Paper No. # 867694

Seismic Isolation Retrofit of a Historical Cathedral in Haiti

H. Kit Miyamoto 1
Miyamoto International
1450 Halyard Drive, West Sacramento, CA, USA
kmiyamoto@miyamotointernational.com

Amir S.J. Gilani 2
Miyamoto International
1450 Halyard Drive, West Sacramento, CA, USA
agilani@miyamotointernational.com

Akira Wada 3
Professor Emeritus Tokyo Institute of Technology,
Tokyo Japan
wada@akira-wada.com

ABSTRACT

The 2010 Haiti Earthquake devastated the country and resulted in many casualties and enormous damage to infrastructure. Following the event, the authors visited the country, conducted a damage assessment program, and developed retrofit programs. While the bulk of retrofit has focused on traditional upgrade of residential units, seismic protection devices (isolators and dampers) were used to provide enhanced performance for important and historical buildings. I particular, two Cathedrals damaged during the 2010 and early earthquakes, were retrofitted with seismic isolators. The design objectives for these structures was to minimize alterations to superstructure and thus to preserve the historical vintage, while providing near operational performance for large earthquakes. A key feature of these buildings is that the main lateral load resisting system is comprised of the rubble walls (stone and rubble without reinforcement). Detailed global mathematical models of the buildings were subjected to motions with site-specific spectrum-compatible emotions. The seismic retrofit goal was to limit the wall drift ratios and accelerations to protect rubble walls. Additional localized finite element analysis and in-situ testing and condition assessments were performed and verified the efficacy of the seismic retrofit solution..

Keywords: *Seismic isolation, structural intervention, Haiti, Cathedral, nonlinear analysis*

1 INTRODUCTION

Saint John Baptist Cathedral of Miragoane (hereafter referred to as the Cathedral) was originally 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 m2 and is nearly rectangular; constructed using concrete floors with an unreinforced masonry and stone 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 7m 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. Figure 1 presents a recent picture of the building. Unreinforced stone masonry (URSM) walls are used to resist gravity and lateral loading.

Figure 1. Photograph of the Cathedral, Looking east

2 SEISMIC RETROFIT METHODOLOGY

2.1 Overview

ASCE/SEI 41-06 [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 [3]. Using this option, alterations of the superstructure is significantly reduced or eliminated. Instead, the structure is de-coupled at the foundation level, since isolators are installed beneath the existing columns or walls. In the past two decades, many buildings in the United States, New Zealand, Japan, and Europe have used this technique.

Base isolation relies on the concepts of structural dynamics to modify the response of the building and reduce the seismic demands on the structural and nonstructural members. For isolated structures, the structural period is shifted away from the high-energy portion of the typical ground motions because the isolation plane is considerably softer than the superstructure, the drift ratios above isolators is reduced. The isolation system also introduces effective supplementary damping to the structures since the force-deformation relation is nonlinear.

2.2 Design objectives and performance goals

The design objective for seismic strengthening of Cathedral was to provide global and local performances that exceeded the requirements of ASCE/SEI 41-06. The enhanced global performance targets at design earthquake (DE) and maximum considered earthquake (MCE) are: DE (475 year): Performance of between immediate occupancy (IO) and life safety (LS), and MCE (2475 year): Performance of between LS and collapse prevention (CP)

The current common seismic retrofit practice targets are to obtain LS and CP for DE and MCE, respectively. Locally, accelerations and drift ratios were reduced to level below the values initiating the in-plane and out-of-plane failure of vulnerable URSM walls. In addition, the displacement of the isolation system was monitored to ensure that it does not exceed the capacity of the system.

3 SEISMIC HAZARD

The seismic hazard coefficients for the site were obtained from the USGS [8] are: short period spectral acceleration (SS) of 1.62g and a 1-sec spectral acceleration (S1) of 0.6g. The geotechnical report wrote that the Cathedral was built on limestone rock with an allowable bearing pressure of 1 MPa. The site condition was classified as soil class C using the data from the 2012 log of boring data. The analysis of the Cathedral was based on the nonlinear response history analysis.

4 SEISMIC RETROFIT

The seismic retrofit program consisted of providing an isolation system to reduce the demand on the building and to provide a robust load path for the transfer of seismic forces.

