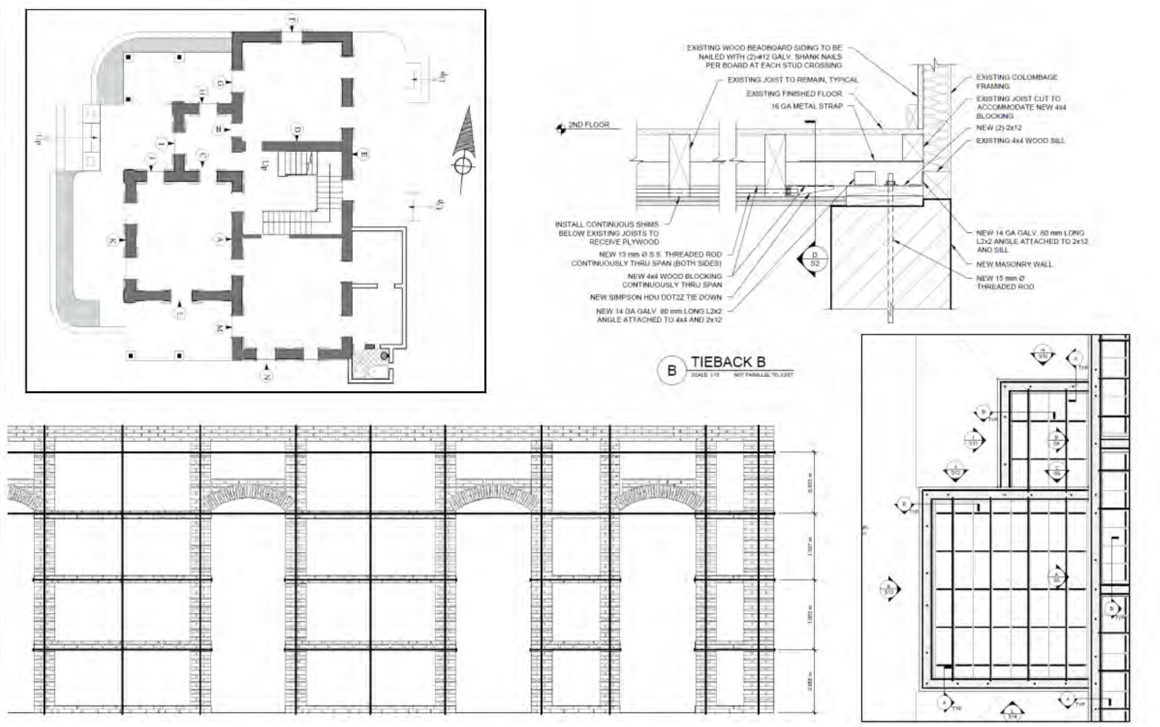

Figure 4. Drawings of rehabilitation of Maison Dufort, clockwise from upper left: 1) Ground floor plan showing wall layout, 2) typical floor-wall detail, 3) partial plan of diaphragm tie rod layout, 4) horizontal and vertical wall tie layout.

With the aspect ratio of many of the original masonry walls of the Maison Dufort, the primary mechanism of in-plane behavior should have been rocking of the piers between the base and the arched doorway openings. In reality, the very low shear strength of the rubble mortar -- binding the infill that makes up a substantial proportion of the overall volume of the wall -- promoted shear cracking and shear failure in many cases. The extremely low mortar strength is particularly evident in Figure 4 where a pier with an aspect ratio of nearly 3-to-1 still exhibits its shear cracking through the infill rubble. This type of behavior makes the application of code parameters such as an allowable height-to-thickness ratio from the 2012 International Existing Building Code [6] meaningless, since the low strength of the mortar drives the behavior.

Due to the flexible diaphragm with no positive connection between the sill plate and the masonry, out-of-plane the walls behave essentially as a cantilever above the foundation. Friction at the sill plate, and the interlocking of the masonry "belt" with the colombage provide low-strength energy dissipation. An additional "seismic belt", consisting of the embedded horizontal chain, fabricated from iron, provides another form of continuity between parallel walls and allowed the out-of-plane translation of each wall to be counteracted by a partner wall moving in the opposite direction.

Several aspects of the original construction, however, led to the wholesale shedding of masonry and rubble during the 15 second earthquake. In addition to the low mortar strength, the walls were also inhibited by the lack of ability to transfer vertical shear between the two different "wythes" -- interior and exterior -- that were connected with a rubble filled collar joint. Two aspects of the construction promoted differential movements between the wythes during ground shaking: the colombage sill plate being supported by the exterior wythe, and the iron chain embedded in the collar joint. Even with these mechanisms, it is possible that if the joists were not connected to the colombage the building could have partially collapsed, and without the iron chain the damage to the walls would have been more severe.

