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Revealing Earthquake-Resistant Geometrical Features in Heritage Masonry Architecture in Santiago, Chile

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ABSTRACT

Chile is in one of the most seismically active zones in the world and its capital, Santiago, has frequently been destroyed by earthquakes since its foundation by Spanish colonialists in 1541. Nonetheless, there are some historic masonry buildings that remain as a testimony of the efforts of builders to erect the new, unfamiliar structures introduced by the Spanish, in a seismic context like Santiago.

This article will explore the geometrical features of churches, public buildings, and Colonial houses—the most representative surviving masonry buildings in Santiago—in order to reveal their common characteristics. These characteristics, in turn, could explain their longevity and good dynamic structural performance. The results of the analysis shows that each typology—after a long process of trial and error induced by earthquakes—has evolved to a set of geometric rules that allowed the buildings to survive the test of time, and have given a strong identity to the heritage of Santiago.

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architectural heritage; earthquake-resistant masonry buildings; geometrical analysis; historical constructions; local seismic culture; Santiago; typological analysis

1. Introduction: high seismic activity in Santiago, a challenge in developing masonry structures

Chile is located on the Pacific Ring of Fire, where the subduction zones between tectonic plates has created one of the world's major seismic and volcanic zones (Rauld 2011). Specifically, the country sits atop the subduction of the Nazca plate under the South American plate, which results in being frequently subjected to intense earthquakes. In fact, the strongest earthquakes registered in history have occurred in Chile, such as the earthquake in Valdivia (39°5'S, 74°5'W) in 1960 of Mw9.5, the greatest magnitude ever registered, and the Maule earthquake (36°3'S, 73°2'W) in 2010 of Mw8.8, the sixth strongest in the world (Table 1). The Chilean National Seismological Centre (2016) reports more than a hundred earthquakes over Mw7 since 1570, which yields an average occurrence of a major earthquake once every 10 years.

As in the rest of the country, the capital Santiago (33°27'S, 70°40'W) also experiences high levels of seismicity. This results from a combination of different

types of source influences which includes not only the influence of intraplate earthquakes, but also the effect of intermediate-depth intraplate and crustal earthquakes, with PGA values of 55% of gravity acceleration (g) for a period of return of 475 years and 72% g for a period of return of 1950 years (Leyton, Ruiz, and Sepúlveda 2010).

Sixteen earthquakes over a magnitude of Mw7 with an epicenter near Santiago have been registered since the Spanish foundation of the city in 1541 (Figure 1). The strongest registered were in 1647 and 1730 and were considered the largest earthquakes of the colonial period; in both cases, the city had to be completely reconstructed. The earthquake of 1647, called the “Magno Earthquake” of Mw8.5 “devastated the city of Santiago and killed approximately a thousand people, one-fifth of its population”¹ (Montessus of Ballore 1912, 18 in Cisternas 2012, 25). According to chronicles, the city was left “without buildings remaining or churches in which to celebrate the divine offices, or houses to be able to live in, or walls that did not threaten danger”² (Hearers of Santiago 1648 in Gay 1852, 456). The earthquake of 1730 of Mw8.7 devastated Santiago again, especially destroying religious buildings

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¹Author's translation from Spanish: “devastó la ciudad de Santiago y mató alrededor de mil personas, es decir, a un quinto de su población”

²Author's translation from Spanish: “sin dejar edificio en pie templo en que poder celebrar los oficios divinos, ni casa en que poder vivir ni pared que no quedase amenazando segundo peligro”

Table 1. Strongest earthquakes in the world. © Jorquera, Lobos and Cortez 2015, based on information available on the webpage of United States Geological Survey. Reproduced by permission of Jorquera, Lobos, and Cortez. Permission to reuse must be obtained from the rightsholders.

	Location	Date UTC	Magnitude	Latitude	Longitude
1	Valdivia, Chile	1960-05-22	9.5	-38.29	-73.05
2	Alaska, USA	1964-03-28	9.2	61.02	-147.65
3	Northern Sumatra, Indonesia	2004-12-26	9.1	3.30	95.78
4	East Coast of Honshu, Japan	2011-03-11	9.0	38.32	142.37
5	Kamchatka, Russia	1952-11-04	9.0	52.76	160.0
6	Maule, Chile	2010-02-27	8.8	-35.85	-72.72
7	Coast of Ecuador	1906-01-31	8.8	1.0	-81.5
8	Rat Island in Alaska, USA	1965-02-04	8.7	51.21	178.50
9	Northern Sumatra, Indonesia	2005-03-28	8.6	2.08	97.01
10	Assam, Tibet	1950-08-15	8.6	28.5	06.5

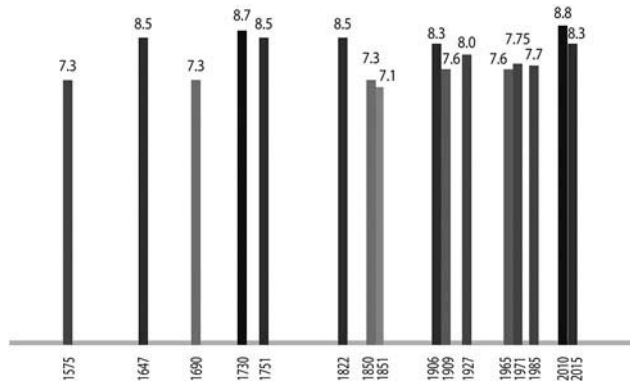


Figure 1. Earthquakes over magnitude Mw7 at their epicenter that have provoked damages in Santiago. (Based on information from the Chilean National Seismological Centre).

while homes “remained battered and ruined like many of its buildings”³ (Medina 1952 in Benavides 1995, 45).

Undoubtedly, this high seismicity conditioned the development of architecture in the city, a reason why indigenous houses of pre-Hispanic people of Santiago were built with half-timbered and daubed earth walls (wooden structures with an in-fill of straw and clay), which were light and elastic. Instead, for the Spanish conquerors that arrived in 1541, it must have been a great challenge to erect large buildings such as churches with the masonry techniques they imported, given their particular vulnerability to seismic events. This was further complicated by the fact that Spanish builders did not have experience in building earthquake-resistant structures, and the native people who were employed in the workforce were not familiar with the new “big architecture” nor the Spanish masonry techniques. These conditions made the first colonial buildings erected by the Spanish very vulnerable to seismic activity, and lead inevitably to their destruction. However, in the following centuries, a

long process of trial and error was prompted after every earthquake, creating a “local seismic culture” (Ferrigni 1990). This was based only on the use of unreinforced masonry (adobe, brick, or stone) since timber, as a construction material, had been abandoned after several fires in Santiago and alternative modern techniques had not yet been invented. This is why between the XVI-XIX centuries the use of masonry was employed for all types of constructions. In addition, particular architectural features were adopted, such as the preference for one story buildings, with “massive forms, very thick walls and low ceilings”⁴ (Villalobos et al. 1990, 39), few openings and “the decrease in the height of the rooms, especially if they were two-storey”⁵ (Benavides 1988, 155). These characteristics were known simply as “traditional Chilean style” which according to the Chilean historian Sergio Villalobos et al. (1990) was established after the earthquakes of 1575 and 1647.

At the urban scale, another earthquake-resistant precaution was developed: the building of entire blocks with the same architectural typology, so that the buildings work as a unique structural unit, controlling displacements in the event of earthquakes. For this reason, the coincidence of the height of the buildings, the location of diaphragms, the location of walls and the use of the same buildings systems were very important.

All this “earthquake-resistant empirical knowledge”, which allowed a better seismic performance was lost with the arrival of modern materials and building codes at the beginning of the 20th century. Furthermore, the widespread urban renewal of Santiago, in the last twenty-five years, has destroyed a larger number of historical buildings than any earthquake in recent history, and is one of the reasons why nowadays there are barely seventy historic buildings in the colonial historic center of Santiago (Figure 2). These remain isolated on

³Author’s translation from Spanish: “maltratadas y arruinada mucha parte de sus edificios”

⁴Author’s translation from Spanish: “formas macizas, paredes muy anchas y techos bajos”.

⁵Author’s translation from Spanish: “... el predominio de los muros llenos sobre los vanos, la disminución en la altura de las habitaciones, especialmente si eran de dos pisos...”.



Figure 2. Location of Santiago and its historic Colonial center defined as study area.

city blocks shaped by new and taller buildings, resulting in the destruction of the previous urban scale earthquake-resistant strategies. In addition, as the buildings remain isolated, they become “unique and extraordinary” cases, which makes it much more difficult to identify the common earthquake-resistant patterns among them, even though individually they are the best examples of accumulated empirical earthquake-resistant knowledge. In fact, after the Maule 2010 earthquake of magnitude Mw8.8, which in Santiago had a VIII intensity and acceleration values of PGA 0.32 g and 0.242 g, many “structures built using weak materials (adobe) and old-fashioned buildings (unreinforced masonry buildings built before the 1940s) were more affected” (Astroza, Ruiz, and Astroza 2012, 146). Nonetheless, none of the unreinforced masonry buildings of the colonial historical center of Santiago suffered substantial damages, like the common out-of-plane damage in tall historical buildings such as churches, which instead was registered in historical buildings in other cities and in other areas of Santiago. Therefore, despite the intrinsic vulnerability of the unreinforced masonry techniques used in Santiago, defined by Monge and Astroza (1989, cited in Astroza, Ruiz, and Astroza 2012) there is something special in the architectural heritage of the historical center that allows it to withstand earthquakes with less local damage.