4.1 Seismic isolation system

For the Cathedral seismic retrofit, the state-of-the-art triple pendulum (TP) isolation system was selected. The isolation plane is selected to occur just below the ground level of the building. The geometric arrangement of the isolators has been selected to preserve the current load path in the URSM walls to avoid introducing additional concentrated loads to these vulnerable components.

4.2 Structural interventions

For the seismic isolation system to be effective, out-of-plane and non-ductile in-plane URSM wall failure type of failure need to be precluded, As such, it is important to connect structural elements and provide a robust path for the transfer of seismic forces. In the United States, this type of failure is mitigated and the seismic load path is developed by addition of either wood or concrete diaphragms to the existing buildings. Since such approach was not feasible in Haiti, the strengthening was provided by a series of steel rods and beams (channels and angles) serve to connect the wall elements and provide horizontal bracing (diaphragm) and vertical bracing. Such approach has been used extensively in Europe and especially in Italy and Greece [6] for retrofit of historic buildings. Figure 2 presents the plan and elevation view (longitudinal and transverse directions) of the Cathedral showing the added steel members.

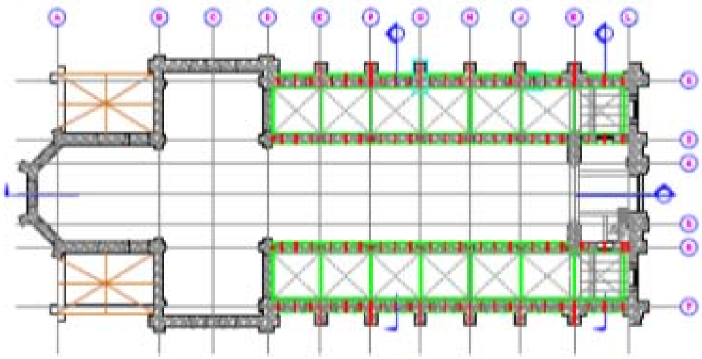


Figure 2. Typical detail of structural intervention

5 STRUCTURAL CAPACITY OF THE WALLS

5.1 Material properties of URSM walls

The Cathedral's URSM walls are the load bearing elements resisting the applied vertical and lateral load applied to the building. Figure 3 depicts exposed sections of the walls with the wall plaster removed for investigation. The composition of the wall is that of unreinforced masonry with irregular-shaped stones or with rectangular-shaped stones and debris placed in mortar

Irregular-shaped stones placed in the mortar

Rectangular-shaped stone and debris embedded in mortar

Figure 3. Typical composition of exposed unreinforced masonry stone walls

The capacity of the URSM wall elements were computed by using the available data and procedures for historic buildings from published references and in-situ testing: conducted during construction for verification

The nominal strength of the URSM walls was based on the provisions of the Italian seismic code for unreinforced walls [5]. The code provides average tabulated values for different types of masonry. The tabulated average values were developed based on the material data available from the large pool of historical buildings in Italy. The URSM walls have the lowest mechanical properties, whose values are listed in Table 1. For evaluation, the lower bound values listed in the table were used to determine the capacity of the walls

Table 1. Average nominal properties for URSM walls

Property	f_m MPa	τ_o kPa	E GPa	G GPa	w (kN/m^3)
Lower bound	1.0	20	0.69	0.23	19
Upper bound	1.8	32	1.05	0.35	

Where:

- f_m = average compression strength
- τ_o = average shear strength
- E = average (uncracked) elastic modulus
- G = average (uncracked) shear modulus
- w = average unit weight

The on-site strength of the URSM walls will be measured during the construction phase using the flat jack method [7].

5.2 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; see Figure 4. Once the steel members are added a larger lateral force (acceleration) will be required to initiate this higher mode failure. In addition, the 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 [4].

