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REINFORCEMENT USING REINFORCED CONCRETE AT THE BEGINNING OF THE 20TH CENTURY IN A SIMPLE MASONRY NEO-GOTHIC TEMPLE WITHIN A SEISMIC CONTEXT

REFUERZO CON HORMIGÓN ARMADO A PRINCIPIOS DEL SIGLO XX EN UN TEMPLO NEOGÓTICO DE ALBAÑILERÍA SIMPLE BAJO UN CONTEXTO SÍSMICO

REFORÇO COM CONCRETO ARMADO NO INÍCIO DO SÉCULO XX EM UM TEMPLO NEOGÓTICO DE ALVENARIA SIMPLES EM UM CONTEXTO SÍSMICO

Figure 0. Confinement of the rose window on the eastern facade of the Church of Santa Filomena. Source: Preparation by the authors.

This research comes from the postgraduate thesis in the Master's Degree in Architectural Heritage Intervention of the University of Chile

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RESUMEN

El alto nivel de vulnerabilidad sísmica de las estructuras históricas de albañilería simple de ladrillo requiere de buscar las técnicas de intervención más adecuadas basadas en la teoría y en la experiencia empírica de su desempeño sísmico. Sin embargo, si una determinada técnica no cumple con algunos de los criterios de intervención presentados por ICOMOS (International Council on Monuments and Sites) como la autenticidad, ¿Cómo podemos validar su uso? En la presente investigación se estudia el efecto de los refuerzos de hormigón armado incorporados producto del terremoto de Talca del año 1928 (Ms 8.3) en la Iglesia de Santa Filomena, la que es un ejemplo de los templos neogóticos de albañilería simple de ladrillo en Santiago de Chile, siendo una de las tipologías más vulnerables a sismos. A partir de su desempeño sísmico histórico y un análisis de los criterios de intervención en estructuras patrimoniales, se busca dar una respuesta a la validación del uso del hormigón armado como una técnica de intervención viable bajo un contexto altamente sísmico que ha sido utilizada desde hace al menos 100 años en Chile como refuerzo.

Palabras clave: neogótico, albañilería, hormigón, sismo, ingeniería civil.

ABSTRACT

The high seismic vulnerability of historic simple brick masonry structures requires searching for the most appropriate intervention techniques based on the theory behind and empirical experience of their seismic performance. However, if a given technique does not meet some of the intervention criteria presented by ICOMOS (International Council on Monuments and Sites), such as authenticity, how can we validate its use? This research studies the effect of the reinforced concrete reinforcements incorporated after the 1928 Talca earthquake (MMI 8.3) in the Santa Filomena Church, which is an example of the simple brick masonry neo-gothic temples in Santiago de Chile, one of the most vulnerable typologies to earthquakes. Using its historical seismic performance and analysis of intervention criteria for heritage structures, this article seeks to provide an answer behind the validation of using reinforced concrete, which has been used for at least 100 years in Chile as reinforcement, as a viable intervention technique within a highly seismic context.

Keywords: neo-gothic, masonry, concrete, earthquake, civil engineering.

RESUMO

O alto nível de vulnerabilidade sísmica das estruturas históricas de alvenaria de tijolos simples exige a busca das técnicas de intervenção mais adequadas com base na teoria e na experiência empírica de seu desempenho sísmico. Entretanto, se uma determinada técnica não atende a alguns dos critérios de intervenção apresentados pelo ICOMOS (International Council on Monuments and Sites), como a autenticidade, como podemos validar seu uso? Esta pesquisa estuda o efeito dos reforços de concreto armado incorporados após o terremoto de Talca de 1928 (Ms 8.3) na Igreja de Santa Filomena, que é um exemplo dos templos neogóticos de alvenaria de tijolos simples em Santiago do Chile, sendo uma das tipologias mais vulneráveis a terremotos. Com base em seu desempenho sísmico histórico e em uma análise dos critérios de intervenção em estruturas patrimoniais, procuramos responder à validação do uso do concreto armado como uma técnica de intervenção viável que tem sido usada há pelo menos 100 anos no Chile como reforço em um contexto altamente sísmico.

Palavras-chave: neogótico, alvenaria, concreto, terremoto, engenharia civil.