Despite the importance of this architectural heritage, not all surviving buildings are recognized as such and few of them have been analyzed, a reason why the research presented here started with the objective of identifying the buildings.

2. Case studies and research phases

In order to recover earthquake-resistant vernacular knowledge, the research project “Rediscovering Vernacular Earthquake-resistant Knowledge: Identification and analysis of built best practice in Chilean masonry architectural heritage” (2013–2016)⁶ has analyzed the “surviving” unreinforced masonry buildings located in the historic Colonial center of Santiago, a well-defined area originally delimited by geographical elements like the two branches of the Mapocho river and the Santa Lucia hill, and which corresponds to what was the entire city of Santiago during the Colonial period (1541–1818). The oldest buildings of Santiago are located in this area, which means that they are the buildings that have survived a major number of earthquakes in the city, and thus, for understanding the earthquake-resistant strategies, they are the best historical testimonies which represent full-scale testing data. This historic Colonial area was also chosen because it has the same type of soil which is, therefore, a common denominator among all buildings. That soil “is characterized by being composed of sandy gravels from the Mapocho” river (Leyton et al. 2011) which has a particular firmness, associated with reduced or limited amplification of the seismic signal coming from the crust rock failures.

The research was divided into three phases during a three-year period: (i) identification of all the masonry buildings in the study area (2014); (ii) classification into typologies and comparative analysis to identify the general rules of good structural behavior (2015); and finally

⁶Funded by the Chilean National Fund for Scientific and Technological Development—FONDECYT under the Initiation project n°11130628.

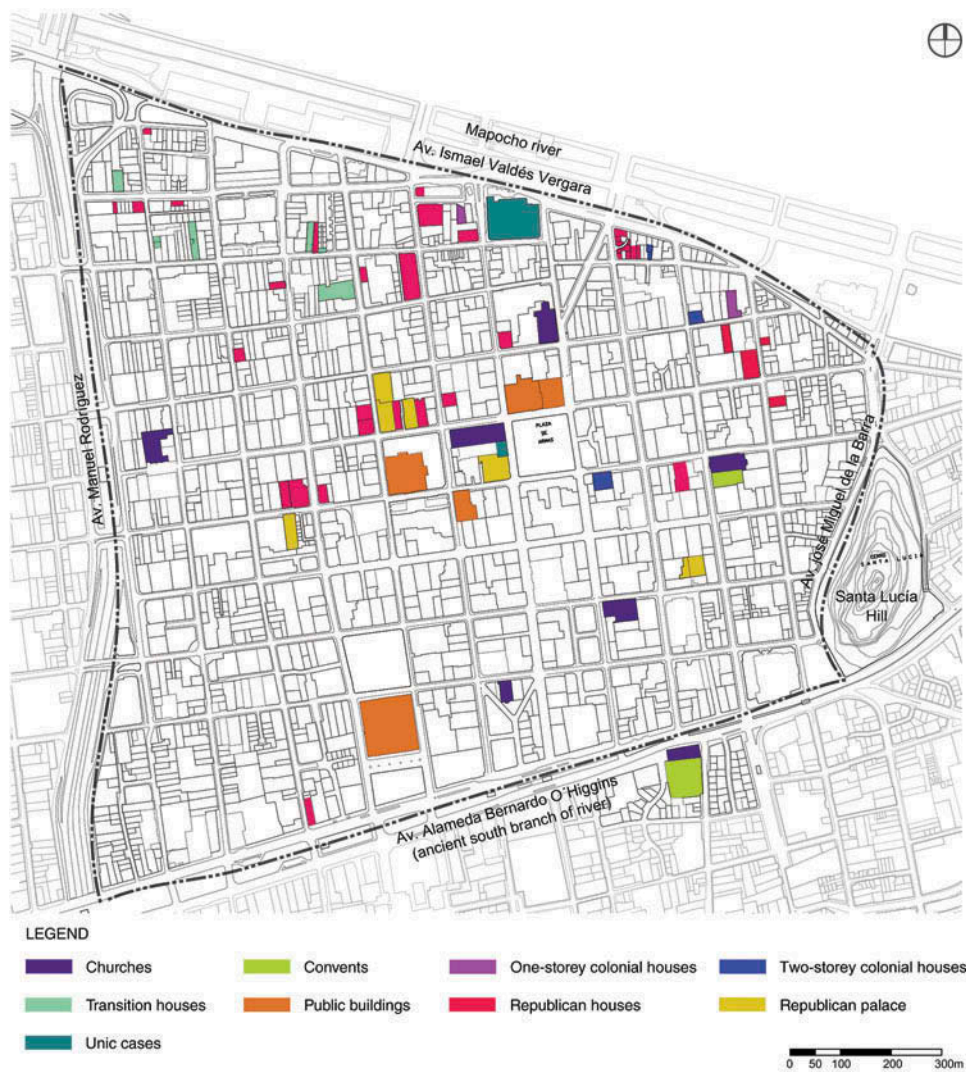


Figure 3. Typologies identification map.

(iii) analysis of those buildings considered the best in terms of earthquake-resistant performance (2016). The first and the second phase are already concluded and are presented here.

During the first phase of the research, around 70 buildings were identified in the designated area. These were selected because: (a) they were built with unreinforced masonry, a brittle material; (b) they do not present serious structural interventions that could have altered their structural behavior; (c) they have presented some local damage during past earthquakes, but have not suffered serious damages like collapses; and (d) they were built between 1541 and 1860, that is to say between the foundation of Santiago and the date of arrival of the first industrial elements of construction using cast iron and Portland cement, materials which could be used as structures or wall reinforcements.

In the first part of the second phase of the research, eight architectural typologies were identified and

classified by recognizing common patterns, such as use, geometry, architectural configuration, constructive materials, and building systems. Figure 3 shows the study area and the distribution of the buildings according to the eight architectural typologies identified in this research. These typologies were both from the Colonial (1541–1818) and Republican period (1818–1891) and included: *churches*, *convents*, *one-storey colonial houses*, *two-storey colonial houses*, *one-storey “transition”-houses*, *republican houses*, *republican palaces* and *public buildings* (Figure 4). The *Colonial* typologies were built entirely in adobe, fired brick, and stone masonry. The *Republican* typologies were built with adobe, fired-brick, and timber frame. From this first classification, it has been possible to observe that although buildings are greatly varied—because of a lot of constructive experimentation following earthquakes—they share many similarities, such as simple geometries, thick walls with few openings, and a “robust”

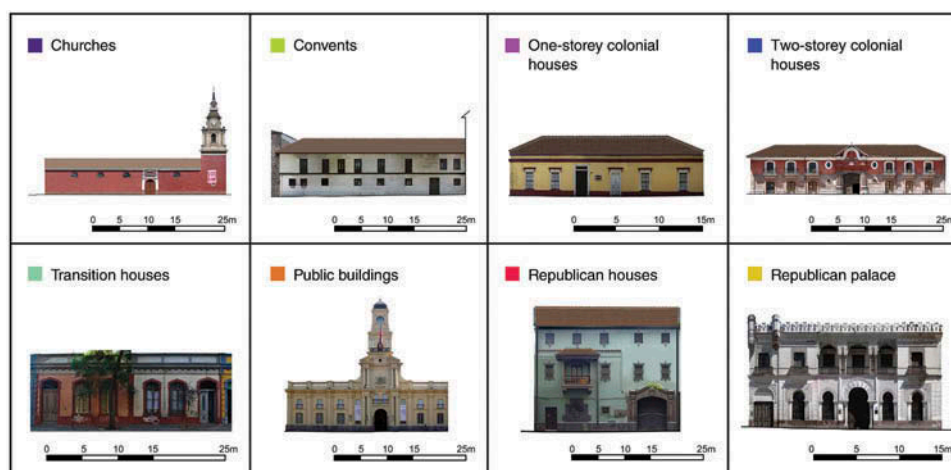


Figure 4. Representative examples of each typology.

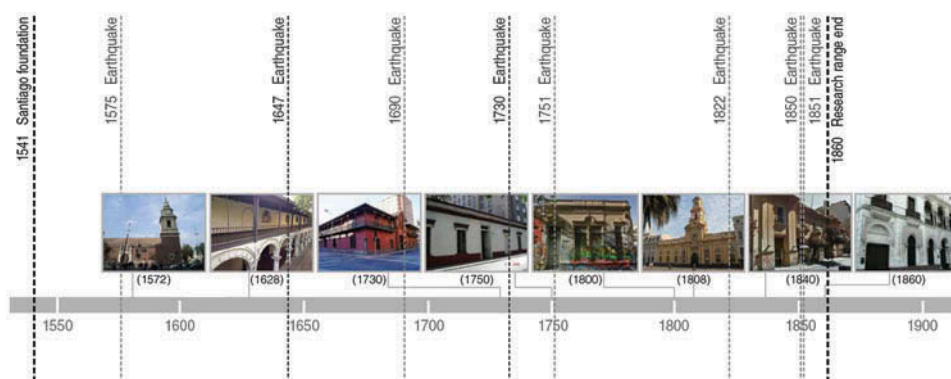


Figure 5. Timeline of the development of typologies in concordance of earthquakes.

style. Following this classification, each of the eight typologies were compared and preliminarily analyzed in terms of their architectural configuration (number of floors, morphology, geometric proportions, area of fenestrations, etc.) and in terms of their constructive features (building systems, characteristics of diaphragms and roofs, etc.) in order to determine the similarities and differences between the 70 case studies.

