Seismic Retrofitting Guidelines for the Conservation of Doctrinal Chapels on the Oyón Highlands in Peru

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Abstract: *In the province of Oyón, Department of Lima, at altitudes between 2500 and 4100 m (8202–13,451 ft.) above sea level, there exist more than forty doctrinal chapels built in the seventeenth century. The Catholic Church built the chapels in order to eliminate persistent pagan idolatries throughout one hundred years of Spanish presence in Peru. The architectural expression of these chapels corresponds to a mestizo-vernacular version of the late Renaissance of the sixteenth century in the central Andes. This paper describes the characteristics of a structural typology that represents this group of chapels and develops recommendations for seismic retrofitting and intervention on historic buildings. Two retrofit designs that drew upon guidelines developed by the Getty Seismic Adobe Project (GSAP) are presented.*

Introduction

The doctrinal chapels of Oyón are located northeast of the city of Lima in the central highlands of Peru, between 2000 and 4000 m (6562–13,123 ft.) above sea level. Under the direction of Spanish missionaries, forty chapels were built by indigenous craftsmen at the end of the sixteenth and beginning of the seventeenth centuries. This area was well known in colonial times because the inhabitants faced violent actions by the Spaniards as they tried to eliminate persistent pagan idolatries. These actions were immediately followed by the construction of chapels, in order to indoctrinate the Indians through paintings, imagery, and exuberant religious icons. Most of these chapels were built over sacred Incan areas or buildings called *huacas*.

Peru is located close to the border of the Nazca and South America plates, which slide and collide during an earthquake. At the border of these plates is the Oceanic Fosse, located approximately 150 km (93 miles) from the coastline (under the Pacific Ocean). The greater sources of seismic risk are the superficial offshore earthquakes of the interplate (at a depth of 0–50 km, or 0–31 miles) and the intermediate-depth earthquakes (50–70 km, or 31–43 miles) along the coast and under the continent. There are deeper earthquakes, but they cause less damage on the surface. The seismic activity instrumentally registered during the last one hundred years reveals an almost total absence of earthquakes in Oyón.

