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# Preserving Historical Value through Innovative Reinforcement Techniques: A Case Study of the San José de Chimbo Church in Ecuador

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***Abstract*** **-** This research study investigates the structural evaluation and reinforcement of the San José de Chimbo Church in Ecuador. This historical architectural monument suffered significant damage during the September 2018 earthquake. An innovative reinforcement method employing injected mortar is proposed to preserve its historical significance. Exhaustive inspections were conducted to comprehensively assess the damages suffered by the church, yielding precise data regarding the deformations and cracks in its structure. Based on the results of the structural evaluation, the use of injected mortar was proposed as a reinforcement technique. This approach offers several advantages, including its ease of application and adaptability to existing forms and cracks. Injected mortar involves introducing a high-strength cementitious material into the damaged areas, effectively strengthening, and restoring the structure without compromising its historical value.

Furthermore, laboratory tests were carried out to assess the mechanical strength and properties of the injected mortar, ensuring its suitability and effectiveness in the Church's rehabilitation. Additional factors such as durability, compatibility with existing materials, and resistance to future seismic events were considered. The proposed reinforcement utilizing injected mortar aims to provide a sustainable and efficient solution for preserving the San José de Chimbó Church, ensuring its structural stability and historical value for future generations. This approach can be applied in other rehabilitation projects concerning heritage structures affected by earthquakes, offering a viable and respectful alternative that honors history and architecture. In summary, this research work introduces an innovative proposal for reinforcement through injected mortar to preserve the historical structure of the San José de Chimbó Church. The outcomes obtained and insights gained have significant implications within engineering rehabilitation and architectural heritage preservation, demonstrating how technical innovation and a respect for historical value can be combined in structural reinforcement projects.

***Keywords*****:** Adhesion, seismic activity, structural analysis, shear stresses, design spectra.

## 1. Introduction

The Ecuadorian territory is located on the South American Plate. It is a significant part of the renowned "Pacific Ring of Fire" and a crucial region for subduction and periodic seismic activities [1]. The geographic location of Ecuador within the South American Plate places it within this dynamic zone, where tectonic forces are constantly at work, resulting in seismic activities [2]. These seismic events, often of considerable magnitude and occurring close to the epicenters, affect the heritage assets in Ecuador. Unfortunately, many of these historical structures lack earthquake-resistant designs due to their age, making them susceptible to structural damage. This vulnerability is evident in the case of the Matriz de San José de Chimbo – Bolívar church, which has suffered structural damage due to these seismic forces.

The Church, constructed eight decades ago, includes an area of 865m$^2$ with a primary structure consisting of rock blocks bounded by mortar, comprising a mixture of lime, water, and sand. In 2006, an 80 cm thick brick altar was built, mirroring the dimensions of the rear facade. However, the Cumandá earthquake led to a phenomenon known as "knocking" between the altar and the facade, resulting in substantial cracks within the mortar (Problem 1). This seismic impact was similar within the Church's interior, with pronounced cracks above the religious center's arches – Problem 2. These cracks can be attributed to the diminished shear capacity of solutions implemented during prior repairs. These issues were evidenced and documented during technical visits conducted by the authors. This article examines the impact on structural elements due to the 2018 earthquake and assesses their resilience in the context of the 2015 Ecuadorian regulatory standards for seismic design. These standards mention an earthquake spectrum 80% more intense than the seismic of September. Likewise, the solution proposed by the local authorities in response to the possibility of facade inclination due to the interaction between the altar and the Church's frontage. This research yields critical findings, which will be mentioned in the conclusion's remarks. In addition to this analysis, economically viable solutions are proposed to increase the resilience of elements affected by seismic movements within the Main Church.