INTRODUCTION

When proposing a reinforcement for a historical brick masonry structure, the concept of not incorporating reinforced concrete elements must be kept in mind for the criterion of authenticity, which indicates that the intervention must respect the elements' integrity and a structure's behavior as a reflection of a construction technology typical of its time. The difference between the temporary and functional development of a historical brick masonry structure and the reinforcement by reinforced concrete initially produces a rejection when using it as a valid reinforcement option from a heritage point of view. However, this idea may be justified based on practical experience because reinforced concrete reinforcements can produce problems from increased mass and modification of rigidity, especially in buildings with poor-quality masonry (Barrientos et al., 2024). It is also a technique that is not cost-effective, given the time required for its implementation (Borri et al., 2008). This has led to a rejection of using reinforced concrete for interventions in historic structures, which can be problematic as this limits the possible intervention options. Therefore, it is proposed that the authenticity criterion should be weighted with the structural security criterion, which provides a measure of the solution's effectiveness in improving the structure's performance and even discusses re-evaluating the meaning of authenticity based on the local context.

In the case of Chile, good seismic performance of historical masonry structures is necessary to ensure their conservation over time because earthquakes have caused the irretrievable loss of many of them. The 2010 Maule earthquake (Mw 8.8) damaged 60% of the simple masonry churches (Barrientos et al., 2024), and in particular, 51% of the Churches in Rancagua had severe damage and 12% collapsed (Goic, 2010). Improving seismic behavior requires searching for the most appropriate intervention techniques for each typology based on the theory and empirical experience of its historical seismic performance. This is the focus of this study, to analyze the effect on the seismic behavior of a historical simple masonry structure that was reinforced with reinforced concrete at the beginning of the 20th century, when structural design codes were not yet developed or there were complex methods of structural analysis, at an intermediate point between the introduction of reinforced concrete in Chile and its positioning as the preferred construction material (Pérez Oyarzún et al., 2021).

The case study presented is the Church of Santa Filomena, a characteristic example of the neo-Gothic temples of simple brick masonry in Santiago, which, due to the Talca earthquake of 1928 (MMI 8.3), was reinforced by horizontal reinforced concrete confinement elements. Since its reinforcement, the structure has faced at least five earthquakes of over 8.0. This study seeks to answer the following question: Would the structure have had a

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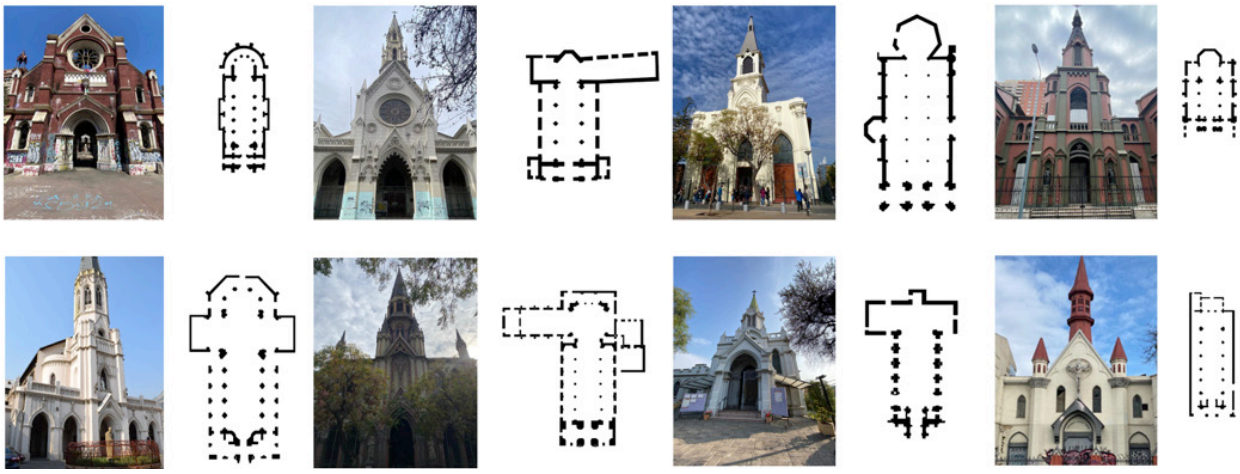

Figure 1. Neo-Gothic simple masonry temples in Santiago de Chile. Source: Preparation by the authors.

different behavior if it had not been reinforced in 1928? This study aims to evaluate whether using reinforced concrete reinforcements can be a viable option for historical simple masonry structures in a country under a seismic context that respects the criteria for intervention in heritage structures.