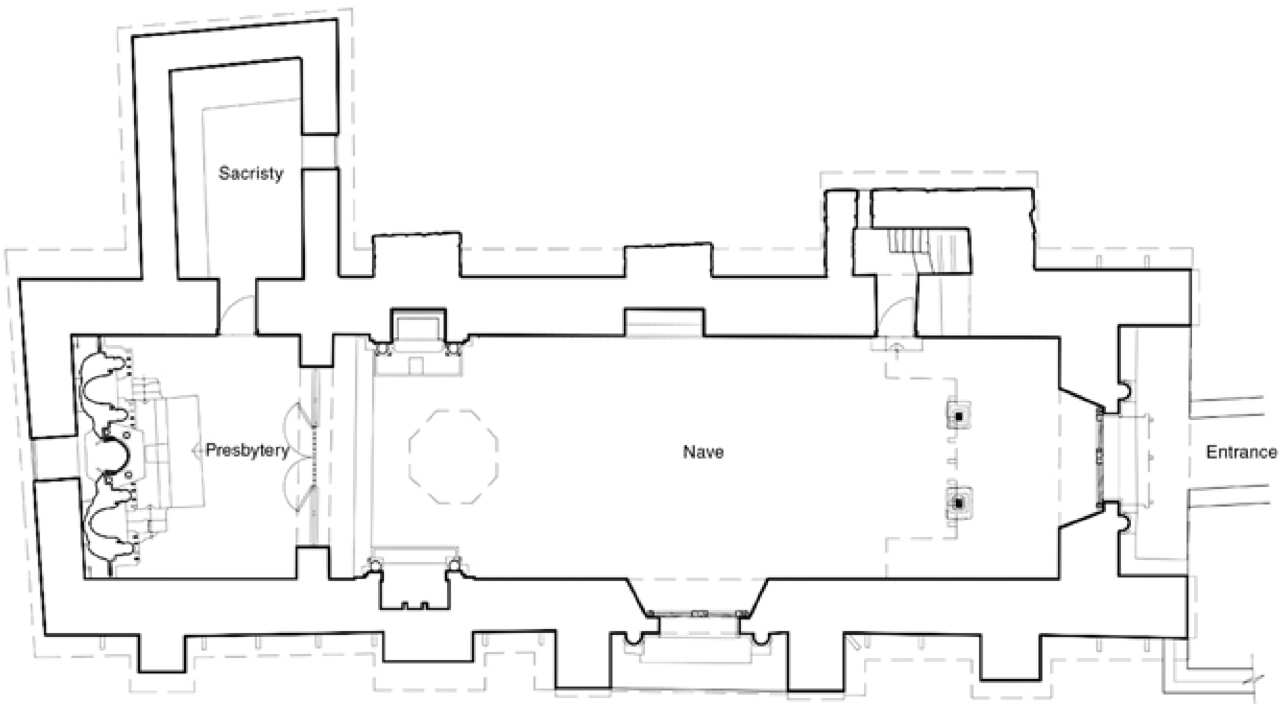
Typical Structural System

The typical configuration of a chapel consists of a single nave ending at the presbytery and an adjacent sacristy. These areas form an L-shaped floor plan, which is irregular and asymmetrical (fig. 1). The walls are generally constructed of adobe or mixed masonry. The roof is a lightweight wooden truss structure.

Existing Materials

Soil Foundation

The soil behavior and the soil-structure interaction are satisfactory. We have not found evidence of differential displacement or wall cracks related to the soil stability.



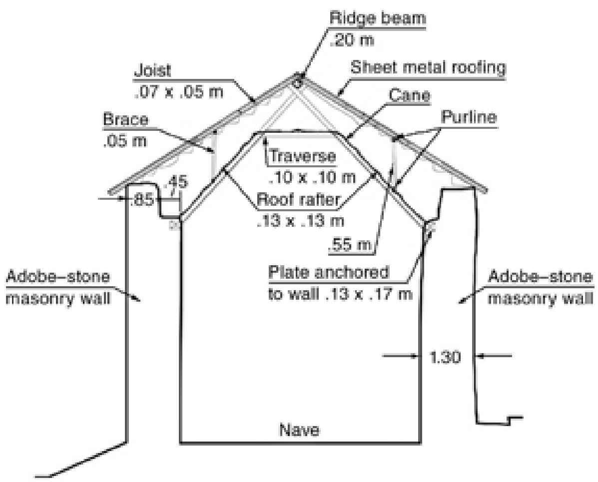


FIGURE 1 Plan and cross section of the Rapaz Missionary Chapel.

Foundation

The chapel's foundation is made of stone masonry with earthen mortar that reaches a depth of about 1.50 m (about 5 ft.). The condition of the material is satisfactory. However, this foundation is permeable and allows moisture to permeate the walls and stucco.

Adobe Masonry

The soil masonry has been proven in the laboratory to be of poor quality and of low resistance to large seismic forces. Some areas are of mixed masonry: layers of adobe alternating with stone layers.

Buttresses

All of the chapels of Oyón have buttresses that are either individual elements or buttresses that run along the longitudinal walls. In any case, these elements are properly tied into to the walls, but they still show large separation cracks. The buttresses are made of stone or adobe masonry.

Wood and Mats

The interior wooden roof trusses are the pair and knot type, spaced 80 cm (31.2 in.) from each other and laid over a bond beam on top of the walls (fig. 2). Secondary wooden rafters resting over the upper wall beams support exterior metallic corrugated sheets. The condition of these wooden elements is structurally acceptable because of the dryness and the altitude of the Andes. Areas exposed directly to the weather and moist walls have mold and show deterioration.

Secondary Nonstructural Elements

The nonstructural or secondary elements of the chapels are very important because they represent the artistic

FIGURE 2 Interior of the Rapaz Missionary Chapel showing roof construction. Photo: Daniel Giannoni.

value and cultural heritage that make these chapels outstanding examples of colonial art history.

Triumphal, or Main, Arch

This element, built in wattle and daub, regionally known as *quincha,* separates the presbytery from the long nave. It is plastered with lime and is polychromed on all surfaces.

Chorus

This is a wooden structure built at the end of the nave, supported on wooden columns and corbels, with polychrome and valuable carved elements.

Retablos

Major and lateral retablos of molded gypsum on a wooden structure are tied to the walls. The artistic mestizo-vernacular expression is unique because of the elements and decoration, which includes telamons, angels, and cherubs.