Additionally, the selected buildings were placed on a time line divided in intervals between the largest earthquakes (Figure 5). Using this method it has been possible to identify the development of the earthquake-resistant strategies over time as well as the evolution of the general typological and constructive features (Jorquera, Lobos, and Farfán 2015). Therefore, in the first period—between the foundation of Santiago and the earthquake of 1647—the architecture is characterized by massive one-floor structures built mainly with adobe masonry without any geometrical precaution.

After this, between the earthquakes of 1647 and 1730, some geometrical improvements were adopted into the architecture such as the preference for simple and symmetric geometries; furthermore, beside adobe, the use of stone masonry was introduced for some churches. Between the earthquakes of 1730 and 1751, in addition to an adequate geometry, buttresses were introduced in some churches and some horizontal timber reinforcements were introduced in the adobe masonry structures, such as the “top collar beam, wooden rings, keys, and diagonals... so well positioned that some [buildings] have resisted other later earthquakes”⁷ (Benavides 1988 [1941], 155). Moreover, the use of fired-brick masonry was tentatively developed in this period. After the earthquake of 1751, two-story architecture was constructed with some strategies to lower the center of gravity, for example, by decreasing the weight of the upper floors. Finally, after the earthquake of 1822, two- and three-story buildings were erected,

⁷ Author’s translation from Spanish: “. . .la introducción en las estructuras de adobe de un sistema de soleras, llaves, cuñas y diagonales tan bien dispuestas que algunas de ellas ha resistido después a otros movimientos sísmicos. . .”.

Table 2. Evolution of architectural typologies, building techniques, and earthquake-resistant principles.

Intervals between earthquakes	1541–1647	1647–1730	1730–1751	1751–1822	1822–1860
Architectural typologies	One floor houses Churches	One floor houses Churches Convents	One floor houses Churches	Two-story houses Churches Public buildings	Three or more story houses Palaces Public buildings
Building techniques	Wattle and daub Adobe masonry	Adobe masonry Rustic stone masonry	Adobe masonry Stone masonry Fired-brick masonry	Adobe masonry Stone ashlars masonry Fired-brick masonry	Adobe masonry Wooden frame filled with asobe Fired-brick masonry
Earthquake resistant criteria	Masive one-floor structures	Masive one-floor structures Research of adequate configuration	Adequate geometric configuratrion Horizontal timber reinforcements Use of butresses	Adequate geometric configuration Horizontal timer reinforcements Strategies to low the gravity center	Adequate geometric configuration Horizontal timer reinforcements Strategies to low the gravity center Structural timber frames

which drew from all the accumulated information of empirical earthquake-resistance. Further, they introduced some structural timber frames, especially in residential architecture (Table 2). This first approach to the development of masonry architectural typologies through time allows the characterization of the existing heritage buildings in concordance with earthquakes and demonstrates that these ancient structures were adjusted to local seismicity.

Subsequently, as part of the second phase of the research, the typologies of *churches*, *Colonial two story houses*, and *public buildings* were analyzed in depth. These were selected because: (a) they are the oldest masonry buildings of the city and, therefore, those that have stood up to the greatest number of earthquakes; (b) they are completely built in unreinforced masonry, and thus, considering the intrinsic vulnerability of the technique, they have a good geometrical configuration that could explain the buildings' superior seismic performance; and (c) they represent three types of very different geometry, and therefore, different grades of intrinsic vulnerability and earthquake-resistant strategies.

3. Geometrical typology analysis method

As many authors affirm, the “seismic behaviour of ancient masonry buildings is particularly difficult to characterize and depends on several factors, namely the properties of the materials, the geometry of the structure, the connections between structural and non-structural elements, the stiffness of the horizontal diaphragms and building condition” (Lourenço et al. 2011, 369). While the characteristics of the construction, the connections, and the ‘wall’s solidity’ resulting from workmanship skills (De Felice 2011) and reinforcements are factors that change building-by-building, geometry is a factor that can be similar in many

buildings and, thus, it can be assessed at a “typological level”. In other words, several buildings of the same typology may have a similar morphology that can be assessed through geometrical parameters, and these parameters could explain their good or poor seismic performance. Therefore, although Santiago’s historical masonry buildings are greatly varied, what they may have in common is a geometry that can explain their survival over time in a seismic context.

Hence, for the purpose of assessing the geometrical configuration, a matrix of analysis with configuration parameters was constructed, which considers both the global capacity of the buildings and the local in-plane and out-of-plane capacity of walls. These parameters were chosen for being the most recurrent in literature, and because they allow a qualitative analysis without the need for numerical verifications.

The following parameters to assess the global capacity of the buildings were considered.

- *Symmetry*, a desired characteristic for buildings in seismic areas, both in plan and elevation, in order to avoid stress concentrations and torsions.
- *Simple and regular shape*, where forms near the square-shape or a circle-shape are most effective because they do not produce stress concentration, improving ‘the seismic performance of masonry structures, preventing local damage and decreasing torsional effects’ (Mendes and Lourenço 2013, 141). A plan could be symmetric but not simple, as a cross-shape for example, and would suffer stress concentration at each of its corners.
- *Ratio of the length to the width of the plan of the building*, where a well-proportioned plan would have a ratio of length/width ≤ 2 (Cruz 1995) to avoid having very rigid walls in one direction and very flexible in the other direction, with different seismic responses.

- *Ratio of the height to the width of the building*, which according to Bazán and Meli (1985) and Arnold and Reitherman (1991) should be inferior to height/width = 3 or 4. Slender buildings are more subjected to overturning failures during earthquakes. In the same way, more horizontal buildings have short periods, and thus, less acceleration during earthquakes.

To assess the local in-plane and out-of-plane capacity of walls the parameters were the following.

- *Density of structure*, defined as the area of all vertical elements divided by the total plan area, which is associated with the base shear strength (Lourenço et al. 2013). In seismic zones, a high density of structure with values at least of 10% (Meli 1998) is recommended, but values around 20% are preferred (Arnold and Reithermann 1991), which allows the building to be better prepared for the in-plane forces.
- *Thick walls*, which according to Eurocode 8 are considered earthquake-resistant only if they are wider than 0.35 m (Eurocode 8 2011).
- *Openings in walls* reduce the in-plane capacity, as the above and below area of the openings “is not considered to contribute to the overall stiffness of the wall”, and thus, the “shear capacity of the overall wall is calculated as the sum of the capacities of the individual segments” (Williams 2004, 326). Therefore, in seismic areas a percentage of openings of less than 40% is recommended (Arnold and Reithermann 1991).
- *Vertical slenderness of walls* (λ), which corresponds to the ratio between the height of the wall and its thickness. A low vertical slenderness avoids the out-of-plane mechanisms of the wall. According to Eurocode 8, slenderness should be less than height/thickness = 9; according to Bazán and Meli (1985) and Arnold and Reithermann (1991), slenderness should be inferior than 8, and according to Chilean Code for Intervention of Historical Adobe Structures-

Nch3332 (Instituto Nacional de Normalización 2013) it should be less than 7 (for adobe structures).

- *Free length of the wall*, which is the distance of the wall between two perpendiculars elements (walls, buttresses) well connected to the main wall. According to some authors, this parameter can be considered as a “horizontal slenderness” (Vargas 2015, personal communication) equivalent to the ratio length/thickness of the wall. In seismic contexts, it is recommended that the ratio be inferior to a free length/thickness = 7, which is the same value proposed by the Chilean Code for Intervention of Historical Adobe Structures-Nch3332 (Instituto Nacional de Normalización (Chile) 2013), in order to avoid the out of plane failure mechanism of masonry walls.

With these parameters a matrix of analysis was created (Table 3) which allows a preliminary comparative assessment of the seismic response among all the buildings of a same typology. For each parameter, such as slenderness, the percentage of openings, ratio, etc., the extreme values, average values, and coefficient of variation (C.V) were calculated. Finally, these results were compared with the reference values given by literature. It is important to mention that specific geometric features concerning the location and distribution of the elements (walls, openings, etc.), which also influence the dynamic response but change building by building, were considered only when they act as a particular example of vulnerability.

4. Analysis of colonial churches

4.1. Typological description

The seven masonry churches identified in the study area are the oldest surviving buildings in Santiago. They were the first big buildings erected by the Spanish with the aim of evangelizing the native Chilean population. From a structural point of view, erecting masonry churches in a seismic context like Santiago must have been a great challenge for the Spanish, as churches require very high and long walls which are very vulnerable to dynamic stresses. This is the reason why today all Santiago's churches are in their third or fourth architectural version, depending on the necessity to rebuild after every earthquake.

In the study area of the colonial historic center of Santiago, the seven remaining churches are, in chronological order: *San Francisco* (1572), *San Agustín* (1665), *La Merced* (1736), *Santo Domingo* (1747), the *Cathedral of Santiago* (1748), *Santa Ana* (1806), and *Las Agustinas* (1857) (Figure 6). These churches have the following typological features in common:

Table 3. Matrix for geometric analysis.