Neo-Gothic brick masonry temples

The neo-Gothic emerged in England during the 18th century as a reinterpretation of the Gothic language, a movement that did not follow the same structural laws, only the appearance. The main architectural Gothic elements were chosen and applied considering the economic reality of the time and the new construction techniques. The neo-Gothic temples in Santiago de Chile are commonly structured using three naves arranged on a basilical or Latin cross plan, and around the central nave, there are two arcades of ogival form arches supported on fasciculated pillars that transfer the weight of the roof through the clerestory to the foundations. The seismic demands and the absence of skilled labor in Chile prevented the development of ribbed vaults, replaced by carpentry vaults using the corbelled vault method, a lightweight solution that does not produce lateral thrusts. Therefore, using flying buttresses or building with the same constructive principles as European Gothic was unnecessary.

The historical description of the neo-Gothic Catholic temples built between 1850 and 1950 in Santiago de Chile by Mirtha Pallarés (2015) was used as the basis for this research. Figure 1 presents the eight neo-Gothic temples initially built based on simple brick masonry considered in this study. During the Maule earthquake of 2010 (Mw 8.8), the neo-Gothic church with simple brick masonry was the typology that presented a higher rate of damage compared to other churches belonging to different architectural styles with the same materiality, such as neoclassical or colonial. Due to their constructive particularities, they had severe damage in 66% of the cases (Palazzi Chiara, 2019). This

METHODOLOGY

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Figure 2. Main facade of the Church of Santa Filomena. Source: Preparation by the authors.

high seismic vulnerability of neo-Gothic temples is controlled by failure mechanisms associated with the slenderness of the structural elements and the lack of connectors between walls that allow an effective box behavior (Palazzi Chiara et al., 2020).

Church of Santa Filomena

The Church of Santa Filomena (Figure 2) is located in Santiago de Chile, on the north side of the Mapocho River in the commune of Recoleta. This sector was known as "La Chimba" during the colonial period, and until the end of the 19th century, the low land value attracted several religious orders to settle in a strategic point of the capital next to

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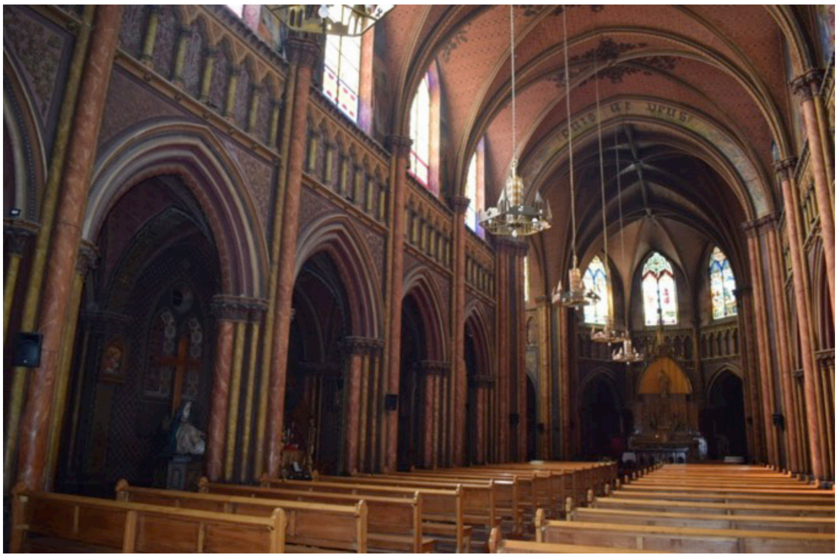

Figure 3. The central nave of the Church of Santa Filomena. Source: Preparation by the authors.