Signs of Structural Damage

Wall Cracks

Moderate cracks are found along the chapel walls. This cracking is old but cumulative. Cracks are due to seismic activity and weather in the highlands, which, at an altitude of 4000 m (13,123 ft.) above sea level, are very cold and dry, with a heavy rainy season. Cracks are located at wall intersections, wall joints, buttresses, and the corners of openings (door and windows). If new seismic activity should occur, the cracks will increase in number and size, forming wall segments separated by cracks. These segments will move independently, shifting until partial or total collapse of walls and roofs occurs.

Wall Moisture

There are three sources of wall moisture in the chapels. The first one is rainwater that falls directly onto the roof. When the roof leaks, water reaches the walls. This moisture is concentrated in the upper sections of the walls and can be detected by the deterioration of mural painting and stucco in these areas (fig. 3). The second source is the effect of rainwater and wind falling laterally on the exterior walls, degrading the plaster and leaving the adobe support exposed to weather conditions. The third is rainwater moisture that rises through capillarity, causing significant damage on lower sections of the wall, especially inside the chapels where decorated finishes are found.

Community Interventions

This damage is inadvertently caused by the good intentions and goodwill of the community people, who,

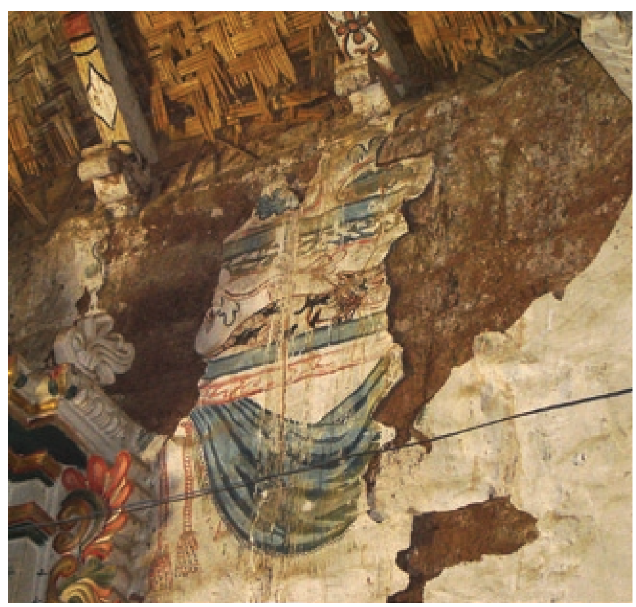


FIGURE 3 Moisture damage at the top of the walls, Rapaz Missionary Chapel.

FIGURE 4 Incompatible materials used at Huacho sin Pescado Missionary Chapel.

through ignorance of adobe techniques and the incompatibility of materials, spend money trying to protect their chapels by using cement plaster on exterior and interior walls to prevent humidity penetration. New concrete elements (columns, towers, interior plaster) tied to the adobe walls have also been built (fig. 4).

Structural Dynamic Conditions

Dynamic conditions refer to the structural performance of the chapels under seismic activity.

Floor Plan Configuration

The L-shaped floor plans of the chapels are asymmetrical and irregular. In the event of seismic activity, the walls tend to vibrate independently, and the stresses are concentrated at the wall joints because of the lack of flexure and shear deformation compatibility. These vertical lines at the wall intersections or at the wall and buttress junctions are the cause of major cracks evident in the chapels.

Slenderness of Walls

The slenderness, or wall height-to-thickness ratio, of the lateral walls is different from that of the frontal and rear walls. The slenderness of the main chapel walls and the sacristy are similar and are approximately 5 for the lateral walls and 7.5 for the walls with gables. This slenderness ratio is satisfactory for walls with appropriate transverse wall connections, but not for walls that are loose or behave independently as a result of cracking.

Materials of Low Quality and Resistance

The materials used in earthen construction are heavy, weak, and fragile. Because of their weight, earth materials undergo greater inertial forces, originated by the acceleration of earthquakes. Since the material is weak, the cracks appear at low stress levels during minor earthquakes. Since the material is brittle, the wall cracks abruptly, with no warning, leaving no time for inhabitants to escape before structural collapse.