GEOMETRIC FEATURES that allow a better earthquake response	
Parameters	Reference
Symmetry of the building	✓
Simple and regular shape of the building	✓
Ratio length/width of the building in plan	≤2
Ratio height/width of the building in facade	≤3 or ≤4
Density of structure of the building	around 20%
Thick of principal structural walls	>0.35 m
Percentage of openings in walls	<40%
Vertical slenderness of walls (height/thickness)	≤7 or ≤9
Free length of the wall (length/thickness)	≤ 7

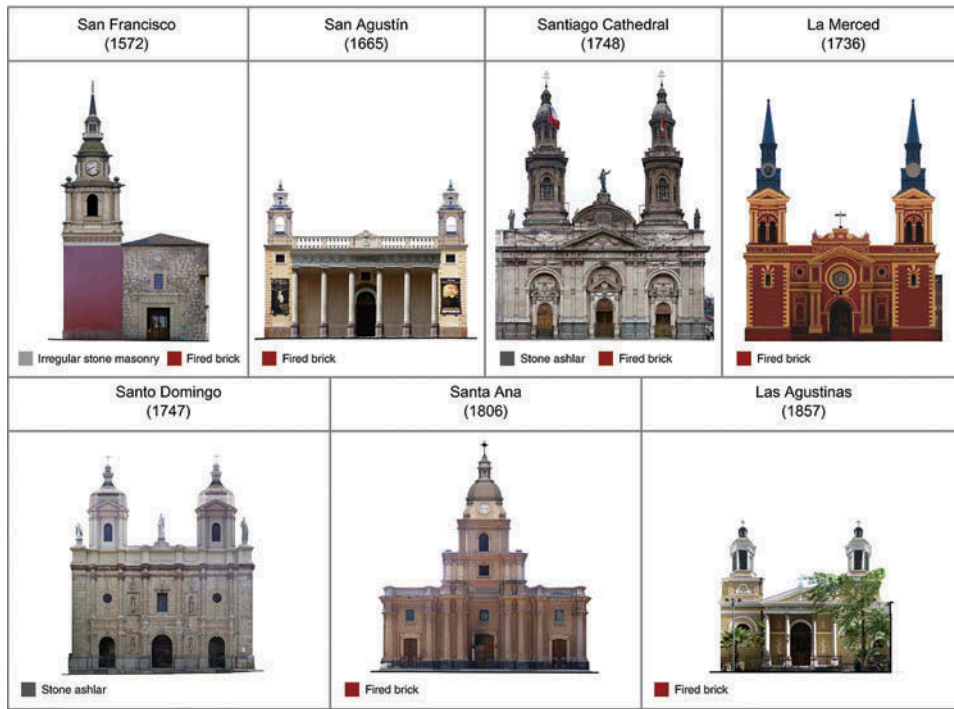


Figure 6. Photogrammetry survey of Churches. Image of Santiago Cathedral © DEPA-MOP. Reproduced by permission of DEPA-MOP. Permission to reuse must be obtained from the rightsholders.

- a basilica floor plan arrangement, with three naves, where the central nave is bigger than the lateral ones;
- a massive perimeter masonry wall, while inside, the separation between central and lateral naves is through a number of columns and arches;
- campanile towers which are often lighter than the rest of the building;
- the main facade wall is thicker than the rest of the perimeter walls, inevitably because older versions of churches' facades were the first elements that fell down during earthquakes;
- all the roof structures are trusses made of timber with inferior timber beams from which a ceiling is

- connected or a false timber vaults hang. No vaults or other thrusts roof structures are present;
- because of the experimentation and transformations over time, there is not a predominant constructive technique, but all types of masonry are present: adobe, fired-brick, rubble stone, and ashlar stone.

4.2. Analysis of earthquake-resistant geometry of churches

All the seven churches identified are composed of a unique simple volume with parallelepiped form, with

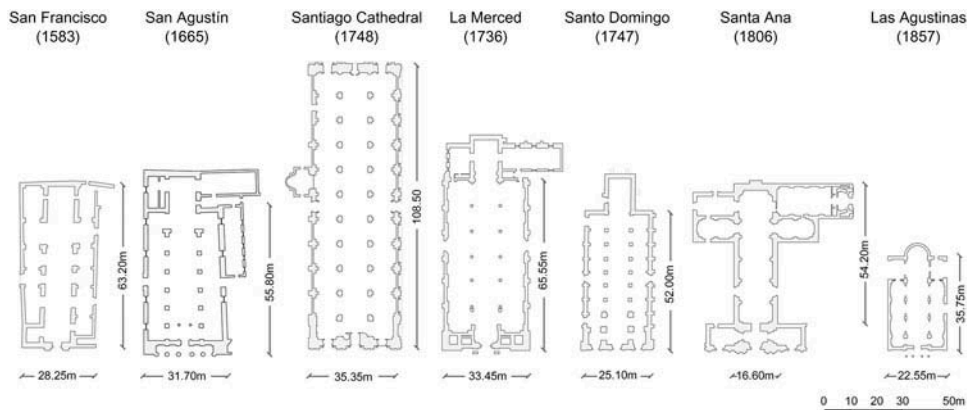


Figure 7. Comparative plans of churches.

the exception of *Santa Ana*, which has a cross-shaped plan that makes it much more vulnerable than the other churches in confronting seismic actions. In four of the cases, the plan is symmetric with respect to their longitudinal axis, with the exception of *San Agustín*, *La Merced*, and *Santa Ana* (Figure 7), due to the later addition of lateral chapels. This addition, nonetheless affects the symmetry, reduces the free-length of perimeter walls and controls the out-of-plane mechanism.

The ratio of the length to the width of the rectangle plan of the buildings is approximately length/width = 2 in most of the cases, with the exception of *Santa Ana* and the Cathedral,⁸ in which this ratio is approximately 3. Even though these ratios of 2 and 3 are near to that proposed by Cruz (1995), they could provoke an unequal seismic response with failures related to out-of-plane mechanism in the longer wall and torsion. To reduce this weakness, all the churches built after the earthquake of 1730 present buttresses in the longer walls, which reduce their free-length and help to control the flexion out-of-plane mechanism. Nevertheless, the values of the parameter length/thickness of the walls range between 3 and 18.8, with an average of 7.8, being only in four of the churches inside the recommendations

(≤ 7). In this regard, it is noteworthy that none of these seven churches has suffered seismic damage related to out-of-plane flexion because of the length of walls.

Regarding the ratio of the height to the width of the main volume measured in the facade (Figure 8), it ranges between 0.33 and 0.68 with an average of 0.47, which means that there is an important predominance of horizontality that differs from most of the Spanish churches in the region which are much more slender. Thus, the “horizontality” of Chilean churches prevents overturning failures and reduces amplification of the ground acceleration to which the buildings are subjected. In this regard, an interesting historical discussion surfaced when the Italian architect Joaquin Toesca arrived in Santiago to finish the Cathedral: he wanted the building be higher in order to respect the proportions established in the architectural treatises, but local masons advised him that the building had to be lower to better resist earthquakes. In turn, a historian of the time said of the Cathedral that “its width and length is quite in proportion, but not its height, because of the fear of destruction by earthquakes”⁹ (Haenke 1942 in Guarda 1997, 171). In addition to this horizontality, the churches of *Santa Domingo* and

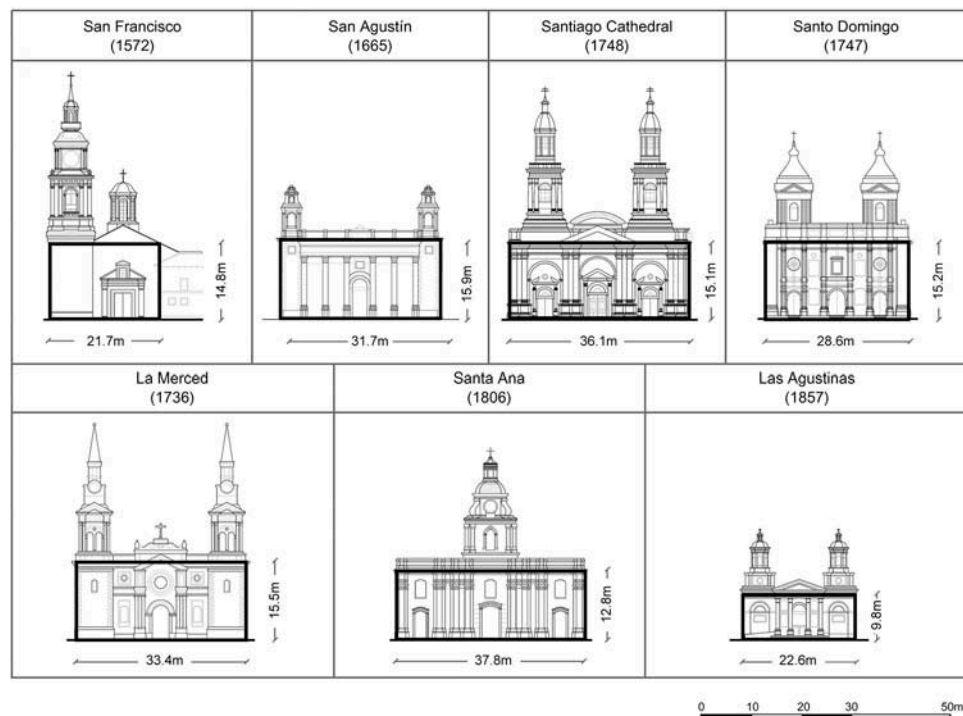


Figure 8. Comparison of elevations and study of proportions of churches facades.