The modeling approach applied to analyze the structural behavior of the Catholic Church includes the use of Finite Element Analysis (FEA), a numerical method that consists of solving differential equations governing various phenomena [3]. A specific technique to assess the Church involves discretizing the monolithic structure into finite components, allowing for examinations of shear stress joints. Furthermore, this structural modeling method has found application in simulating areas prone to mass movements along the coastal region of the State of Carabobo in Venezuela in response to geological warnings [4]. The simulation results have indicated instability in four zones, showing a risk to the neighboring community due to vertical displacements, stresses, and unit deformations [4]. The National University of Colombia also uses this analytical approach to study doctrinal churches in the Colombian Altiplano Cundiboyacense (1579-1616). The research focuses on analyzing masonry techniques and stone elements that are fragile. Solid elements in the church wall system are used to model the structures, which involves discretizing the shell elements with varying wall thicknesses, with the specific subdivision of areas dependent on the dimensions of the blocks [5].

Based on this methodology, a comprehensive analysis of the rock structure has been carried out, focusing on identifying vulnerable areas in the cement paste, particularly in the context of the September 2018 earthquake. A seismic model has also been developed to ensure the structural integrity of the religious center, following the 2015 Construction Standard in force in Ecuador. The dimensions of the rock blocks were measured during the construction of the central structure, using total station laser measurements to accurately verify the dimensions of the structure, including walls, columns, and internal arches. The columns are represented as walls of thicker rock blocks in the model to simplify the modeling process, and specific masonry properties such as elastic modulus and simple compressive strength are considered.

## 2. Methodology

The methodology applied in this article follows a structured waterfall approach. It commences with on-site inspections to assess the condition and impact on the heritage structure. Subsequently, a comprehensive analysis is conducted using computer software to facilitate this process, and field and laboratory tests are conducted to gather material properties from the structure. Based on the findings, solutions are proposed to enhance the structural capacity of the most vulnerable elements. Addressing the challenges presented, which primarily involve the cracking of the binder and the insufficient strength of mortar applied in previous restoration efforts, requires a thorough examination of the religious center and its susceptibility to accidental forces. The outcomes of this analysis are generated using the SAP2000 structural analysis software.

### 2.1. Inspection and collection of information

During the initial inspection, more minor cracks were observed in the columns, arches, and rock walls of the structure, as well as larger cracks with openings of approximately 5 cm and lengths of up to 2 m, primarily located in the central nave adjacent to the brick altar- the area displaying the most significant damage (figure 1).

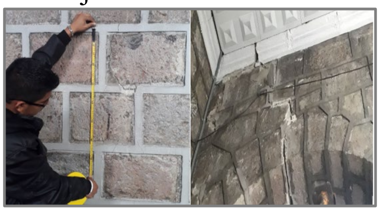

Fig. 1 Measurement of cracks in the Church.

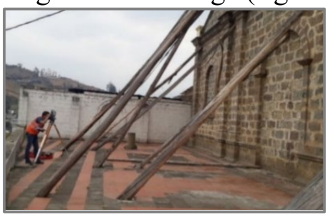

Fig. 2 Altimetric survey of rear wall.

Additionally, during the exterior inspection, lengthy wooden supports were found, which had been installed by the town's administrators (Figure 2). An altimetric survey using a total station was carried out to verify the integrity of the rear facade and assess whether any inclination was present. This process involved 70 points measured through laser shooting, followed by input into the AutoCAD 2019 [6] computer drawing program, and allowed to determine whether the rear facade exhibited any inclination that might require the use of the wooden struts. The data collected provided the necessary dimensions to model the most severely affected components. Moreover, essential information was gathered regarding the materials employed in the structure, and their mechanical properties were examined. These detailed characteristics were subsequently analyzed within the SAP2000 software.

### 2.2. Experimental Investigations

Non-destructive tests were conducted to obtain the properties of the elements, and laboratory samples were subjected to fracture testing (Figure 4). The rebound hammer method [6] assessed the simple compression strength of the original mortar and the mortar used in prior restoration efforts. Ten rebound measurements were obtained from the same area to calculate an average value in each case. This approach minimizes the influence of potential measurement inaccuracies resulting from unfavorable positioning or other external factors, ensuring more reliable results [6] [7].

Cylinder fracture tests following the ASTM D2938-95 recommendations [8] (Figure 4) determined the andesite rock's compressive strength, which comprises the wall blocks. These tests adhere to a 2:1 ratio between the height and diameter of the cylinders. The samples for these tests were brought from a construction site adjacent to the Church in the canton of San José of Chimbo. Figures 5 and 6 show both the destructive and non-destructive testing procedures conducted.