Stability Versus Strength Criteria

The traditional systems for repairing historic monuments have emphasized increasing strength and delaying the time it takes for the wall to crack. Nevertheless, severe earthquakes will always cause cracks in adobe walls, separation between them, and eventual collapse. To confront this situation, the GSAP project proposed the design of retrofit measures that control the displacement of walls damaged by earthquakes and prevent collapse (fig. 5). These new criteria point toward the

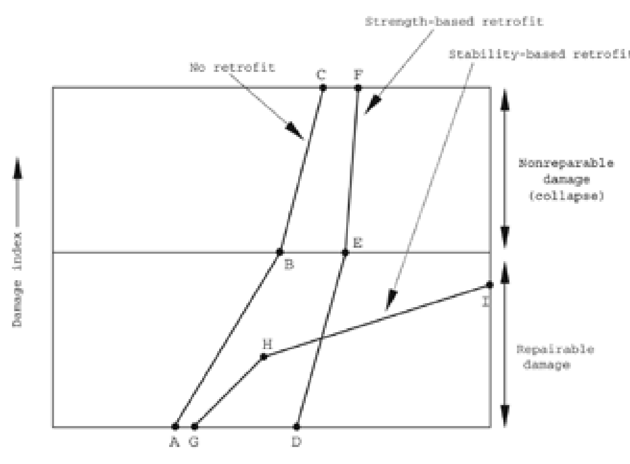


FIGURE 5 Damage-progression index versus earthquake severity for unretrofitted structures (ABC) and for strength-based (DEF) and stability-based (GHI) retrofitted structures. In the stability-based retrofit, cracks and displacement are controlled; this prevents collapse and allows for future repair. (From Tolles, Kimbro, and Ginell 2002, 45, fig. 4.1.)

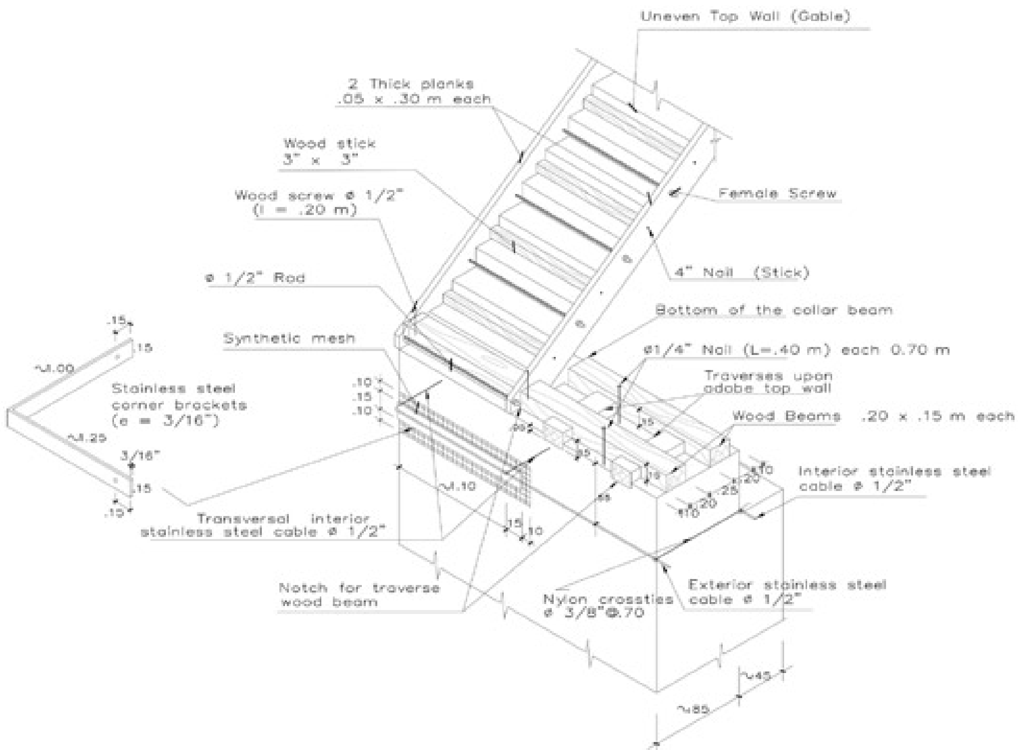


FIGURE 6 Design of a minimal intervention reinforcement for the Church of Rapaz (detail of upper corner).

preservation of human life and cultural heritage. The way to achieve this is to apply a series of redundant reinforcements to the structure, providing alternate paths for the distribution of earthquake-induced forces. These reinforcements are meant to confine the walls, preventing greater displacements of damaged walls. This design ensures the continuity and connection of cracked elements (Tolles, Kimbro, and Ginell 2002).