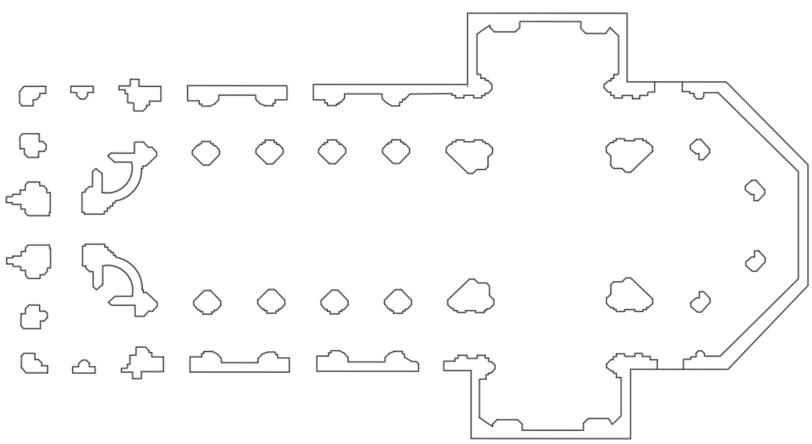

Figure 4. Floor plan of the Church of Santa Filomena. Source: Preparation by the authors based on the plans of the DUOC Foundation (1996).

a population with limited resources with whom they could continue their evangelizing work. The church's materialization was carried out as one of the charitable actions promoted by the encyclical Rerum Novarum of Pope Leo XIII and the work of the priest Marchant Pereira to satisfy social needs and educate in the Catholic faith (Hermosilla & Ortega, 1995). The Franciscan Friar Andresito was in charge of planning the temple; the design and construction were commissioned to the French architect and engineer Eugene Joannon Croizer in 1892 and was completed in 1894.

Of the eight neo-Gothic temples presented in Figure 1, the Church of Santa Filomena is the largest structure (49 m long and 21 m wide), with high slenderness of walls (1:12) and the only one with a wall density in both directions below the average; 4% in the longitudinal and 2% in the transverse direction, when the average wall density in the neo-Gothic temples of Santiago is 7% and 4%, respectively (Sáenz Muñoz, 2023). It has been a Historical Monument since 1995 (Ministry of Education [MINEDUC], 1995), and its reinforced concrete reinforcements are visible to the naked eye from the outside.

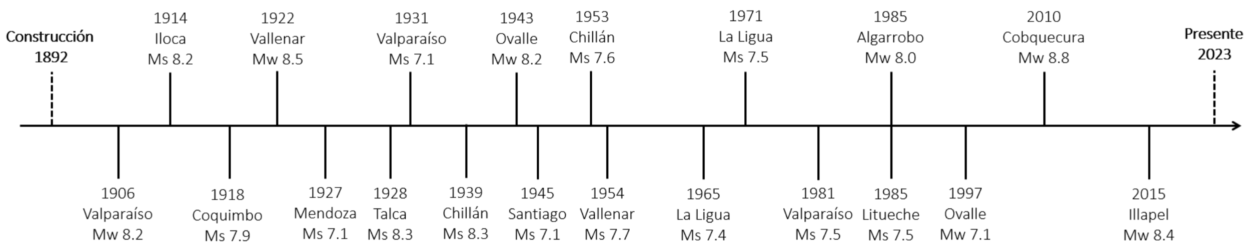

Figure 5. Timeline of relevant earthquakes in Santiago with a magnitude of over 7.0. Source: Preparation by the authors.

The structure's perimeter on the ground floor comprises simple brick masonry walls with 70 cm thick and 840 cm high lime mortar. Inside, the 200 cm diameter polylobed pillars of the masonry form arches receive the weight of the clerestory (Figure 3). The four pillars connect the longitudinal naves and the transept in the intersection. The lateral naves and transept walls work as shear walls that stiffen the structure in both directions; on the other hand, the clerestory and the arcades act as a system of frames that transfer the weight from the roof to the foundations (Figure 4).