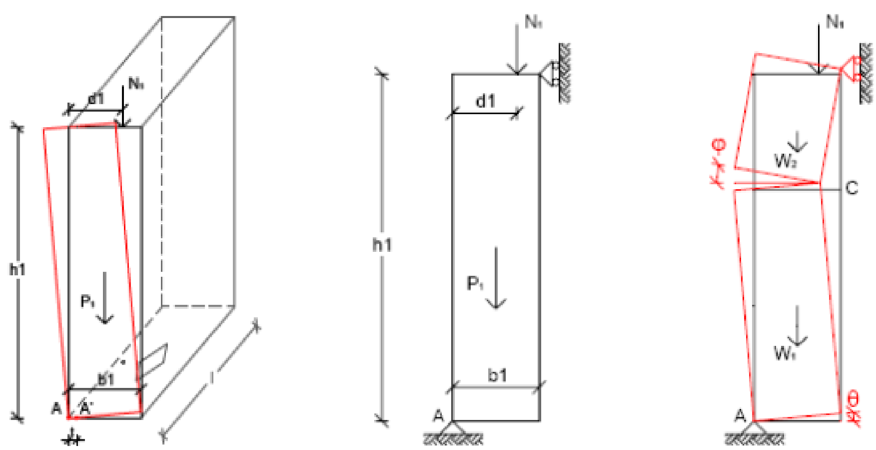


Figure 4. Out-of-plane failure modes for a typical wall segment

The key parameter for development of the out-of-plane strength is the lateral acceleration (a_o) at the base of the wall and perpendicular to its plane. The computed capacities are adjusted by two factors: i) knowledge factor κ to account for uncertainties in material properties, construction details, and geometric characteristics; and ii) behaviour factor q to account that the limited ductility of the walls and constraint by adjacent elements to provide restraint to the out-of-plane rotation of the wall segment under consideration. At the time of analysis, no field test data was available, a κ factor of 0.75 (1/1.35) was used as prescribed in the Italian seismic code [5]. Similarly, the Italian code recommends using a value of 2.0 for q when a simplified linear procedure (as is the case for this building) is utilized. Equilibrium kinematic analyses of various walls of the Cathedral were conducted. Table 2 summarizes the findings. The highlighted values are the modified strength values. As shown in the table, the critical lateral accelerations are 0.25g at the ground level.

Table 2. Computed out-of-plane capacity of Cathedral walls

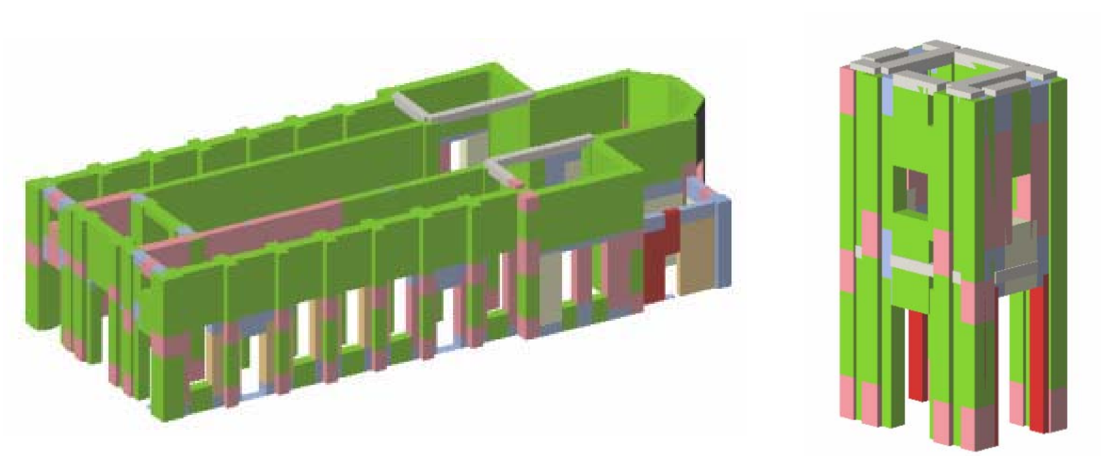
Wall segment	Capacity, g	
	Computed (a_o)	Modified ($q\kappa a_o$)
Typ. Segment between windows	0.27	0.39
Transept end wall	0.17	**0.25**
Central walls	0.30	0.44
Apse	0.55	0.82
Upper masonry above windows	1.66	2.46
Upper transept end wall	0.49	0.73
Bell tower	0.35	0.52