Structural Intervention Proposal

The doctrinal chapels of Oyón described herein show damage levels that within GSAP are classified as moderate (Tolles, Kimbro, and Ginell 2002, 54), meaning that cracks are shown at all expected locations of the building, but there are no major or permanent deformations and no unstable segments. According to this statement, the goals of interventions are:

- Minimize the impact on the historic integrity and actual appearance of the building.
- Allow for possible future removal of the intervention without permanent effect.
- Locate work in areas of less patrimonial or legacy value (respect for the mural paintings).
- Diminish damage due to low or moderate earthquakes; avoid or decrease structural damage and avoid total collapse in the event of large earthquakes.

On behalf of these goals, the following structural interventions have been decided upon (fig. 6).

Upper Wooden Bond Beam

There is a perimeter bond made of wooden elements on the main sacristy. On the side walls of the chapel, reinforcement consists of two parallel longitudinal pieces well connected by transverse wooden elements. Vertical constraint between the bond beam and the walls is achieved through 6 mm (0.23 in.) diameter and 0.60 m (23.6 in.) long forged iron nails. The main purpose of the beam is to achieve anchoring and continuity between the masonry walls and the wooden roof system, which rests on the side walls and the pair and knot trusses. Simultaneously, the pair and knot trusses rest on the longitudinal beam embedded in the wall, which transfers vertical and horizontal loads. It is expected that this continuity delivers the upper lateral restriction that the long side walls require during a seismic event that tends to overturn the walls. During the inelastic

FIGURE 7 Typical vertical seismic cracks at the wall intersections, Church of Rapaz.

phase when walls have cracked, the bond beam system also provides lateral restriction, keeping the wall segments formed by the major cracks together.

Stainless Steel Upper Cables

The installation of perimeter horizontal cables on the interior and exterior surfaces of the walls produces a structural global confinement that is very effective in controlling crack development during earthquakes. The cables should be of stainless rather than galvanized steel, in order to prevent alkaline reactions when they are in contact with lime products, commonly used in stuccos and paintings. Cables will be concealed between the two roof structures previously described.

Crack Repair at the Corners of the Walls

Because of the importance of the mural paintings along the interior and exterior walls (fig. 7), it is extremely difficult to repair these cracks without intrusion. The traditional solution for large crack repair was to demolish parts of the wall and rebuild them, producing an effective structural integration and recovering monolithic behavior. There are alternative repair methods yet to be developed, and studied in seismic tests in order to verify their effectiveness, such as sealing by injection of an adhesive grout. Use of grout injections that produce rigid material, such as cement mortars, is not recommended because they create stiffness discontinuities in the masonry. These discontinuities would concentrate stresses and cause new cracks during an earthquake. The current state of the art of the injection technique does not guarantee the real structural integration of the walls that is needed to recover a monolithic behavior.

Series of Nonstructural Emergency Works

We have designed very simple tasks or work that can be done in order to prevent damage (fig. 8) and to help the chapels to survive even before structural work is performed:

- Avoid rainwater penetration by replacing the deteriorated metal roof sheets and enlarging or oversizing the washers at the points of attachment.
- Avoid rainwater penetration by installing new glass in the chapel skylight.
- Construction of a perimeter stone walkway that slopes away from the monument to prevent groundwater accumulation along the foundation walls (fig. 8).
- Conservation and consolidation of the retablos, wooden elements, main arches, and pulpits.

FIGURE 8 A perimeter stone walkway diverts water from the foundation walls.

Fieldwork

During 2005, Patrimonio Perú received a grant from the World Monuments Fund to develop the Identification and Emergency Works of Nine Doctrinal Chapels Project. This project gave the authors the opportunity to execute some of the proposals described above and, most important, to instruct the local people about the benefits and the techniques of earthen construction, which they have already forgotten.

San Pedro de Navan

The San Pedro de Navan Chapel was one of the most damaged and unstable chapels in the area. We designed several restoration details (fig. 9), relying on engineer Julio Vargas Neumann's expertise. Additionally, with the help of the community's people, we were able to work on the following tasks relating to crack repair:

- Cracks in the sacristy and baptistery walls were repaired in the traditional way, since there was a lack of evidence of mural painting on the interior and exterior surfaces (fig. 10).
- We performed field tests to check strength and microcracking in the adobe, in an effort to optimize the seismic strength of the adobe masonry (Vargas N. et al. 1984; 1986, 257).