The tower comprises simple brick masonry at the base up to 15 m in height. From this point to the tower's summit, unlike the rest of the structure, its construction system is brick masonry and reinforced concrete (Sáenz Muñoz, 2023). Although the church's construction was completed in 1894, it did not include the tower due to a lack of resources to complete the project. It was not until 1913 that the funds were gathered, and Eugenio Joannon was hired again to complete it. As an architect and engineer, he decided to continue building the tower by modifying the system. Unlike the simple masonry base, he proposed that the rest of the tower be made of brick and reinforced concrete masonry. This research does not address the tower's influence on the main structure because it does not constitute a reinforcement, but rather a technological update with the construction systems of the time.

Reinforced concrete reinforcements

Figure 5 presents a timeline of all the earthquakes of over 7.0 that have impacted the city of Santiago. Since the construction of the Church of Santa Filomena began in 1892, it has been subjected every 6 years to an earthquake of around 7.0 in magnitude and every 15 years to one of about 8.0.

The church was built about 15 years before the introduction of reinforced concrete in Chile (Duarte, 2009), so this type of structure was built based on simple brick masonry with lime mortar and without reinforcements in wall transepts. According to Hermosilla and Ortega (1995), the 1928 Talca earthquake (Ms 8.3) produced fissures around the rose windows of the transept, and, therefore,

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Figure 6. Reinforced concrete reinforcements in west transept. Source: National Monuments Council [CMN] (2008).

the structure was reinforced by reinforced concrete elements. This reinforcement consisted of confining the rose windows using a concrete frame formed by two chains and two pillars (Figures 6 and 8). A concrete chain was arranged around the perimeter of the walls at half height and the level of the crowning (Figures 6 and 7). The thickness of the masonry walls is 70 cm, and although it is not possible to observe the depth of the confinement inside the structure, it is enough that the concrete elements cross the wall throughout its thickness. The height of the confinement elements is approximately 20 cm for the chains that run around the perimeter (Figure 7) and 50 cm for the elements of the rose windows (Figure 8). These reinforcements are symmetrical to the longitudinal axis of the structure. Since the reinforcement date in 1928, some adjoining side spaces have been added to the church, and some minor repairs were made after the 1985 earthquake but have not been reinforced.

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Figure 7. Reinforced concrete reinforcements crowning of the clerestory. Source: Preparation by the authors.

Figure 8. Reinforced concrete reinforcements in east transept. Source: Preparation by the authors.

RESULTS

Effect of reinforcements on seismic behavior

An earthquake selects the most vulnerable portions of a structure, called macro-elements, which have a behavior relatively independent of the structure's overall response (Giuffré, 1991), controlled by the type of joint with the adjacent walls and their dimensions (Lourenço et al., 2022). In church typology structures, the common macro-elements are the facade, narthex, tower, lateral or transverse walls, transept, and apse (Doglioni, 2000). Due to the presence of macro-elements in a structure, it can collapse according to each macro-element's different means of failure. Therefore, a structure is seismically vulnerable, i.e., it can present a certain level of damage since each macro-element has a probability of failure associated with a certain seismic intensity. When an overall box

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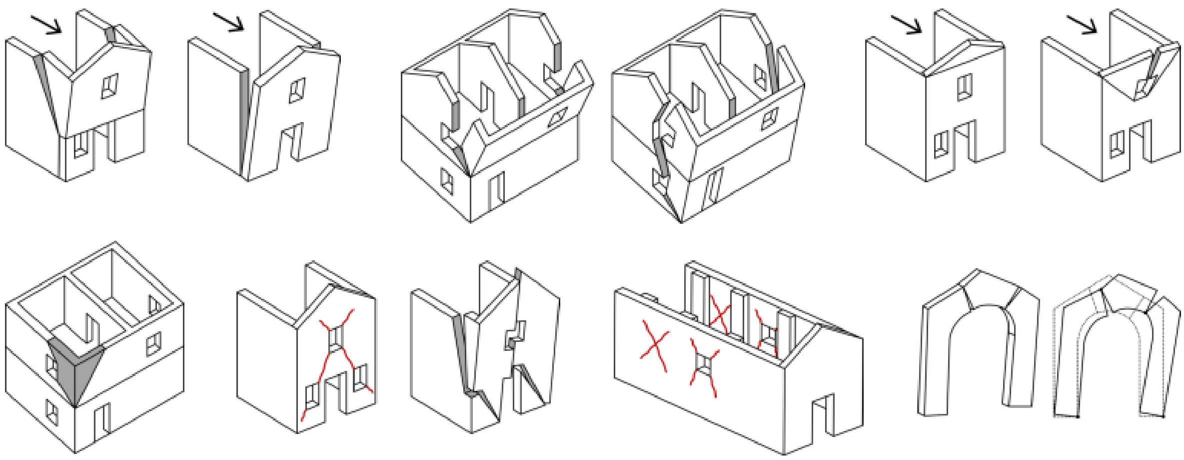