⁸In the Cathedral the original ratio was 2, but after an intervention done by the famous Italian architect Toesca at the end of the 18th century, one-third to the plan was added and it became length/width = 3

⁹Author's translation from Spanish: “su latitud y ancho es bastante proporcionado, pero no su altura, con el justo recelo de la ruina padecida por los temblores de tierra”



Figure 9. Buttresses and base reinforcement in the churches of Santo Domingo and La Merced.

La Merced, built after the earthquake of 1730 presented plinths in the base of the longer walls, which help to lower the center of gravity of the building (Figure 9), resist the overturning of the entire volume, and improve the in-plane and out-plane capacity of the walls.

The density of structure ranges between 18.4% and 31.1% in the churches of *Las Agustinas* and *Santa Ana*, respectively, with an average of 20.40% considered as a sufficient mass to resist lateral forces. In terms of the geometry of the single elements, the load bearing walls are very thick, with extreme values of 0.6 m in *Las Agustinas* church (the newest construction) and 1.87 m on *San Francisco* church (the oldest construction), with an average of 1.39 m of wall thickness among the 7 churches. The openings are vertical rectangles, with windows whose dimensions range from 1 m × 2 m (width × height) to 2 m × 4 m. The dimensions of doors range from 2.7 m × 4.6 m to 3.4 m × 6.9 m, and in most of the cases arches are used, except for *San Francisco*. The openings are well distributed (symmetrically and far away from corners) and are concentrated on the main facades, where the entrance is located.

Nonetheless, their percentage of area with respect to the wall area is very low, with values between 5.5% in the church of *San Agustín* and 11.4% in the *Santa Ana* church, with fewer openings in the oldest churches. In the other perimeter walls, the percentage of openings is even lower, and in some cases there are no openings. These three parameters indicate that the walls of the churches have a large capacity to withstand in-plane efforts caused by earthquakes, demonstrated by the fact that no shear diagonal cracks have been reported in these churches following the most recent earthquakes.

Finally, the vertical slenderness of the walls is low in all the cases, with extreme values between 3.5 in part of the Cathedral and 8 in the church of *San Agustín*. Therefore, they are all considered to be low and help to prevent the out-of-plane overturning during earthquakes. In the facade walls, slenderness is even lower (around 4), as all the facade walls are thicker than the rest of the walls (with values that range between 1.1 m and 3.4 m). This last aspect is relevant as the overturning of the facade—as an independent *macro-element*—is one of the most typical failure mechanisms in churches (Lagomarsino and

Table 4. Synthesis of churches earthquake-resistant principles.

Parameters	GEOMETRIC FEATURES IN CHURCH TYPOLOGY			
	Extreme values	Average	C.V	Reference
Symmetry of the building	✓	–	–	✓
Simple and regular shape of the building	±	–	–	✓
Ratio length/width of the building in plan	1.6–3.4	2.32	27%	≤2
Ratio high/width of the building in facade	0.33–0.68	0.47	21%	≤3 or ≤4
Density of structure	18.4–31.1%	20.4%	21%	around 20%
Thick of principal structural walls	1.1–3.4 m	2.03 m	32%	>0.35 m
Percentage of openings in walls	0.6–1.87 m	1.39 m	31%	>0.35 m
Vertical slenderness of walls (height/thickness)	5.5–11%	7.56%	26%	<40%
Free length of the wall (length/thickness)	3.5–8	8.09	29%	≤7 or ≤9
	3–18.8	7.8	60%	≤7

Podestà 2004). Thanks to this characteristic, no overturning of the façade has been registered in the most recent big earthquakes in Santiago, with the exception of the Cathedral, which during the 2010 earthquake presented a little “detachment of the facade” (D’Ayala and Benzoni 2012, 430). Also in the case of *San Francisco*, the church presented in past earthquakes a gable overturning of main façade, consisting of cuneiform blocks, and overturning out-of-plane around the two oblique cylindrical hinges (Jorquera et al. 2017), which is already an active failure mechanism.

Table 4 shows the Summary of the values of the analyzed parameters of churches.

4.3. Seismic vulnerability of Santiago churches

Among all the macro-elements that composed the churches, the towers are the most vulnerable in the face of seismic action as they function like an independent appendix. Because of their location at the top of the buildings and their slenderness, they have a different vibration period than the rest of the structure. This provokes their collapse by overturning, which much of the time triggers “the detachment of the facade from the lateral walls” (D’Ayala and Benzoni 2012, 448). This explains why in Santiago’s churches most of the campanile towers were replaced, and they are now in their third or fourth versions. In the case studies, different specific situations have occurred regarding church towers. For instance, the towers of the *San Agustín* and *Las Agustinas* churches are flexible and built with lighter timber structures, and they are not particularly high respect to the main volume. For this reason, no damages due to collapse have been registered. *San Francisco*’s tower (the oldest church), originally built in stone masonry, was destroyed three times during earthquakes. The fourth and current tower was built with timber in 1857 by the prestigious Chilean architect Fermín Vivaceta. *Santo Domingo*’s towers, unlike the rest of the church that is built with stone, were built with fired brick to reduce the weight of the upper part of the building

and its seismic response. But despite this precaution, they were reinforced with concrete after the earthquake of 1927. The Cathedral’s towers, rebuilt many times due to aesthetics transformations and collapses after earthquakes, and the towers of *La Merced* and *Santa Ana* churches are also too slender and heavy, as they are built in fired-brick masonry. However, they have not presented serious damages or overturning after the last earthquakes, which can mean that they are well connected to the main volume.

Regarding the presence of thrust structures, as mentioned, there are no roof thrust structures that could create stresses in the upper part of longitudinal walls, provoking bending out-of-plane mechanisms. Nevertheless, the separation between central and lateral naves through arcs provokes some thrusts, which are counteracted by the solid walls. In any case, this specific assessment has to be done building by building, as it is difficult to determine the real thrust in a preliminary geometric-typological analysis.

Finally, it is not possible to determine the box-behaviour of the churches in a geometric preliminary approach, as it depends on many constructive factors, and, therefore, it could change church by church. However, the absence of the typical failure of cracks or separation of walls at the corners could indicate that churches have a box-behavior.

At a typological level, there are no other vulnerabilities shared by the seven churches derived from their geometry. Other typical mechanics of failure like “the overturning of the facade, the overturning of the gable and shear mechanisms in the façade” (Lagomarsino and Podestà 2004) have not been registered in the case studies, with the before-mentioned exception of *San Francisco*. This is demonstrated by the absence of damages during recent earthquakes, like the severe Maule earthquake of 2010, in which only *Santa Ana* presented some shear cracks in walls due to its irregular cross-shaped plan. Serious damages in other churches in Santiago after that earthquake, like the church *Nuestra Señora de la Providencia* which, according to reports, “lost the top of the tower and experienced

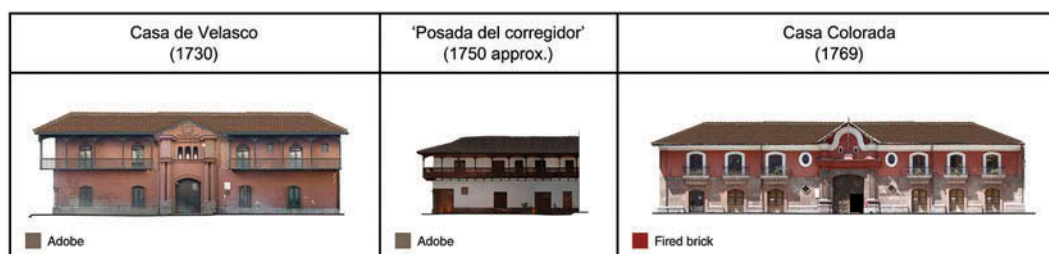


Figure 10. Photogrammetry survey of colonial two-story houses.

damage consisting of the disconnection between the apse and the back wall, and between the facade and the side walls” (D’Ayala and Benzoni 2012, 433), shows that the studied churches have a favorable geometry that resulted from accumulated knowledge collected from the destruction or transformations of their previous versions. This is evidence that these churches learned important lessons from previous earthquakes and improved their characteristics to the point of achieving a less vulnerable model.

5. Analysis of colonial two-story houses

5.1. Typological description

Two-story colonial houses are a typology that represents the high standard of housing during the 18th century. Today there are only three remaining houses of this typology in the Colonial historic center of Santiago: two of them built in adobe masonry and the newest one of fired-brick masonry. They are, in chronological order: *Casa Velasco* (1730), *Posada del Corregidor* (1750 approximately), and *Casa Colorada* (1769) (Figure 10).

This typology is characterized by an orthogonal square or rectangular plan of two stories, with an interior courtyard around which perimeter rectangular units are located. Their morphology is robust, with a clear predominance of wide and horizontal proportions, which besides being part of their characteristic image, helps to improve their performance in the event of seismic action. Originally, they were large structures with two or three courtyards, but with the growth and modernization of Santiago, parts of these houses have been demolished.

No vaults, arches, or other thrusts structures are present in this typology. The roof structure is formed of a series of timber trusses, and a mezzanine is formed by timber beams. Openings are vertical rectangles with lintels. The three houses are located in a block together with other buildings and share some of their perimeter walls.

5.2. Analysis of earthquake-resistant geometry of colonial two-story houses

The general geometry of colonial two-story houses is simple and regular over their two floors, without outstanding additional volumes besides light wooden balconies in *Casa Velasco* and *Posada del Corregidor*. *Casa Velasco* and *Casa Colorada* have a square shape divided in different rectangular units, while the *Posada del Corregidor* is a unique rectangular unit. *Casa Colorada* is symmetrical with respect to both axes. In contrast, the other two houses (Figure 11), because of their location in the corner of an urban block, present an unequal distribution of walls and windows which creates a different seismic response in their different parts. Nonetheless, no torsion mechanisms derived from this asymmetry are produced as these houses don’t have a rigid diaphragm. And as happens in a large number of Colonial houses in other regions of Chile, every rectangular unit acts as a separate single structure.