FIGURE 9 Retrofit design details, San Pedro de Navan.

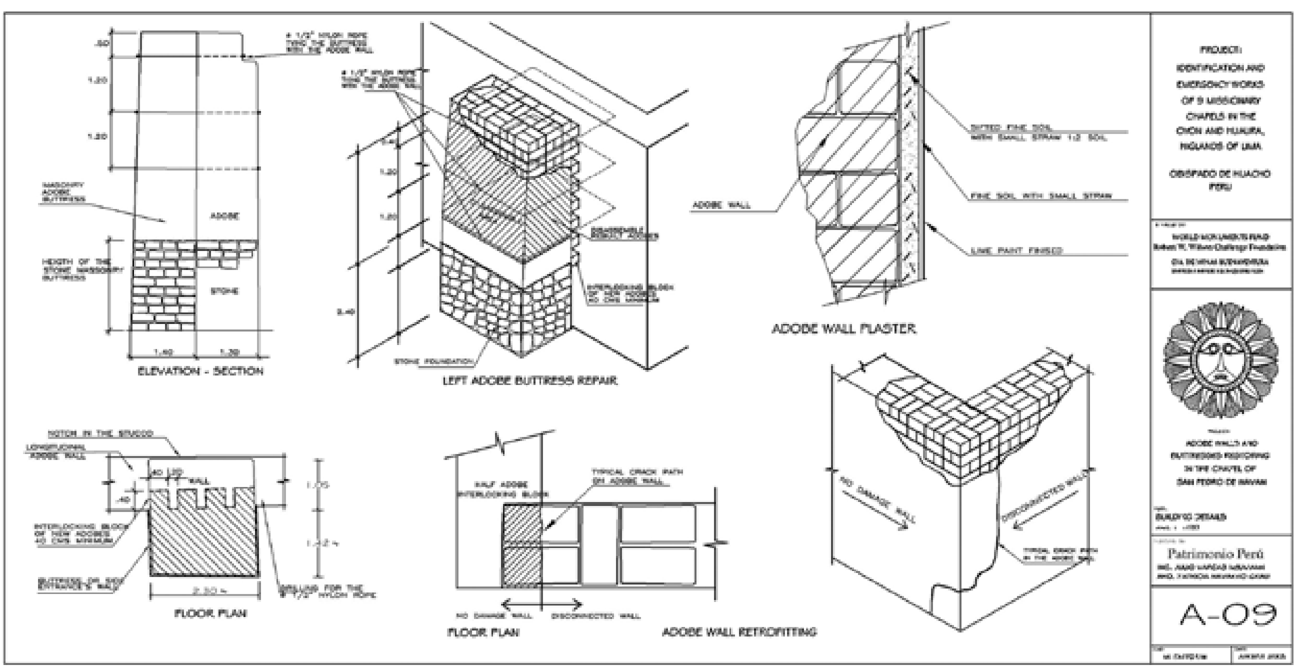


FIGURE 10 Damaged corner in the process of being demolished and rebuilt, San Pedro de Navan.

FIGURE 11 Bell tower in the process of being repaired, San Bartolomé de Curay.

San Bartolomé de Curay

The community of Curay asked Patrimonio Perú to restore the bell tower with funding by a locally operated mining company (fig. 11). We designed our working schedule in order to carry out the emergency works and the bell tower restoration at the same time. We had the hand labor of people in the community, and therefore we were able to instruct them on the earthen construction techniques and the field tests. Restoration of the bell tower included:

- removal of cement mortars
- filling of eroded areas with adobes and mud plaster
- application of mud and lime plasters
- application of color according to evidence found on the intrados of the high windows

Conclusion

Because of similarities between Peruvian monumental earthen buildings and the California earthen building prototypes used in developing the GSAP guidelines, the guidelines can be applied to many buildings in Peru and throughout the Latin American region. The Spanish- and Moorish-influenced design of these monumental structures has deep roots that reach back to the Spanish colonization of the Americas. We have drawn upon the GSAP principles in designing the work described in this paper. These are the first steps toward the application of GSAP techniques to buildings in Latin America.

Acknowledgments

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