Fig. 4 Sclerometer test.


Fig. 4 Rock Cores and Brick Block.

### 2.3. Structural Analysis using SAP2000 Software

Within the software, comprehensive data concerning the materials found within the Church were input, including details regarding the support structure, gravitational forces, and the accidental earthquake forces resulting from the September 6 earthquake event. This process also incorporated the consideration of load combinations following the NEC-2015 regulations. The Church's walls are primarily composed of rock blocks, each approximately measuring 30x30. This particular dimension was employed to discretize the Shell elements within the SAP2000 software. Furthermore, the thickness of these elements is defined as "Thin" for elements measuring less than 800 mm, while those exceeding 800 mm in thickness, representing the columns within the internal walls where the affected arches are located, are classified as "Thick."

The gravitational forces acting upon the structure include the self-weight of the structure materials, namely the andesite rock walls, bricks, a 0.30 mm galvalume cover, and wooden stringers employed as support for the cover. The cover, sourced from the manufacturer DIPAC, possessed a distributed load per unit area of 2.87 kg/m2, accompanied by a point load assignment of 600 kgf on the andesite rock wall. For the modeling of earthquake forces, data on ground acceleration was recorded by the EPN Geophysical Institute during the earthquake event, affecting the essential structure employed. This data facilitated the construction of a design spectrum using the PRISM software and was taken for modeling the earthquake forces present in the Church on the analysis date.

The NEC – 2015 earthquake regulations present higher acceleration values, primarily due to specific considerations that govern essential structural masonry structures, which include a reduction factor (R) of 1. Furthermore, the regulations account for the soil type in the Canton of San José de Chimbo, is categorized as type C soil. The seismic zone value, influenced by the Church's specific location, is determined as Z = 0.35 for the community under examination. After performing calculations relating to the parameters mentioned in the previous paragraph, the subsequent step involves deriving the design spectral function alongside the spectrum observed during the September 6, 2018, earthquake in Cumandá. Subsequently, having analyzed the impact from the September earthquake, it extracted the acceleration data corresponding to the design earthquake, extrapolating from the data recorded in 2018.

## 2.4. Examination of Problem-Solving Approaches

The proposed solutions for addressing the cracking issues within the Main Church consist of two compositions: projected concrete for problem 1 and injected mortar for problem 2. The selection of projected concrete is motivated by the need to stabilize the rear rock facade, which has experienced cracking due to the impact from the brick altar and rock wall during moderate 6.2 Mw earthquakes. Therefore, the dosage of shotcrete requires rigorous material characterization and subsequent quality control tests. Similarly, strict control must be carried out for the mortar intended for injection into the cracks of the internal arches and areas near the altar, where the most significant openings are observed. An evaluation of the additive's percentage is also tested to optimize quantities and take advantage of its performance efficiency.

## 2.5. Limitations on Concrete and Mortar Dosages

The materials used in shotcrete construction are similar to those used in conventional concrete, with specific distinctions in the size of fine and coarse aggregates to facilitate on-site pumping. Aggregates between 4.75 and 15 mm, river sand, drinking water, and cement with a water-cement ratio of 0.45 were used. An additive called Sikament 115 was added to the mix. Potable water is employed for the preparation of the shotcrete mix.

# 3. Results And Discussion

By conducting the sclerometer test on-site, employing the Schmidt hammer with ten rebounds, the average strength of the Andesite rock, mortar, and the mortar and brick compositions found within the structure were determined. An empirical correlation based on laboratory data was employed to convert the surface hardness values (measured in rebounds) into estimates of compressive strength in units of MPa, as shown in Table 3.1.