Figure 9. Examples of collapse mechanisms in masonry structures. Source: Directive of the President of the Consiglio dei Ministerri [DPCM] (2011).

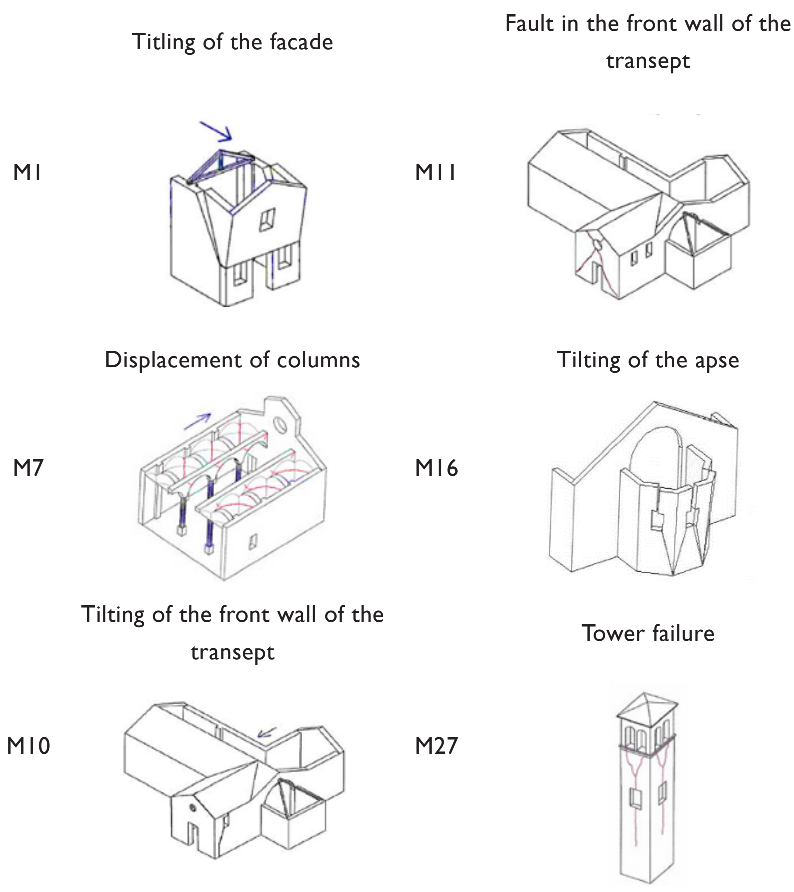

Figure 10. Collapse mechanisms observed in the church. Source: Directive of the President of the Consiglio dei Ministerri [DPCM] (2011).

behavior is not guaranteed due to the lack of confinement and the low strength of the masonry, the walls become vulnerable to out-of-plane failures (Figure 9). This is the leading cause of damage or collapse of existing masonry structures (Casapulla et al., 2017).

According to Hermosilla and Ortega (1995), the 1985 earthquake (Mw 8.0) produced cracks in the walls of the apse, partial collapses, cracks in the front walls, damage to the form arches,

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Figure 11. State of the apse prior to the Maule earthquake (Mw 8.8). Source: National Monuments Council [CMN] (2008).

Figure 12. State of the apse after the Maule earthquake (Mw 8.8). Source: Preparation by the authors.

and bricks crumbling. Based on a survey of structural damages carried out in 2023 (Sáenz Muñoz, 2023), it was determined that the damages the structure has are moderate and from the activation of mechanisms by faults inside and outside the plane of the walls, such as: tilting of the facade, displacement of columns, tilting of the front wall of the transept, failure in the front wall of the transept, tilting of the apse and failure of the tower (Figure 10). Therefore, the damages repaired after the 1985 earthquake reappeared, possibly due to the 2010 earthquake (Mw 8.8) or the 2015 Illapel earthquake (Mw 8.4).