The ratio of the length to the width in plan is length/width = 1.2 in *Casa Colorada* and in *Casa Velasco*, while in the case of the *Posada del Corregidor* the ratio is 2.4, which indicates that the houses are more or less well proportioned. Nonetheless, because of the mentioned differences of symmetry and mass of the single units, there is not a global equal seismic response.

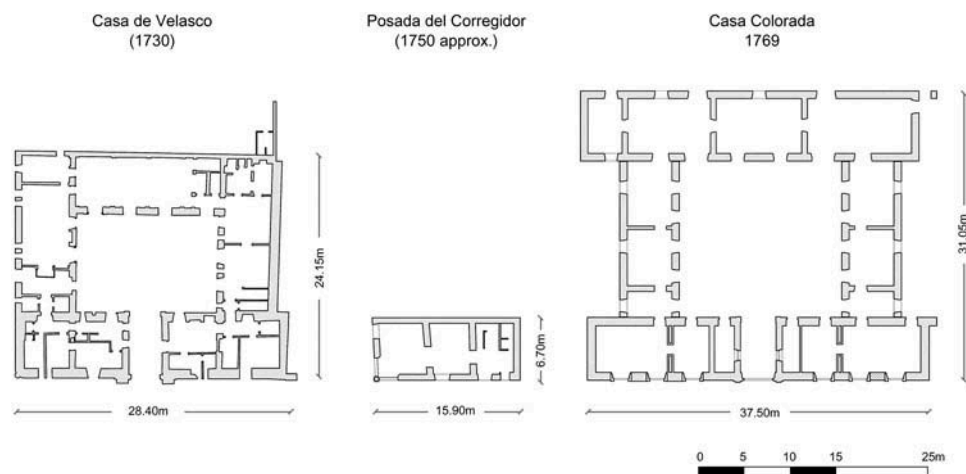


Figure 11. Comparison of ground floor plans of Colonial Houses.

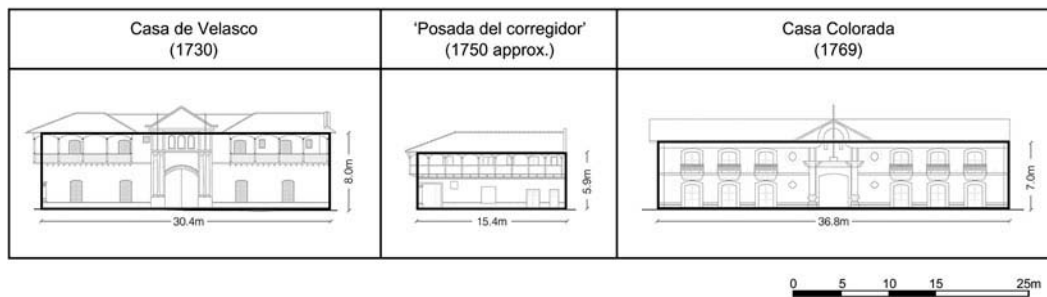


Figure 12. Comparison of elevations and study of proportions of the houses.

Regarding the orthogonal walls that divide the single units, there is no rule: at the *Casa Velasco* the main volume of façade has adequate transversal walls that reduce the free length with a minimum value of length/thickness = 2.5 and a maximum value of 5. In the other three volumes there are not sufficient orthogonal walls and the free length is not adequate, with an extreme value of length/thickness = 24 in the lateral façade, and an average of 13.8. This means that some walls could suffer out-of-plane flexion. At *Posada del Corregidor*, orthogonal walls are well distributed on the ground floor, with a ratio length/thickness = 7, but on the first floor this ratio reaches 24, which is not adequate. At *Casa Colorada*, the ratio length/thickness is 16.5 in the façade wall, and it ranges between 3.5 and 14.9 in the rest of the walls. These values are higher than length/thickness = 7 suggested by the Chilean code for Earthen Historical buildings-NCh3332 (Instituto Nacional de Normalización 2013) and would mean that some walls are subjected to out-of-plane flexion during earthquakes. Nonetheless, because of the predominant horizontality of the houses (ratio height/width = 0.26 at *Casa Velasco*, 0.38 at *Posada del Corregidor*, and 0.19 at *Casa Colorada*) (Figure 12), which control the amplification of the ground acceleration, and because of the low slenderness of the walls (average height/thickness wall = 5.16 in the three cases) the possibility of overturning or out-of-plane flexion failures are reduced. Furthermore, in all the cases the houses have a stone basement, and their first floor is smaller and lighter than the ground floor as a strategy to lower the center of gravity and to avoid overturning. In fact, no damages from the out-of-plane mechanisms have been reported in the last big earthquakes.

Regarding the in-plane response, the density of structure of the plan is 22.67% at *Casa de Velasco*, 22.6% at *Casa Colorada* and 33.1% at the *Posada del Corregidor* which meet the criteria given by Arnold and

Reithermann (1991). In addition, the walls are sufficiently thick, with widths of 1.0 m at *Casa Velasco*, 0.8 m at *Casa Colorada*, and 0.65 m in the *Posada del Corregidor*. To this respect, during an assessment of the damages after the 1985 earthquake in other adobe houses of similar typologies, experts affirmed that “only the historical buildings that have massive walls with thicknesses around one meter and that were in a good conservation conditions escaped from the total collapse”¹⁰ (Cruz, Riddell, and Hidalgo 1988, 81).

In relation to the openings, they are vertical rectangles, with lintels and segmental arcs in some cases. Their dimensions range between 1.3 m × 1.9 m and 1.6 m × 2.5 m (width × height); their area respect to the wall represent 16.6% at *Casa Velasco*, 19.59% at *Posada del Corregidor*, and 20.9% at *Casa Colorada*, which are within the recommendations. These three parameters indicate a predominance of mass in the three cases and imply that walls can affront in-plane effects caused by earthquakes. Nevertheless, while in *Casa Colorada* the distribution of openings is regular and symmetric, in the case of *Casa Velasco* and *Posada del Corregidor*, openings are not well distributed. This is because they are both located at the corner of an urban block. As a result, they have two complete massive walls (the dividing walls between adjacent buildings), and two other walls (those of the two façades) with a lot of openings. This means that there are some axes better prepared to withstand in-plane efforts, while other axes are very vulnerable to shear efforts with the subsequent propensity to suffer shear cracks.

Table 5 shows the summary of the lowest and highest values of the analyzed parameters in colonial two-story houses.

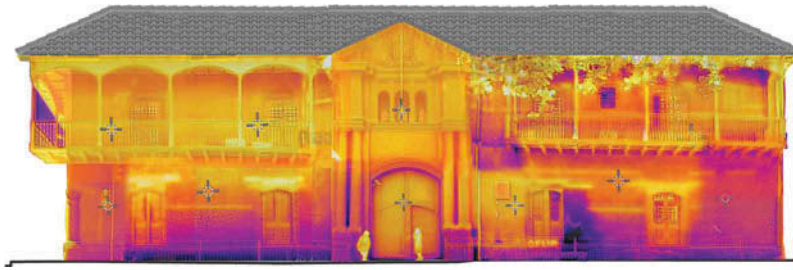
Seismic vulnerabilities of colonial two-story houses

As mentioned, at the typological level, some factors of vulnerability derived from the geometry of the houses

¹⁰Author's translation from Spanish: “sólo se libraron del colapso las construcciones masivas que empleaban muros masivos con espesores del orden de un metro y que se encontraban en buen estado de conservación”.

Table 5. Synthesis of earthquake-resistant principles in colonial two-story houses.

GEOMETRIC FEATURES IN TWO-STORY COLONIAL HOUSES TYPOLOGY				
Parameters	Extreme values	Average	C.V	Reference
Symmetry of the building	✓	–	–	✓
Simple and regular shape of the building	✓	–	–	✓
Ratio length/width of the building in plan	1.2–2.4	1.6	35%	≤2
Ratio height/width of the building in facade	0.19–0.38	0.27	28%	≤3 or ≤4
Density of structure	22.6–33.1%	26.11%	18%	around 20%
Thick of principal structural walls	0.65–1.0 m	0.81 m	17%	> 0.35 m
Percentage of openings in walls	16.6–20.9%	19.04%	9%	<40%
Vertical slenderness of walls (height/thickness)	4.9–5.45	5.16	4%	≤7 or ≤9
Free length of the wall (length/thickness)	2.5–24	13.8	45%	≤ 7

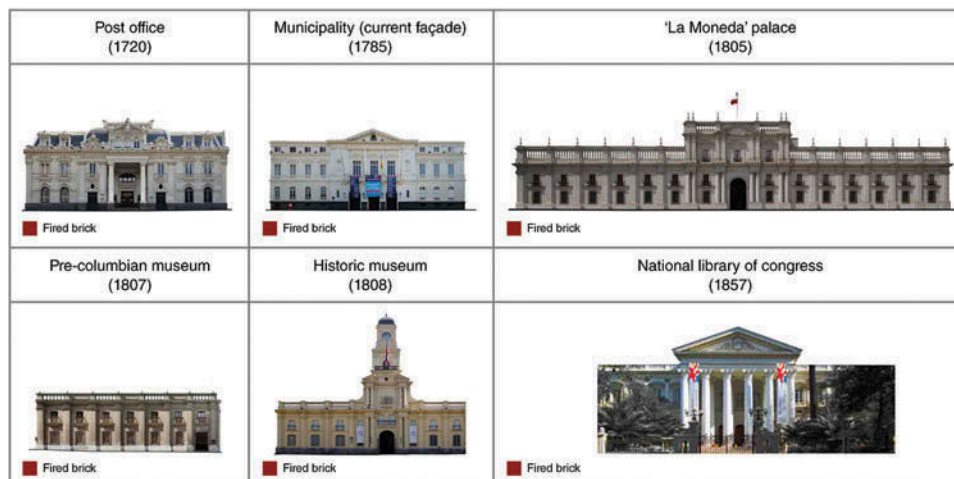
**Figure 13.** Thermographic analysis of the *Casa Velasco*.

were noticed: the non-symmetric distribution of walls and openings in addition to the disconnection of the different units, which generate the separation-of-the-walls-failure mechanism. The *Casa Velasco* is the most vulnerable building from the geometric point of view, but there, disconnections of the parts are counteracted by a wooden hoping that links portions of walls between the openings. This structural device was revealed using thermographic analysis (Figure 13).