Table 3.1 Strength of the church components

| Material | Measured in rebounds | Compressive strength [MPa] |
|---|---|---|
| Andesite Rock | 24 | 41.9 |
| Argamasa | 18 | 20.1 |
| Mortar | 16 | 27.0 |
| Brick | 19 | 32.1 |

In the laboratory testing, similar results were obtained for the compressive strength of the rock constituting the walls, which reached up to 50 MPa. According to the Ecuadorian standards, the modulus of elasticity used to define sections with varying thicknesses in the SAP2000 program for structural modeling is $E_{LAD}$=3517.50 MPa. For instance, the provided example demonstrates the elastic modulus value for the brick material, the simple compressive stress of which was determined as 4.69 MPa through laboratory testing. The Young's modulus value for the pulpit wall falls below the permissible limit stipulated by NEC-2015 for masonry elements. Initially, the walls were delineated using the rectangular area option and subdivided into approximate sections measuring 30x30 cm. Given the constraints imposed by materials and dimensions, an analysis on determining the shear stresses induced by the 6.2 Mw Cumanda earthquake.

## 3.1 Impact on the Rear Facade: Problem 1.

For this analysis, the isolated rear wall of the entire structure is considered, including the brick wall representing the altar, while considering property support and income restrictions. The maximum shear stress demand from the 2018 earthquake is calculated at 6.82 kg/cm2, representing the shear force resulting from the interaction between attached walls with different moduli of elasticity. The efforts to be identified are associated with Problem 1 concerning the rear facade and the proposed 300 kg/cm2 projected concrete to address this. The shear capacity is $0.53\sqrt{f'c}$.The shotcrete's capacity is determined to be 9.18 kg/cm2, which represents 75% of its capacity during the earthquake that occurred on September 6, 2018, DCR = 0.74 < 1.

The following shear force demands have been obtained by inputting the acceleration data generated by the design earthquake according to current regulations. The demand generated by the design earthquake on the rear facade is 40.93. When multiplied by the area (50 cm x100 cm) subjected to shear, accounting for the entire wall excluding the concrete solution, it gives 204650 kg.

The analysis involves assessing the capacity of the rear wall and concrete projection assembly by applying shotcrete. In addition, it considers the thickness used in addressing the solution of problem 1, which is e = 10 cm compared to the current block wall, as shown in Table 3.2. The nominal shear resisted by the concrete is Vn= 216409.6kg

Table 3.2 Rear wall and shotcrete capacity

| | f'c | b | h | Vn | Vn |
|---|---|---|---|---|---|
| | Mpa | mm | mm | Ton | kg |
| | 50 | 1000 | 500 | 353.6 | 353550 |
| | 30 | 1000 | 100 | 54.8 | 54770 |
| | | Capacity, Vn | | | 408320 |

In this way, the final relationship of the concrete solution and resistance contribution of the rock wall is obtained as DCR = 0.9 < 1.

In addition to the structural system, reinforced concrete props have been introduced at the lower section of the facade, authorized by the religious center's authorities (Figure 7). This addition has impacted the existing structural configuration of the forest wall and the altar, resulting in a shear stress demand of 120.53 kg/cm$^2$, a value directly affecting the mortar binding the rock blocks. In a design earthquake, the wall's stability is affected in the area where the concrete props are located. This observation is demonstrated and supported through the use of SAP 2000.

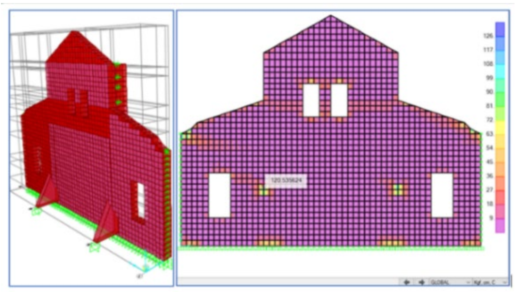

Fig. 7 Analysis of concrete props next to the rear façade.

