Preservation of Cultural Heritage in Earthquake-Prone Countries

Akira Wada[a], Hideki Kit Miyamoto[b], and Amir S. J. Gilani[c]

[a] Professor Emeritus, Tokyo Institute of Technology, Tokyo, Japan, wada@akira-wada.com
[b] President, Miyamoto International, Inc. Los Angeles, CA, USA; [c] Manager, Earthquake Engineering, Miyamoto International, Inc., Sacramento, CA, USA

Abstract

Historic and heritage buildings have sustained severe damage and collapse in recent earthquakes, including in L'Aquila, Italy (2009), Port-au-Prince, Haiti (2010), Christchurch, New Zealand (2011) and Bohol, Philippine (2013). The same has been in case in past earthquakes in Japan (1891, 1923).

Damaged two Cathedrals attacked by strong earthquakes in Port-au-Prince, Haiti and in Bohol, Philippine, respectively

The main vertical and lateral load bearing members for these buildings are typically made of unreinforced masonry walls. These walls have experienced both in-plane and out-of-plane failures leading to the collapse of the structures. Given that the walls have little lateral capacity, it is critical to limit the input forces acting on them. In addition, these structures do not have a well-defined load path or diaphragm for the transfer of seismic loading.

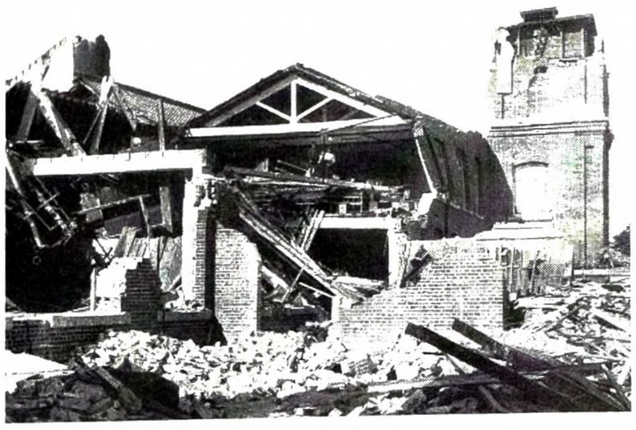
A proposed mitigation strategy combining seismic isolation and superstructure intervention is discussed to address these deficiencies. The proposed method significantly reduces the level of seismic excitation acting on the existing walls and limits the superstructure retrofit and, thus, preserves the historical features of the structures. Finally, application of this technique to Miragoane Cathedral in Haiti is presently under construction.

Seismic Performance of Masonry Structures in Japan

After Japan opened to the world in 1868, the country imported many technologies of construction from Europe. Unlike Japan, however, England, Germany and other developed European countries are not located in regions of high seismicity. Accordingly, these imported technologies did not account for earthquake activity and its potential damage.

In the Kanto Great Earthquake in 1923, many buildings constructed of masonry wall systems collapsed. Dr. Toshikata Sano, Professor at the Imperial University of Tokyo, led a very important decision to prohibit the use of masonry structural systems in Japan from then on.

Ninety two years have passed since that time and several well-designed and beautifully constructed structures using masonry wall systems built prior to 1923 remain in Tokyo. These buildings use very thick walls and steel members for reinforcement and sustained only minor damage during the Kanto Great Earthquake. Examples of the above-mentioned buildings include the Prime Minister's House, the Main Office of the Bank of Japan, and the Tokyo Station. In the past 20 years, we installed seismic isolation devices beneath these buildings to provide earthquake protection.



Damaged brick factory constructed by imported technology after Nobi Earthquake 1891

Collapsed 13 story masonry wall tower after Kanto Great Earthquake 1923

The Tokyo Station constructed in 1911 and completed retrofitting by seismic isolation on 2010.

Haiti Great Earthquake in January 12, 2010

In 2010, a large earthquake struck Haiti. According to official estimates, 316,000 people were killed, 300,000 injured, 1.3 million displaced, 97,000 houses destroyed and 188,000 damaged in the Port-au-Prince area and in much of southern Haiti. The National Cathedral in Port-au-Prince constructed in 1884 collapsed. The Miragoane Cathedral was constructed in 1880 and retrofitted using seismic isolation, designed by Miyamoto International. The Jacmel Cathedral, constructed on 1859, also was retrofitted after the 2010 earthquake. Both structural designs were peer reviewed by Prof. Akira Wada.