In general, the colombage was undamaged after the earthquake, with only several panels of rubble infill lost. In the locations where the colombage was damaged other deteriorative mechanisms were nearly always at play, particularly termite damage. Some other locations had cracking the colombage mainly where there was a loss of gravity support from the masonry walls below. Although the colombage is earthquake resilient and adds significant stiffness and heft to a structure that may be helpful in certain tropical calamities, such as hurricanes, its significant weight also adds significant seismic mass during an earthquake. Hand calculations demonstrate that for a typical wall pier at Maison Dufort, the added seismic demands are not counterbalanced by the resistance to overturning. This is particularly true since the presumed failure mode of many of the walls (shear failure) is influenced very little by the amount of dead load on the walls.

We did not discover any damage to the wood framed partition walls of the second floor and third floor attic that we could attribute to the 2010 earthquake.

4 EMERGENCY STABILIZATION

The initial shoring that was installed prior to our work was composed of metal lally columns that spanned between the first and second floor structures. This system was found to be wholly inadequate as the columns bore upon the first floor wood planks and did not take into account the crawlspace beneath. In addition the exterior colombage walls were left wholly unsupported. A wooden shoring plan developed by the Belgian-based *institute du patrimoine wallon* was designed and implemented that anticipated future work, allowed for structure realignment and provided safety for workers as they reconstructed the masonry walls.

5 OBJECTIVE OF THE MAISON DUFORT PROJECT

As a means of rehabilitating the Gingerbread neighborhoods, Fondasyon Konesans ak Libète [Foundation for Knowledge and Liberty] (FOKAL) decided to purchase some of the Gingerbread houses for rehabilitation in order to set a positive example in heritage conservation for other homeowners. Maison Dufort was a flagship in this effort and the first property slated for rehabilitation.

FOKAL and the World Monuments Fund determined that the Maison Dufort would be used as a heritage building trades training center to teach the crafts of masonry and carpentry to local builders. Therefore, its rehabilitation was to provide a pedagogical model suitable for various construction conservation and restoration techniques. The *Institut du patrimoine wallon* agreed to provide the guild training during the rehabilitation.

Any intervention on the building was to follow internationally recognized recommendations for the conservation, restoration and maintenance of historic buildings, such as those outlined in the Venice Charter and the ISCARSAH Principles. The rehabilitation was to both physically and visually convey the appropriate traditional techniques, using local methods and materials.

The rehabilitation was also to utilize the best technical standards related to seismic retrofit of pre-modern heritage structures of traditional or archaic structural systems. The retrofit was to be innovative and meet the constructive logic of the Maison Dufort in the selection and implementation of materials and techniques, and to utilize materials and methods that would be compatible with the original materials and workmanship.

6 SEISMIC RETROFIT

Several seismic retrofits were considered at the beginning but mostly did not fit with the pedagogical model that had been established by FOKAL. Some of the other retrofit systems that were considered included:

6.1 Shear walls

Shear walls composed of either confined masonry, reinforced concrete, or corrugated steel frames and metal studs. Shear walls in general were found to be incompatible with the existing unreinforced masonry in that they were too rigid and had deformability that was in variance with the existing structure. Use of shear walls was quickly determined to be unsuitable.

6.2 Exterior-applied confined masonry

Exterior steel confined masonry shows promise for gingerbread houses where the unreinforced masonry is still intact and does not require disassembly ad reassembly. It respects the traditional construction techniques and enhances them and also would promote pier rocking. However it can be an unaesthetic approach unless handled with absolute care and precision.

6.3 Reinforced masonry with stainless steel

The chosen seismic retrofit (Figure 4) can be described as durable (stainless steel) and developing the natural strength of the masonry while offering confinement. The system is perceivable from the exterior but the retrofit is by and large within the walls and not intrusive to the overall composition of the Maison Dufort.

7 CONCLUSIONS

The seismic retrofit for the lower portion of the Maison Dufort at the time of this writing is about 75% completed. By understanding the typical seismic behavior of the Gingerbread houses as well as the Maison Dufort, and understanding the traditional techniques utilized with the Maison Dufort, the authors were able to develop a seismic retrofit system that respects the traditional construction techniques and enhance the strengthening techniques that were already in place, namely the horizontal metal ties that were original in place at the top of the unreinforced brick masonry walls.

The Maison Dufort is schedules for substantial completion in October of 2014 and will serve a s a model for repair and seismic retrofit of numerous other Gingerbreads in Port-au-Prince as well as those in Cap Haitien and Gonaives.

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