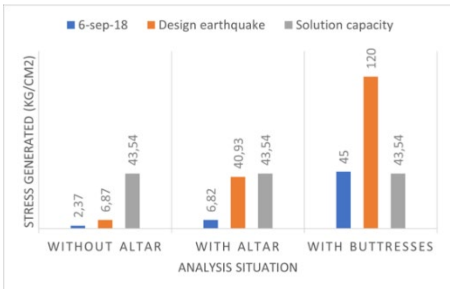


Fig.8 Analysis of the 3 situations presented in the Church

Below, the analysis of the three scenarios is presented: one without an altar, one with an altar, and the one involving the placement of reinforced concrete props. In this part, the primary focus will be on the current situation that considers the placement of the props. As mentioned, introducing these props has harmed structural stability, particularly in earthquakes exceeding 6.5 Mw, such as the one that occurred on September 6, 2018. Under these conditions, the shotcrete alone may not have the capacity to address the imposed structural demands. The knocking phenomenon would not have occurred in the situation presented as "Without Altar", which represents the conditions a decade ago. Therefore, the stresses induced by the design earthquake would not have led to the development of cracks in the wall. In the "With Altar" case, the stresses resulting from the design earthquake exceed the capacity of the binder when the pounding is generated, and in turn, causes the appearance of cracks. In response, a shotcrete solution with a shear stress rating higher than the earthquake's is proposed to ensure wall stability. Lastly, in the "Struts" scenario presented in December 2018, the stresses produced by the design earthquake are three times greater than the solution's capacity. Consequently, the stability of most of the rock walls is affected (Figure 8).

For the final solution, the reinforced concrete props must be removed due to the increase in shear stresses to project the concrete and act at its maximum capacity without increases in stress generated by this solution detected in December. However, it is crucial to note that the altar cannot be dismantled due to its cultural and heritage significance and the substantial financial investment made in recent years.

### 3.2 Affectation of the binder in internal arches: Problem 2.

A similar analysis has been conducted for the 80 cm thick internal walls, wherein 5 cm thick cracks have emerged in regions adjacent to the altar, coinciding with the areas where knocking is generated. The internal arches are examined, employing the seismic design force parameter specified in NEC-2015 to obtain the shear force demands in the areas where the most significant impact was observed, cracks with a length of 2 m and greater depth thickness. These arches have been measured to span 3.40 meters.

In this way, a Vu=10 kg/cm2 is presented due to the design seismic load; the demand occurred in the columns and near the central part of the arches. For problem 2, the injection of mortar based on GU-type cement is proposed, and additives that help increase adhesion and resistance. The proposed mortar presented a simple compression resistance of 500 kg/cm2 and a slight increase in volume provided by the Intraplast Z additive from Sika Ecuatoriana S.A, the latter providing an adjustment between the blocks due to the friction presented when increasing the volume. The shear capacity of the mortar of f'c=500 kg/cm$^2$ was obtained with Eq 2, reaching Vn=11.85 kg/cm$^2$. The demand-capacity of the proposed solution to earthquake design demand was considered for the highest shear stress presented in axes 2-3, having the following relationship DCR = 0.84 < 1. The shear resistance of the mortar, earthquake design, and the mortar dosed by the authors. Thus, we can ensure that using the 50 MPa mortar provides 84% of its capacity before shear stresses, which occur in the design earthquake of the Ecuadorian regulations.

### 3.3 Design of concrete and injection mortar dosages.

The dosages have been made based on GU cement of 2850 kg/m3. The common additive for both solutions is the Sikament N115 water reducer, dosed at different percentages for each proposal.

The shotcrete was dosed with a maximum gravel size of 12.5 mm, representing the 34% occupied by the aggregates and the sand. This percentage is used to find the combined curve that allows me to be within the rule's limits. [9]

The optimal amount of gravel and sand was verified, and the other concrete components were tested. The amount of cement and the percentage of additive was tested in the laboratory, adjusting to the restrictions of the methodology, obtaining the quantities to be used for 1 m3 as shown in Table 3.3. The water reducer and accelerator percentages were 1.98% and 1.30%, respectively.

Table 3.3 4 Shotcrete dosage f'c = 30 Mpa.

| **Materials** | | **Cement** | **Rock #7** | **Sand River** | **Water** | **N115** | **Sigunit L-600** |
|---|---|---|---|---|---|---|---|
| Weights S.S.S **x m3** | **Kg** | 447 | 585 | 1144 | 181 | 6.48 | 5.81 |
| Mixed Quantity **S.S.S** | **Kg** | 7.65 | 10.01 | 19.58 | 3.32 | 0.151 | |

With the mixed amount of concrete, slump tests were carried out and cylindrical specimens of 10 cm in diameter were made to know the resistance obtained within days of failure. For problem 2, mortar injection has been chosen due to the thinner cracks generated at the joints of the internal walls; thicknesses from 3 to 10 mm were found in the lower parts of the columns. The thickest ones can reach 50 mm. The dosage of the mortar reaches 500 kg/cm$^2$, which allows for greater capacity against the shear forces that affect the binder of the blocks. For its preparation, an electric mixer was used to produce cubic specimens. The mixing process should not exceed 30 minutes like the concrete mix.