5.3 In-plane capacity of main Cathedral walls

The capacity of the main cathedral and bell tower walls were determined using static pushover analysis using plastic hinges whose properties were obtained from interaction analysis. Both flexural and shear failure modes were accounted for in the nonlinear analysis. The progression of the nonlinear response in the bell tower is listed in Table 3. Shown in Figure 5 are the state of cathedral walls and tower bell structure at its limit state. In this figure: i) Green denote wall segments that remain elastic; ii) Pink corresponds to flexural yielding; iii) Red designates flexural failure; iv) Ivory indicates shear yielding , and v) Light blue represents traction failure

Table 3. Progression of nonlinear response in the main Cathedral

State	Cathedral	Bell Tower
Flexural yielding at the base of the walls	0.04g	0.04g
Shear yielding	0.05g	0.05g
Shear failure	0.09g	--
Flexural failure	0.10g	0.11g
limit state	0.12g	0.11g



Main cathedral Bell Tower

Figure 5. Main Cathedral, mathematical model, and failure mode

6 ANALYTICAL MODEL

6.1 General model properties

A three-dimensional analytical model of the building was prepared using the program ETABS [2]; see Figure 6. The isolation system and new steel members are highlighted for clarity. The total inertial mass of the structure is estimated at 2,800 Mg. The individual isolators were model as bilinear link elements using the friction and curvature properties provided by the TP bearing manufacturer.

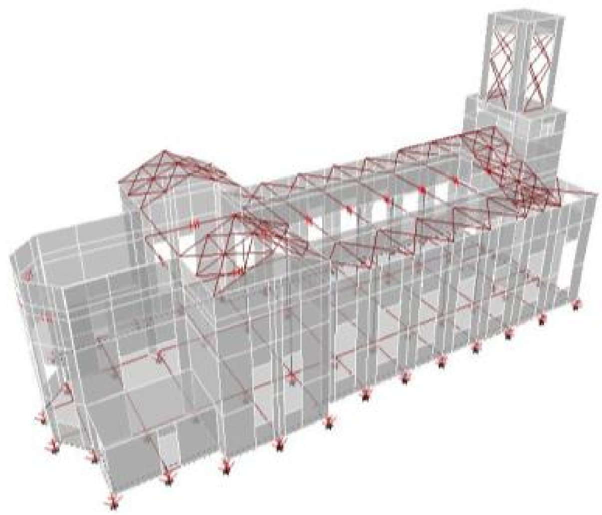


Figure 6. Analytical model of the building

7 ANALYSIS RESULTS

For unreinforced masonry non-infill walls, ASCE 41-06 has the following limitations on drift ratios 0f 0.3%, 0.6%, and 1.0%, at IO, LS, and CP, respectively. For the retrofitted structure, at both DE and MCE levels, performance of between IO and LS are obtained; see Figure 7, and thus the enhanced performance criteria are satisfied for drift response.

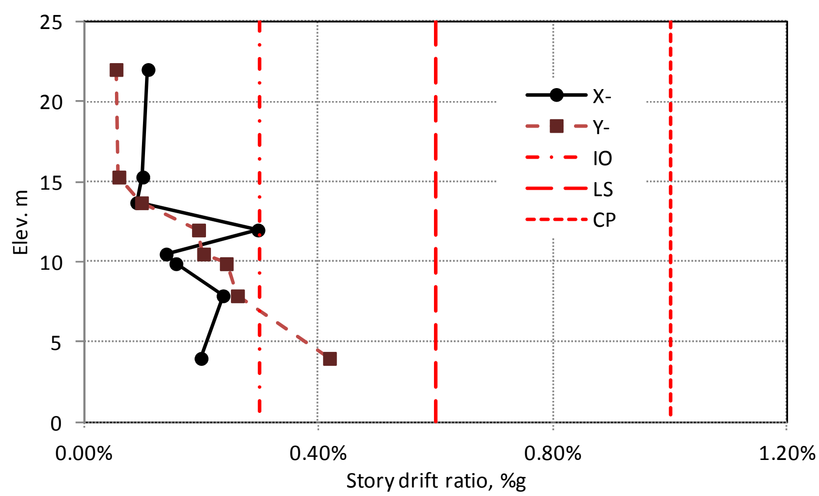


Figure 7. Computed story drift ratios (DE) and ASCE/SEI 41 performance limits

Figure 8 presents the bi-direction MCE displacement response of a typical isolator. Also shown in the figure is the displacement limit (500 mm) as specified by the manufacturer. As seen, the isolator MCE displacements in any direction are less than its allowed maximum motion.