Saint John Baptist Cathedral of Miragoane in Haiti

Building description

Saint John Baptist Cathedral of Miragoane (hereafter referred to as the Cathedral) was constructed in 1880 and is one of the oldest Cathedrals in Miragoane, a coastal town approximately 80 km west of Port-au-Prince, the capital of Haiti.

The building has an area of approximately 580 m^2 and is nearly rectangular shape. The building is constructed using concrete floors with unreinforced masonry and stone (USRM) walls over stone masonry foundations. There is a ground floor and a mezzanine with access to the upper tower that houses the bell. The roof structure is assembled with trusses that combine both wood and steel and is approximately 13.9 m tall at its peak. The roof is supported by the walls on the exterior and by uniformly placed columns along the interior.

The front entrance of the cathedral has a bell tower that stands approximately 30.5 m high. The tower is constructed with steel frames above the walls. There is a concrete mezzanine that sits about 7 m above the finished floor of the cathedral. The walls along the perimeter vary from 500 mm to 750 mm in thickness and are the primary gravity and lateral load resisting members. The Cathedral suffered minor damage, primarily minor cracking during the 2010 Haiti Earthquake. The damage to the building was minor because it was not located near the epicenter of the 2010 earthquake.

Photograph of the Cathedral Miragoane

Seismic evaluation and retrofit

ASCE/SEI 41[1] served as the principal document used for retrofit evaluation. To achieve the design objectives and parameters, it is proposed to seismically isolate the building. This retrofit option was selected because it provides reliable seismic performance, while preserving the historical features of this cultural heritage building and minimizing retrofit of the superstructure. For historical or essential facilities, base isolation provides an attractive retrofit option.[2] Using this option, alterations of the superstructure are significantly reduced or eliminated.

Seismic isolation system

The owner was provided the option of using either elastomeric or sliding isolation systems. The isolation system parameters were chosen to obtain an approximate effective period of 4 sec and equivalent supplementary damping of 30% at MCE. Given the large shift in period and additional damping, it was expected that only a minor retrofit of the URSM walls would be required. The isolation plane is selected to occur just below the ground level of the building.

The isolators will consist of a combination of 54 bearings. The geometric arrangement of the isolators was selected to preserve the current load path in the URSM walls to avoid introducing additional concentrated loads to these vulnerable components. To install isolators, the existing walls will be reinforced on either side by permanent shoring beams, above and below the isolation plane. Next, a wall section will be removed and isolators installed. Finally, the remaining wall will be cut in order to complete the isolation plane.

Structural load path intervention

The building in its existing configuration lacks a well-defined load path for seismic forces. For example, the existing floors are not designed or detailed to serve as diaphragms and they do not have adequate connection to the perimeter walls to transfer lateral forces to the vertical members. In the absence of such load path, the vulnerable unreinforced walls will act as cantilevers, unsupported at the top and are susceptible to out-of-plane failure.

For seismic isolation system to be effective, this type of failure needs to be precluded. In the United States, this type of failure is mitigated and the seismic load path is developed by the addition of either wood or concrete diaphragms to existing buildings.

Since such an approach was not feasible in Haiti, the strengthening was provided by a series of steel rods and beams (channels and angles) that serve to connect the wall elements and provide horizontal bracing (diaphragm) and vertical bracing. The horizontal bracing prevent out of plane mechanisms and connect the internal columns to the external walls. Such an approach has been used extensively in Europe and especially in Italy and Greece[3] for the retrofit of historic buildings.

As shown in the figures, steel members are added:

a) Horizontal tie-down steel rods are added to the building to connect the perimeter walls in both directions,

b) System of steel truss works is added to provide diaphragm action in plane and vertical bracing,

c) Bracing is added to reinforce the tower and to connect this segment to the rest of the Cathedral,

d) Vertical tie-down rods are added to reinforce the walls at tower base and to improve its flexural capacity, and e) Steel longitudinal reinforcement is added to the tower walls.