In the same way as shotcrete, the percentages of Sikament N100 and Intraplast Z additive were tested to obtain a resistance close to rock blocks, 1.40% and 3.00% about the weight of the cement as shown in Table 3.4, evidencing the volumetric increase provided by the expanding additive.

Table 3.5 Dosage of mortar to inject, f'c = 50 Mpa.

| **DOSAGE** | | |
|---|---|---|
| **Components** | **Quantity** | **Unit** |
| Cement GU | 50 | kg |
| Water | 15.6 | kg |
| Water reducer (Sikament – N 100) | 442 | grams |
| Expander (Intraplast Z) | 1.5 | kg |

The achieved strength of the concrete is 500 kg/cm$^2$, which provides sufficient capacity for the shear demands generated by the design earthquake. The strength was reached after 28 days of breaking 50x50x50 mm cubes. In this way, the two solutions based on GU-type cement have the capacity the affected elements require when the design earthquake occurs. At the same time, they have been designed for loads generated by moderate earthquakes such as the one that occurred in September 2018. The resistances achieved have been strictly controlled in terms of the curing of the specimens; in the same way, a safety factor was taken for the calculation of the capacities of the solutions. For example, the mortar reached a simple compression resistance of 520 kg/cm2. However, for calculations, the value of 50 Mpa was chosen. This consideration was also applied to the shotcrete of problem 1. The slump achieved in the concrete allows for the fluidity required for pumping the concrete, which must be between 12 to 18 cm, and it was possible to obtain a slump of 14 cm, a value that, according to the EHE-08 standard [10], in its Article 31, indicates that the mixture is very workable.

## 4. Conclusions

Differences in structural resistance between masonry elements (andesite rock blocks) and mortar result in cracks in the lower-resistance component, mainly when the ratio between rock blocks and binding mortar is approximately 2:1.

Through the altimetric survey on the rear facade, the verticality of the structural element was corroborated. The shotcrete solution is designed to enhance stability against cracking induced by the design earthquake and potential inclination during seismic activity; compared to the events of September, the design earthquake imposes an 80% higher demand on stability.

The reinforced concrete struts, placed in December 2018, affect the stability of the rear facade. They increase shear stresses, directly affecting the blocks' binding mortar. Moreover, these struts increase the shear forces beyond the structural wall's capacity. The increased demand during the design earthquake is attributed to the continued pounding generated by the brick altar and the addition of the concrete props, leading to the detachment of the blocks comprising the rear facade.

The solution to problem 1 exhibits greater resistance against the shear forces responsible for cracking the rear facade. Relative to the 2018 earthquake, the concrete projection achieves 75% of its shear strength. However, in the context of the design earthquake, the 10 cm thickness provides a nominal resistive force equivalent to 95% of the shear force specified in NEC – 2015.

The mortar joint possesses a simple compression resistance of 20 MPa, resulting in a shear resistance of 2.37 kg/cm$^2$. This value is less than the 6.14 kg/cm$^2$ stress imposed by the design earthquake, primarily due to the mortar's limited capacity. Conversely, the injected mortar solution has been dosed for the design earthquake, generating a maximum shear demand of 10 kg/cm$^2$. The 50 MPa mortar, boasting a resistant shear stress of 11.85 kg/cm$^2$, acts at 84 % of its capacity.

In previous repair efforts, 27 MPa mortars were employed, failing to provide the capacity and adhesion necessary for the blocks near the rear facade. Consequently, these joints experienced overstressing and developed larger cracks. In the event of a design earthquake, the blocks would reach their maximum stress, leading to breakage and instability in the internal arches.

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