During the last big earthquakes experienced by Santiago, in 1985 and 2010, the three cases studied suffered moderate damages derived from the vulnerabilities noted. These

included cracks on the corners and shear cracks in the walls with a major number of openings.

One last specific factor of vulnerability recognized at the *Posada del Corregidor* is the location of one big fenestration on one corner of the building where the main entrance is located. This defect has provoked serious local damage, such as separation of the corner, shear diagonals in the exterior walls, and some out-of-plane movement due to the intersection of the forces on that point. These local damages have been repaired many times after earthquakes, without resolving the vulnerabilities, and indicate that the mechanisms will be activated again in the next earthquakes.

**Figure 14.** Photogrammetry survey of public buildings.

Despite the vulnerabilities, it is important to notice that only in two parameters (ratio length/width in plan, and the free length of walls) two-story houses do not meet the reference values. And, those vulnerabilities are compensated by a considerable horizontality (ratio height/width of the building), density of structure, thick walls, and an appropriate vertical slenderness. Therefore, no collapse has been registered in past earthquakes.

6. Analysis of public buildings

6.1. Typological description of public buildings

Public buildings represent the efforts of the young Chilean nation in the late 18th and early 19th century to create big institutional buildings with earthquake-resistant structures.

This typology is characterized by large square buildings of two or three stories, with units organized

peripherally around one or more courtyards. The volumes are simple and symmetric, with a clear predominance of horizontality and a major influence of neoclassical style, introduced in Chile by the Italian architect Toesca. Façades present vertical openings and some decorative elements like balustrades, cornices, and pilasters. The latter elements act, somewhat, as buttresses and contribute towards a better seismic response from the walls. Timber trusses form the roof structures, and timber beams form the mezzanines; therefore, no thrusts structures are present in this typology. All these buildings are built in fired-brick masonry.

In the study area there are six remaining buildings that belong to this category: the current *Post Office* (1720); the City Hall building or *Municipality of Santiago* (1785); the current Government Palace, known as “*La Moneda*” (1805); the ex-Customs House, currently housing the *Pre-Columbian Museum*

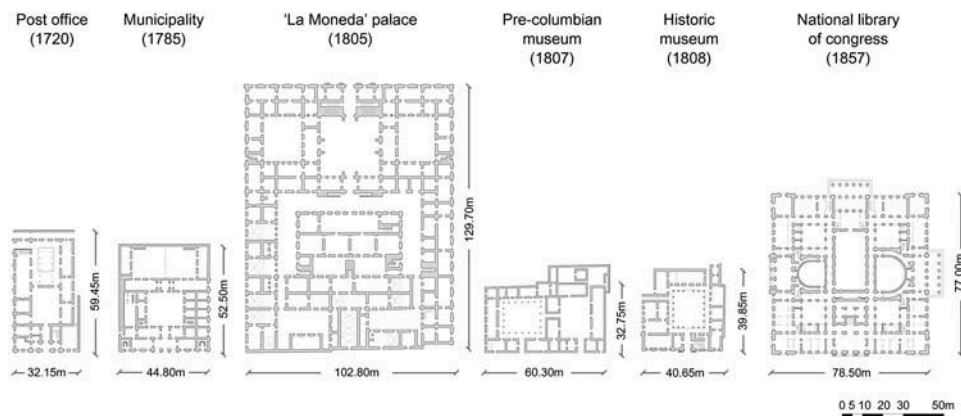


Figure 15. Plans of public buildings.

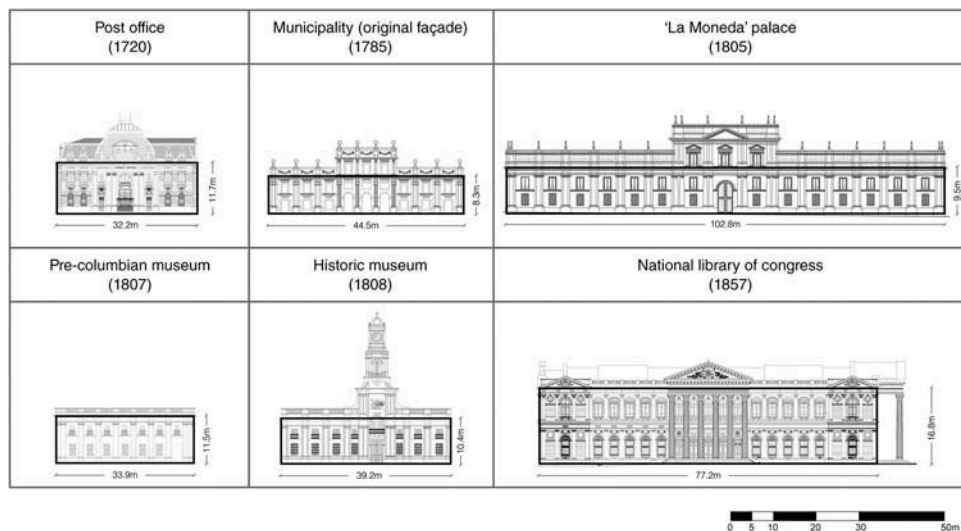


Figure 16. Comparison of elevations and study of proportions of public buildings.

(1807); the ex-Royal Audience, currently the *National Historic Museum* (1808); and the ex-Parliament house, currently the *National Library of Congress* (1857) (Figure 14). All the buildings, with the exception of the Municipality, have changed their original use and all have modified their internal spaces, changes that presented a structural challenge in a seismic region.

6.2. Analysis of earthquake-resistant geometry of public buildings

Public buildings have a simple and orthogonal square shape. Despite being large buildings (with lengths from 32–103 m), they are divided into many small volumes organized around one or more courtyards (Figure 15). All the plans are more or less symmetrical and the ratio of the length/width is one in four of the cases, and two in the current *Post-office* and the *Municipality*. This indicates a similar seismic response in both directions and no torsional problems, since in most of the cases the center of gravity coincides with the center of mass.

As in the previous typologies, there is a predominance of horizontal shape (Figure 16) with proportions of the ratio height/width of facade volumes that range from 0.09 in “*La Moneda*” to 0.36 in the *Post Office*, values that indicate that no overturning of the buildings should occur during earthquakes. In addition, these values indicate the structures should not suffer amplification of the ground acceleration. Further, all the buildings present upper floors that are smaller and lighter than the ground floor, ensuring a low center of gravity. “*La Moneda*” additionally presents a 4.3 m-thick base plinth around the stairs on the ground floor, which further lowers the center of gravity. Only the *National Historic Museum* (1808) breaks the regular shape on the façade with the presence of a tower, built after the earthquake of 1850.

The different volumes that constitute the buildings are divided into rooms with many orthogonal walls in both directions. Nonetheless, the ratio length/thickness of the walls (free-length) ranges between 6.3 in “*La Moneda*” and 8.6 in the *National Library of Congress*,

with an average of 7.56. This range slightly exceeds the reference value given by the literature (≤ 7), which means that walls could suffer out-of-plane-flexion mechanism. To avoid that mechanism, the presence of pilasters embedded in the perimeter walls act as buttresses and help to reduce that free-length. In addition, the vertical slenderness of the walls are all low, with values that range between 3.5 in the current *National Library of Congress* and 5.8 in the current *Pre-Columbian Museum*, which mean that no overturning or out-of-plane flexion should occur during earthquakes. Thanks to these characteristics no damages from out-of-plane mechanisms have been registered in these buildings after big earthquakes.

In regard to the in-plane response in this typology, the walls are still very thick but less than in the other two typologies, with widths between 70 cm in the *National Library of Congress* (the newest building) and 1.2 m in “*La Moneda*” (the oldest building). The density of structure, in plan, ranges between 15.3% and 18.7%, which is less than in the other two typologies and slightly inferior to that suggested by literature (around 20%). This reduction of the wall section and the density of the structure were balanced with the improvement of the building techniques, as all these buildings were made of standard fired-brick with resistant lime mortars that have allowed a good in-plane response over time.