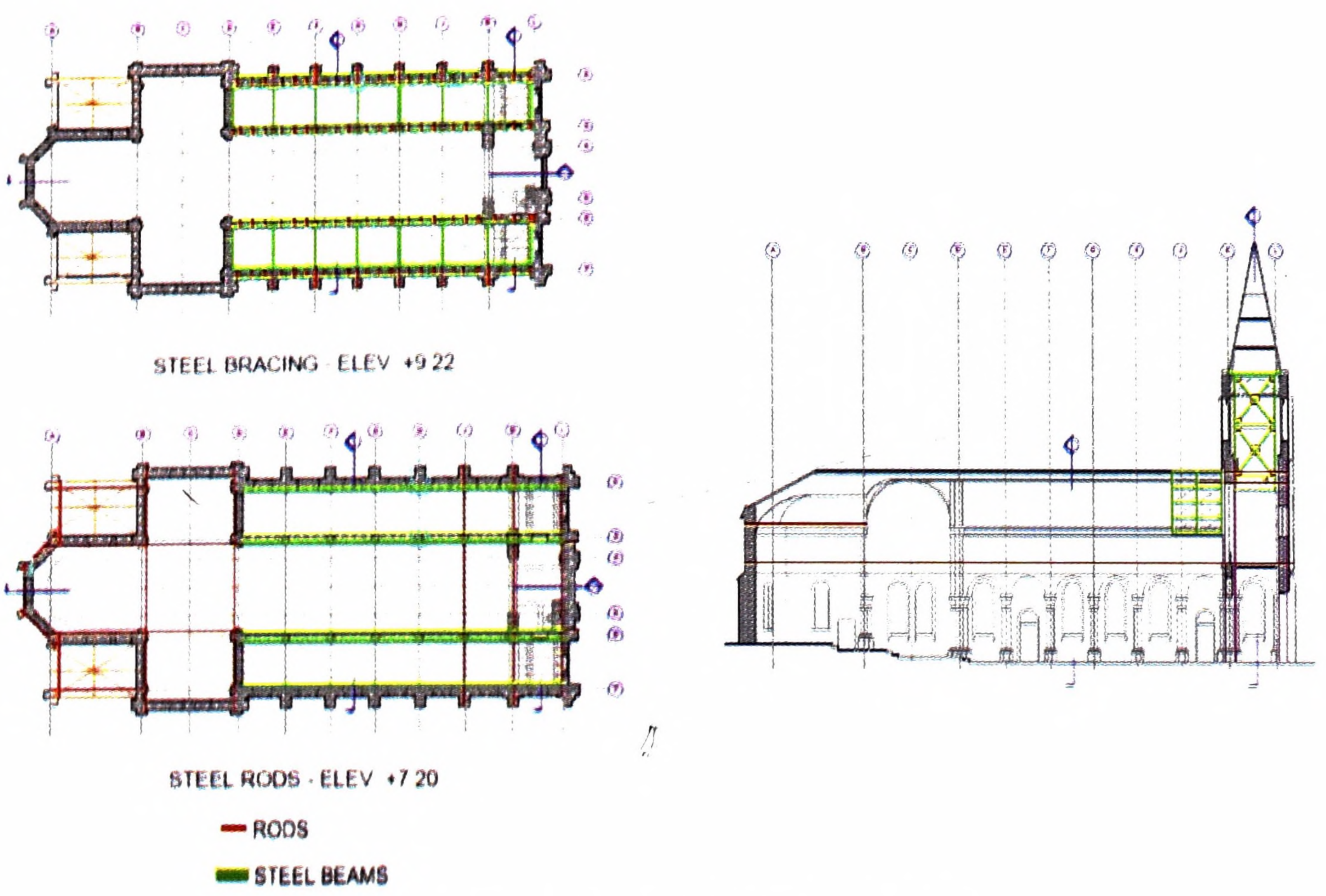
Structural capacity of the walls

The Cathedral's unreinforced stone masonry (URSM) walls are the load bearing elements resisting the applied vertical and lateral load applied to the building. Exposed sections of the walls with the wall plaster were removed for investigation. The composition of the wall was that of unreinforced masonry with irregular-shaped or rectangular-shaped stones and debris placed in the mortar.

The nominal strength of the URSM walls was based on the provisions of the Italian seismic code for unreinforced walls.[4] The code provides average tabulated values for different types of masonry based on the data available from the large pool of historical buildings in Italy. The URSM walls have the lowest mechanical properties per Italian seismic code.

Strength of URSM walls.

The addition of the steel tie rods and rolled members increases the capacity of the existing walls and was accounted for in-plane and out-of-plane strength calculations of walls. Linear (code-based) and nonlinear (static pushover) analyses methods can be used to determine the in-plane strength of the walls. The equilibrium kinematic approach (see for example Varela-Rivera[5]) was used to determine the out-of-plane capacity of the walls.