The structural typology of the neo-Gothic churches of simple brick masonry has specific constructive characteristics that imply a greater seismic vulnerability, such as high slenderness of walls, absence of connecting elements, and a wide variety of macro-elements, among others. However, in the case of the Church of

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Santa Filomena, since its last reinforcement in 1928, it has been subjected to 5 earthquakes of over 8.0. The damages are minor, and the most important thing is that the structure has not collapsed. Why has it not suffered a collapse in all this time?

In Figure 11 and Figure 12, the damage to the church's apse before the Maule earthquake in 2010 can be compared with the current state. It is observed that damage has reappeared in the keys of the arches and vertical fissures in the meeting of walls, which coincides with areas that were intervened prior to 2010. Similarly, if one compares the vertical fissures under the rose windows in the transept walls in Figures 6 and 8, these fissures have remained stable even after the earthquakes.

Have the built-in reinforced concrete reinforcements worked properly? Characterizing a good seismic behavior of a structure from the function of a single element can be a simplification of the problem, but the simple masonry churches that had severe damage after the 2010 earthquake (Mw 8.8) did not have elements that allowed an adequate box behavior (Palazzi Chiara, 2019). In the Church of Santa Filomena, the reinforced concrete reinforcements incorporated in 1928 fulfill two main roles: connecting the walls to avoid failure in the joints and avoiding failure outside the plane due to tilting.

Validation of the use of reinforced concrete reinforcements

Prior to the creation of ICOMOS in 1965, UNESCO (United Nations Educational, Scientific and Cultural Organization) held the Athens Conference in 1931 (UNESCO, 1931), where its resolution N°5 indicates the following regarding the use of modern materials for the consolidation of old buildings:

> "The judicious use of all modern technology resources is approved, especially that of reinforced cement (...) These means of reinforcement must be concealed so as not to alter the appearance and character of the building."

This conference was contemporary with the reinforcements used in the Church of Santa Filomena and allows one to understand that the reinforced concrete technique as reinforcement was already applied globally to intervene in historic structures. Additionally, it is indicated that the "appearance" and "character" of the building should not be altered, which is currently understood more comprehensively.

The safeguarding of the "aesthetic and historical" values of heritage structures is recognized by the Venice Charter of 1964 (International Council on Monuments and Sites [ICOMOS], 1965)

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and the principles of the ISCARSAH committee in the Zimbabwe Charter of 2003 (ICOMOS, 2003). Both charters presented by ICOMOS (International Council on Monuments and Sites) defined the necessary criteria to be considered when intervening in a historical value structure respecting its values and attributes. When a structure of historical value is intervened, the desired structural safety goes beyond avoiding structural failures and the loss of lives. It is also necessary to "safeguard the intrinsic values of the property" (Peña Mondragón & Lourenço, 2012). Currently, the Chilean standard for intervention in heritage buildings NCh3389:2020 (INN, 2020) presents different intervention criteria separated between design, structural, and heritage criteria. It indicates that the intervention project must consider the "heritage values and attributes" and that the requirements must "achieve both structural safety and the integrity of the heritage value."

The ICOMOS intervention criteria and the Chilean regulations are not explicit with a single concept or organized by a hierarchy of importance because, for each structure in its particular context, the team of professionals will use the intervention criteria differently to achieve the final objective, which is to restore the built element as a whole.

The Zimbabwe Charter of 2003 (ICOMOS, 2003), in section 3.3.7, indicates the following regarding the use of new intervention techniques:

> The choice between "traditional" and "innovative" techniques must be weighed on a case-by-case basis, always giving preference to those that produce a less invasive effect and are more compatible with the values of cultural heritage while never forgetting to comply with the requirements imposed by safety and durability."

Among the existing intervention criteria, such as reversibility, compatibility, and minimum intervention, the analysis to justify using reinforced concrete reinforcements can be approached from two main criteria (Sáenz Muñoz, 2023): authenticity and structural safety. The definitions of these criteria for this study are as follows:

- Authenticity: Refers to the integrity of a structure's elements as a reflection of a constructive technology typical of its time. Therefore, the fundamental principles of the structure's behavior and its original materiality must be preserved.
- Structural safety: If the structure has damage, the intervention must consider the possible artistic and cultural damages in the structure and prioritize safeguarding the property's intrinsic values.