The openings are vertical rectangles, with windows whose dimensions range from 1.1 m \times 2.3 m (width \times height) to 2 m \times 4.8 m, and doors whose dimensions range from 2 m \times 4.5 m to 3.6 m \times 7.4 m. They have lintels, semi-circular arcs, and segmental arcs, which are tidily and symmetrically distributed, in concordance with the neoclassical style. Concerning the percentages of openings respect to the wall mass, they range from 3.2% in the *National Historic Museum* and 17.8% in the current *National Library of Congress*. These values are still low, and the openings are well distributed in the façades, resulting in satisfactory in-plane capacity. In fact, no shear diagonal cracks associated with the openings were reported in the public buildings in the earthquake of 2010.

Table 6. Synthesis of earthquake-resistant principles in public buildings.

GEOMETRIC FEATURES IN PUBLIC BUILDINGS TYPOLOGY				
Parameters	Extreme values	Average	C.V	Reference
Symmetry of the building	✓	–	–	✓
Simple and regular shape of the building	✓	–	–	✓
Ratio length/width of the building in plan	1–2	1.3	30%	≤ 2
Ratio height/width of the building in façade	0.09–0.36	0.23	38%	≤ 3 or ≤ 4
Density of structure	15.3–18.7%	17.33%	6%	around 20%
Thick of principal structural walls	0.7–1.2 m	0.92 m	15%	>0.35 m
Percentage of openings in walls	3.2–17.8%	13.22%	20%	$< 40\%$
Vertical slenderness of walls (height/thickness)	3.5–5.8	4.6	33%	≤ 7 or ≤ 9
Free length of the wall (length/thickness)	6.3–8.6	7.56	11%	≤ 7

Regarding the box behaviour, even if in this first geometric assessment no constructive features were analyzed, there is some information concerning the distance and the sections of the wooden beams of the mezzanines which suggests that they act as diaphragms, helping to join the walls into a unitary earthquake response. In fact, no separation of the corners has been registered during the last earthquakes, with the exception of the upper floor of the *National Library of Congress*.

In synthesis, the buildings of this typology present a conservative geometry that respect most of the reference parameters (with the exception of the free-length of walls), and they meet what the Italian professor Antonino Giuffrè states as: “buildings in highly seismic areas are hardly ever more than three stories high; the wall grid is seldom based on a span of more than five to six metres in either direction; and the thickness of the walls is rarely less than 1/7 of the height” (1995, 837). These geometrical features derived from Neoclassical Style and also, from a more advanced constructive phase when the builders had collected more knowledge from precedent following earthquakes.

Table 6 shows the summary of the parameters analyzed in public buildings.

6.3. Seismic vulnerabilities of public buildings

The original geometry of the public buildings does not present many vulnerabilities: most of the cases respect all the reference parameters, with a few exceptions regarding free length of the walls (length/thickness) and the density of structure. These exceptions are counteracted by the aforementioned pilasters acting as buttresses, whose effect is demonstrated by the absence of severe structural damages during the most recent earthquakes.

However, most recently some factors of vulnerability have appeared, because of interventions carried out in some buildings. For example:

- in some cases, the original regular shape and symmetry have been lost, because of the addition of dividing walls. These additions have increased the distance from the center of mass to the center of rigidity, making buildings more vulnerable to torsions and overturns;
- in “*La Moneda*”, the thickness of some walls was reduced during the interventions of 1929 and 1974, with the subsequent increase of the vertical slenderness and the reduction of the structural density in the first story;

- at the *National Historic Museum*, the original two-story configuration was divided into five-stories, increasing the loads and distorting the slenderness of the walls; and
- at the *National Library of the Congress*, the ground floor was divided into two-stories, resulting in a total of three stories and changing the relation of slenderness among the different elements of the building.

All these modifications have been mostly motivated by the need to adapt public buildings to new cultural and civic functions.

7. Discussion and conclusions

The identification and typological classification of all pre-20th century unreinforced masonry buildings in the historic Colonial center of Santiago is an important step to characterize and enhance the architectural heritage of Chile’s capital, much of which is not recognized nor safeguarded by the Chilean Law of Monuments (Consejo de Monumentos Nacionales 1970). The characterization of the main typologies and their geometric analysis allows the understanding of common factors and the differences of a very varied heritage. In addition, this constitutes a first approach to the earthquake-resistant characteristics in common among a large number of buildings, and also describes their seismic vulnerabilities. Furthermore, the simplified geometric analysis can be understood by a wide range of professionals who work in the safeguarding of cultural heritage in Chile, such as architects, archaeologists, cultural managers, etc. As such, it can become a useful tool for simplified analysis of the seismic performance of a wide range of buildings at a territorial scale; nonetheless, it has to be considered as a simple indicator and not a safety assessment. Subsequently, a deeper analysis with numerical parameters can be undertaken in selected buildings, as well as a deeper structural-constructive analysis in single buildings, for which more detailed information is required. This more detailed analysis is undergoing in the third phase of the research, still in progress.

The analysis demonstrates that the surviving buildings possess some geometric rules or “non-written codes” in common, derived from the builder’s knowledge that was created from the continuous trial and error processes prompted by earthquakes. These rules were quantified, and thanks to them, today it is possible to better characterize objectively the Santiago architectural typologies. Additionally, the quantification of the geometric rules has allowed comparing them with the earthquake-resistant parameters given by literature, and outlines the geometrical

requirements that unreinforced masonry buildings must respect in seismic areas. Nonetheless, it is important to remember that the seismic behaviour of unreinforced masonry buildings depends on many factors, and thus, if one geometric aspect is respected, it does not ensure a good or bad seismic performance overall. In the same way, if a parameter is not respected, that weakness may be counteracted by the other characteristics of the building. Therefore, although the parameters were evaluated one by one, the behaviour of a building depends on the conjunction of all its characteristics. This could explain why some of the studied buildings have had a good seismic performance, even if they do not respect all the evaluated parameters. For the same reason, one vulnerability could be balanced by other variables, such as an accurate building technique, proper connections between the different parts, outstanding brickwork, etc.

Furthermore, the analysis shows some particular aspects.

- Churches, which are normally the most vulnerable structures, have proved to be less vulnerable in Santiago. They respect many of the evaluated parameters, with the exception of the *ratio length/width* of the building in plan and the *free-length of the wall*, which is the value that is further away from that suggested by the literature and presents a big coefficient variation of 60%. However, these two un-respected parameters have not become a vulnerability as they are counteracted by the other parameters, especially for the large horizontality (ratio height/width of the building) and the thickness of the walls. These factors allow a more or less adequate global response, and local out-of-plane and in-plane capacity. Thus, the seven churches analyzed that have survived until today do so primarily because their builders learned the lessons of those previous churches that had fallen down during earthquakes. The more appropriate the geometry, as in the case of Santo Domingo's church, the less damage sustained. The more irregular the geometry, like in Santa Ana's church, the more damage that is inflicted by an earthquake.
- Two-story colonial houses do not always meet the geometric earthquake-resistant criteria—especially the free-length of the wall—but because of their horizontality and small dimensions they suffer fewer seismic challenges. For these reasons, they have not presented important structural damages, and have

survived over the centuries. Despite this, their vulnerabilities have to be controlled, most of all in the case of the opening on the corner of *Posada del Corregidor*.

- Public buildings, despite their large dimensions and the presence of some geometric parameters that are slightly different from that suggested by literature (density of structure and free-length of the wall), present a very regular and simple geometry with a big horizontality. Besides, the adequate distribution and location of openings together with a homogeneous construction technique (fired-brick) has ensured a good response to seismic activity over time, which is demonstrated in the absence of damages in past earthquakes.

Among the three typologies, there are some common geometric parameters, which include:

- the ratio length/width in plan between 1 and 3.4;
- a big tendency to horizontality;
- density of structure around 20%;
- walls with minimum 60 cm thickness; and
- vertical slenderness of walls around 5.

In contrast, the parameters that are always different are the free-length of walls and the percentage of openings in walls, which do not seem to follow a specific rule.

Churches and public buildings have many geometric characteristics in common, but two-story houses differ in many of their characteristics. This could be explained since churches and public buildings were the result of collective efforts, and they used the experience of their predecessors as a reference, while houses were individual private initiatives, possibly without many past references.

The earthquake-resistant geometric features have been proven by the absence of severe damages during past earthquakes, while vulnerabilities are expressed on local damage mechanisms, which if not well repaired could provoke cumulative damage. Another important aspect is that the buildings analyzed are in use and in a good state of conservation, which shows the importance of both factors in the good seismic response. By comparison, deteriorated buildings that have not been maintained always suffer much more damage from earthquakes. For that reason, a 'plan of periodic maintenance proposed by the Chilean pre-code appears of critical importance' (D'Ayala and Benzoni 2012, 448).

The identified geometric rules should not be changed and should help to generate guidelines to promote appropriate interventions and preventive measures to contribute to the conservation of architectural heritage. On the other hand, the identified vulnerabilities derived from geometry

should be the first elements to be addressed through the control of displacements, the improvement of the connections, etc., in order to prevent future damage. In the medium term, “recovered” knowledge could become the basis for the development of technical standards for historic masonry buildings, which do not exist in Chile today.

Considering that “the value of architectural heritage is not only in its appearance, but also in the integrity of all its components as a unique product of the specific building technology of its time” (International Council of Monuments and Sites 2003), geometric characteristics of masonry heritage of Santiago are the physical testimony of the long effort of Chilean builders to erect structures able to withstand strong earthquakes. As part of the cultural tradition and architectural heritage of Chile, they must be preserved and enhanced.

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