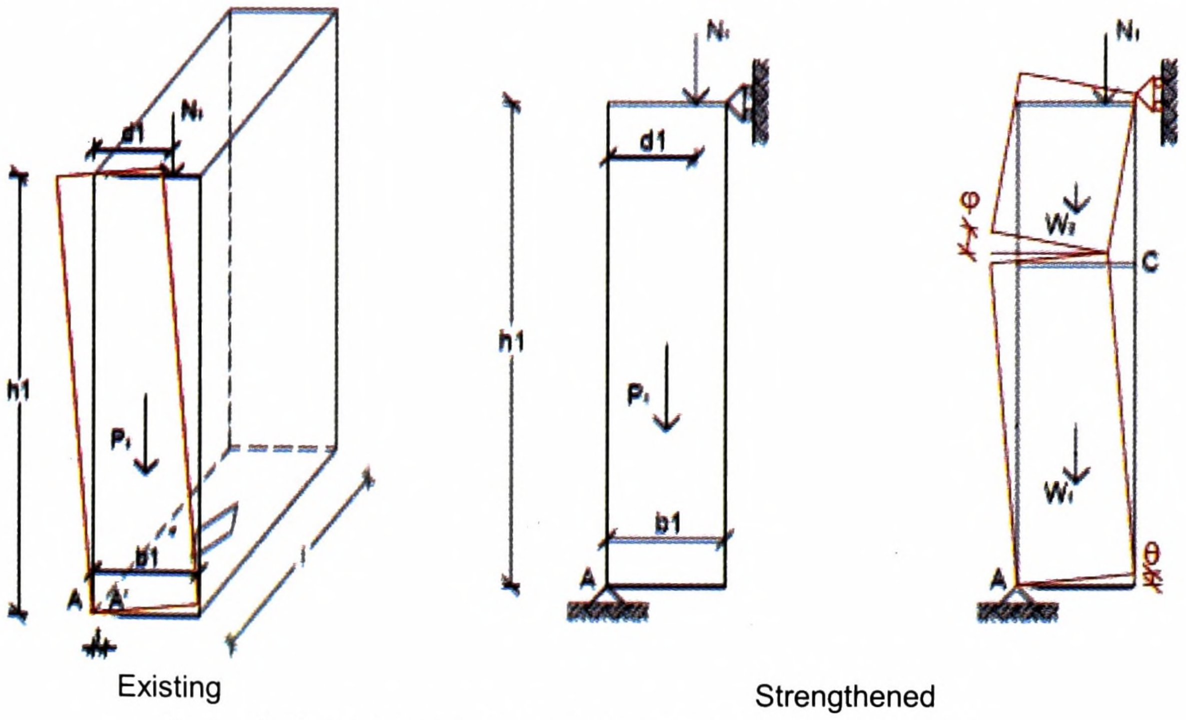
Strengthening of the Cathedral Miragoane

Out-of-plane capacity of walls.

The wall failure in the original configuration will be comprised of the rigid motion (rocking) of the wall about its base. This kinematic condition is possible because the top of the wall is not attached to a diaphragm. The lateral load (acceleration) required to initiate failure is resisted by the vertical load acting on the wall. Once steel members are added, the diaphragm action excludes this mode of failure. Instead, the failure mechanism will include formation of a hinge along the height of the wall. A larger lateral force (acceleration) will be required to initiate this higher mode failure.

In addition, tie-down rods provide additional resistance to overturning and thus serve to increase the lateral load required to initiate out-of-plane failure of walls.[6] The key parameter for development of out-of-plane strength is lateral acceleration at the base of the wall and perpendicular to its plane that initiates failure.

The computed capacities are adjusted by two factors: a. knowledge factor to account for uncertainties in material properties, construction details, and geometric characteristics; and b. behavior factor to account for the limited ductility of the walls. Constraint by adjacent elements to provide restraint to the out-of-plane rotation of the wall segment under consideration was included in analysis and equilibrium kinematic analyses of various walls of the Cathedral were conducted.



Existing

Strengthened

Out-of-plane failure modes for a typical wall segment

Thus, the critical lateral accelerations were calculated to be 0.25g at the ground level and 0.52g at the roof. As long as the isolated building's acceleration demands at these two levels are less than the governing values, out-of-plane failure will not occur.