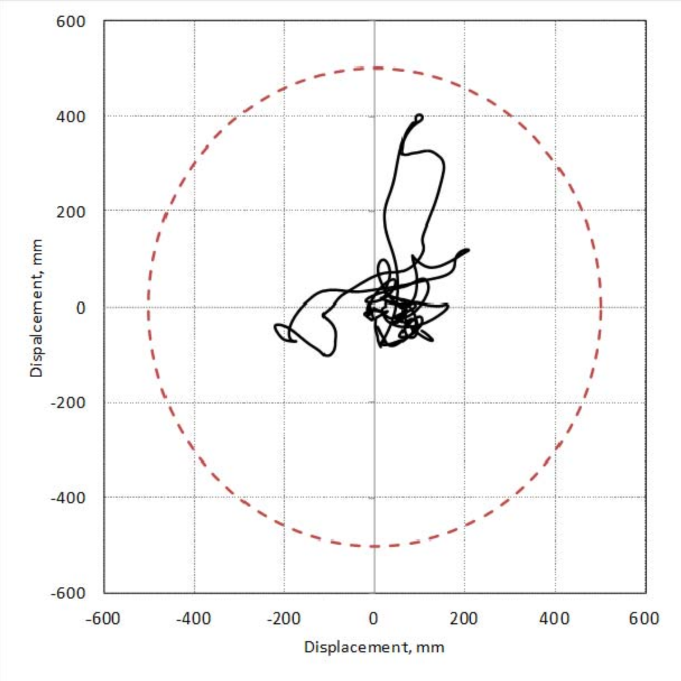


Figure 8. Bi-directional response of a typical isolator

Table 4 summarizes the computed response of the retrofitted Cathedral and the limiting response values. It is noted that the retrofitted Cathedral meets its design goals for both DE and MCE levels.

Table 4. Design criteria evaluation

Response	DE		MCE		Check
	Dem	Cap	Dem	Cap	
Story drift ratio, %	0.42	0.60	0.49	1.00	OK
Out-of-plane spectral acceleration, g	0.08	0.25	--	--	OK
Cathedral n-plane acceleration, g	0.08	0.12	--	--	OK
Tower bell in-plane spectral acceleration	0.08	0.11	--	--	OK
Isolator displacement, mm	--	--	420	500	OK

8 CONCLUSIONS

The Miragoane Cathedral is constructed of nonductile 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 increase the 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

9 REFERENCES

[1] ASCE/SEI 41-06 (2006), Seismic Rehabilitation of Existing Buildings, American Society of Civil Engineers, Reston, VA.

[2] CSI (2012), ETABS: Linear and nonlinear static and dynamic analysis and design of building systems, Computers and Structures, Inc., Berkeley, CA.

[3] De Luca, A. , Mele, E., , Molina, J., Verzeletti, G,, and Pintos, A.V. (2000) The retrofit of historic buildings through seismic isolation: Results of pseudodynamic tests on a full-scale specimen, proceedings of the 12th World Conference in Earthquake Engineering, Auckland, New Zealand

[4] Ismail, N. and Ingham, J.M. (2012) Cyclic Out-of-Plane Behavior of Slender Clay Brick Masonry Walls Seismically Strengthened Using Post tensioning, Vol 138 No 10 pp 1255-1266, Journal of Structural Engineering, American Society of Civil Engineers (ASCE), Ralston, VA, United States.

[5] Ministry of Public Works (MPW) (2008) Instructions for the application of Italian Building Code DM, Rome Italy

[6] Pezzullo, D., Cavuoto, F;, De Cunzo, M;, Del Giudice, M. (1992) Seismic retrofit of historical buildings, proceedings of the 10th World Conference in Earthquake Engineering, Barcelona, Spain

[7] Simões, A. Gago, A. Lopes R. and. Bento M. (2012) Characterization of Old Masonry Walls: Flat-Jack Method proceedings of the 15th World Conference in Earthquake Engineering, Lisbon, Portugal

[8] USGS (2012) United States geological Survey https://geohazards.usgs.gov/secure/designmaps/ww/signup.php