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It would have been reasonable to make a local repair of the damages produced after the earthquake of 1928 without having corrected some of the seismic design problems that the structure could present in the long term and that had been observed in multiple churches of simple masonry product of previous earthquakes. However, the structural reinforcement of the Church of Santa Filomena is a clear example that has managed to preserve the structure until now only with moderate damage and without altering its earthquake-resistant behavior and architectural values or attributes. If another reinforcement option had been chosen in the past that prioritized authenticity, it is possible that the structure would have suffered more significant damage and even collapsed. Therefore, although the concept of authenticity in its most purist and rigorous conception is not respected by this type of intervention with reinforced concrete, it should be taken into consideration that Chile is a highly seismic country, and this local context invites us to consider authenticity under a new gaze where structural safety takes a more significant role intending to preserve the heritage over time. These new considerations may allow the recent Chilean standard for intervention in heritage buildings NCh3389:2020 (National Institute of Standardization [INN], 2020) to be updated to better adapt to the safety requirements that our seismicity imposes on heritage.

CONCLUSIONS

Is the use of reinforced concrete reinforcements justified in intervening in historical structures? The answer will depend on each structure since it requires a unique analysis. However, in the case of simple brick masonry structures located in countries with a highly seismic context, such as Chile, the most appropriate intervention techniques based on theory and empirical experience of their historical performance should be sought to improve their seismic behavior.

The use of reinforced concrete in restoration has generated controversy over time. From the beginning to the middle of the 20th century, it was thought to be the solution for any deterioration in historical buildings. Until the end of the same century, it was observed that, in some cases, interventions with reinforced concrete manifested incompatibilities with the elements due to the internal characteristics of the materials or the work (Esponda, 2004), which can produce structural issues due to changes in its mass and rigidity. However, if executed correctly, they avoid typical failures in structures of this type that can trigger a collapse. As indicated above, it is possible to argue that this type of reinforcement does not meet the criterion of authenticity in its strict definition for brick masonry structures, given the difference between both systems and constructive techniques. Nevertheless, each intervention criterion must be weighed through a cost-benefit analysis to ensure the best heritage conservation over time and in the local context, which is highly seismic in this research case. Therefore, the invitation is to consider the authenticity criterion with a new look where structural safety is more important.

Have the reinforced concrete reinforcements incorporated into the Santa Filomena Church worked properly? These have fulfilled two leading roles: to connect the walls to avoid failures at the joints and to avoid failures outside the plane due to tilting. It should be borne in mind that the structure has been subjected to at least five earthquakes of over 8.0 in magnitude since the last reinforcement in 1928, and no severe damage or collapse has occurred. These reinforcements were executed when there were still no design codes or complex structural analysis methods. They have managed to preserve the structure until now only with moderate damage and without altering the earthquake-resistant behavior or its architectural values or attributes.

The example shown in this research is a specific case of reinforced concrete reinforcement in a historical brick masonry structure that has had good seismic behavior. Thus, the limitation is that the result might not apply to a similar structure. Therefore, in future research, the seismic performance of a more extensive set of cases of historical structures that have been intervened in this way should be compared to understand in greater detail the effect of incorporating reinforced concrete reinforcements that contribute to the building's structural safety while respecting the heritage intervention criteria. It is also proposed that a method that allows systematizing the selection of structural reinforcement techniques with less impact for a specific structural typology be investigated in the future.

CONTRIBUTION OF AUTHORS CREDIT

Conceptualization, S.S.M.; Data curation, S.S.M.; Formal analysis, S.S.M.; Acquisition of financing S.S.M.; Research, S.S.M.; Methodology, S.S.M.; Project management, S.S.M.; Resources, S.S.M.; Software, S.S.M.; Supervision, G.M.S.; Validation, G.M.S.; Visualization, S.S.M.; Writing - original draft, S.S.M.; Writing - proofreading and editing, G.M.S.

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