In-plane capacity walls.

The walls at the perimeter of the bell tower are strengthened by adding eight (8) #5 (16 mm) reinforcement on each side. Holes will be drilled the height of the wall and vertical (longitudinal) reinforcement will be grouted in the holes. The reinforcement will be hooked at the base into the foundation to ensure that the reinforcing bars are developed and thus the full moment capacity of the walls can be achieved.

Cross-sectional analysis was conducted to develop the axial force-bending moment interaction diagram for the bell tower and main Cathedral walls The capacity of the bell tower walls was determined using static pushover analysis using plastic hinges whose properties were obtained from interaction analysis and program 3Muri.7 Both flexural and shear failure modes were accounted for in the nonlinear analysis.

The observation of damages on existing structures has led to the definition of masonry as a macro-element that captures the shear behavior in its central part and buckling behavior in outlying areas.The kinematic model used is described by eight degrees of freedom: the six components of displacement of end nodes and the two components of the macro-element. The overturning mechanism of the panel, caused by the absence of a significant tensile strength of the material, is represented assuming elastic contact in interfaces, while the mechanism of shear failure is schematized considering a state of uniform tension in the central module. Maximum deformations (drift) acceptable for the panels are settled to define the collapse mechanism, due to the mechanisms of shear and bending.

For the bell tower and Cathedral, no shear failure was developed and limit state is reached when walls reach their ductile flexural capacity. The failure states were reached at a base spectral acceleration of 0.11g and 0.12g.

Analysis model and results

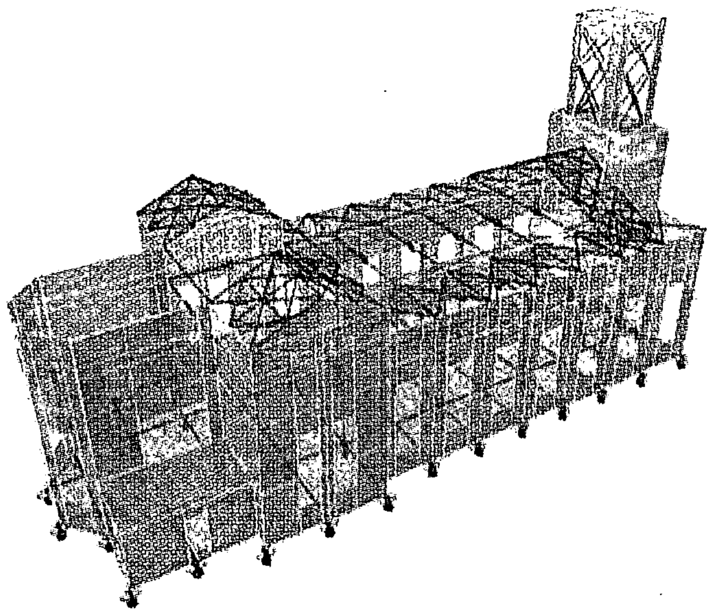
A three-dimensional analytical model of the building was prepared. The isolation system and new steel members are highlighted for clarity. The total inertial mass of the structure is estimated at 2,800 Mg.

For unreinforced masonry non-infill walls, ASCE 411 limits drift ratios to 0.6% and 1% for life safety and collapse prevention, respectively. Therefore, for the retrofitted structure, at both DE and MCE levels.

Story shear: The addition of the isolation system has served to significantly reduce the demand on the structure.

Out-of-plane accelerations: No out-of-plane failure is anticipated even at the maximum considered earthquake.

Response of the isolation system: The isolator displacements are less than the capacity and less than the limit (500 mm) as specified by the manufacturer.



Analytical model of the building

Conclusions

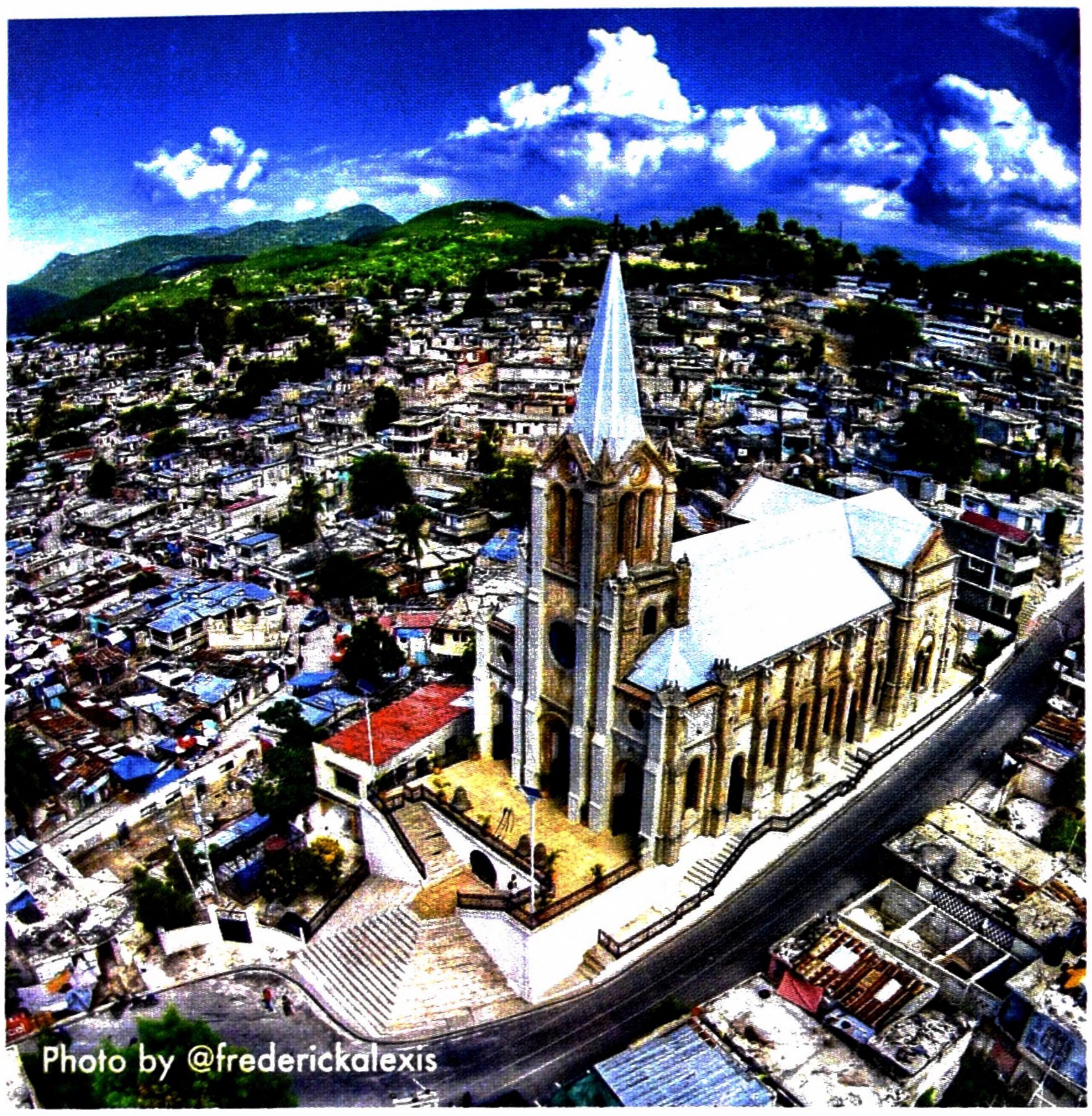
The Miragoane Cathedral is constructed of non-ductile URSM walls and does not meet the current code requirements for seismic performance. The structure is being retrofitted with an isolation system and strengthening measures to improve its load path and the out-of-plane capacity of the walls.

Analysis showed that the retrofit, including the addition of the isolation system, will significantly reduce the story drifts, accelerations, and shear.

Steel tie-downs significantly increased out-of-plane capacity of the walls. Truss assemblage of steel members provided a reliable load path for seismic forces. Added reinforcing steel increased the flexural capacity of the tower bell walls.

The isolation retrofit will significantly reduce the demand (drift and acceleration) on the URSM walls and the unreduced demand on the walls was reduced below member capacities.

Although many ancient masonry buildings in the world have been lost in earthquakes, many have survived when earthquakes were not so big and we can do more to protect them using seismic structural engineering. The authors have used seismic isolation systems to retrofit two large heritage cathedrals in Haiti with the goal of providing earthquake protection for these historic and beautiful buildings



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