Open Minds

Internacional Journal

ISSN 2675-5157 vol. 1, n. 3, 2025

ARTICLE 10

Acceptance date: 27/11/2025

SEISMIC VULNERABILITY IN THE COMMUNITIES OF SAN LUCAS AND SAN JUAN EVANGELISTA, A CHALLENGE FOR MASONRY CONSTRUCTION

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Abstract: Natural phenomena of geological, hydrological, and atmospheric origin—earthquakes, volcanic eruptions, floods, hurricanes, etc.—are events that represent latent dangers that are considered a threat to the social and economic development of a region or country. San Juan Evangelista and San Lucas Evangelista, ancient towns in Tlajomulco that make up the Franciscan Route, are part of the municipality's cultural heritage due to their handicrafts and Baroque churches, which are considered architectural monuments. However, their buildings, like their communities, are vulnerable to natural disasters such as those mentioned above, testing the resilience of society and government, which are failing in terms of comprehensive disaster management. Experience in field research in seismic engineering and disaster assessment highlights the need to update Guadalajara's Seismic Resistance Regulations, as it is possible to mitigate natural effects by applying the basic principles of seismic engineering. The objective of this work is to satisfactorily assess the seismic risk of a group of homes and to study h r corrective measures to reduce the risk that earthquakes can cause to structures made of unreinforced masonry and adobe. The methodology is that implemented by the Pacific Earthquake Engineering Research Center (PEER), as it is a robust tool for evaluating structural performance in terms of probabilistic analysis. The results obtained were the evaluation of the cost and recovery time of a structure that has been damaged by an earthquake and that can be discretized into two time intervals called rational and irrational. It was concluded that parallel repair was more expensive because it requires a significant number of workers to carry out rehabilitation activities. Congestion problems were also identified when the threshold of workers per unit area was exceeded. With regard to irrational factors, it was concluded that due to the complexity of the problem, a generic sequence was used, as shown in Figure 2.

Keywords: Vulnerable, disasters, resilience, masonry.

Introduction

San Lucas and San Juan Evangelista both belong to the municipality of Tlajomulco de Zúñiga and are part of the Guadalajara Metropolitan Area (AMG). They are located approximately 35 km southwest of Guadalajara, Their geographical coordinates are 20° 24′ north latitude and 103° 20′ west longitude at an altitude of 1560 meters above sea level. The surface area of San Lucas Evangelista is approximately 98 ha, while the surface area of San Juan Evangelista is 126 ha. while the municipality of Tlajomulco, to which both towns belong, covers 636 km², as shown in Figure 1 (POE, 2010).

These towns are part of the Franciscan route, which is considered a cultural heritage site by UNESCO, as well as being recognized as an archaeological zone by the INAH.

Fortunately, some buildings are still preserved, which is precisely the objective of this work: the conservation, maintenance, reinforcement, and shoring up of the historic temples of the Franciscan route of Tlajomulco de Zúñiga, which is made up of nine temples of non-confined masonry dating between 200 and 400 years old, built during the colonial period between

Figure 1. Satellite image of the Cajititlán riverbank and its surrounding towns.

Source: www.earth.google.com

the 17th and 18th centuries (Preciado *et al.,* 2015).

In the national context, Tlajomulco de Zúñiga is part of the Central-Western Region of the country and the AMG, being one of the two metropolises with the most infrastructure and manufacturing services in the country. The city of Guadalajara is interconnected through the Canada-Mexico corridor, as well as the corridor of the Treaty between Mexico, the United States, and Canada (T-MEC).

The dynamics of the region are a result of Silicon Valley and logistics companies that have reconfigured their corridors, an example of which is the macro-bypass that connects the city of Guadalajara with the Pacific and Mexico City, as shown in Figure 2, as its corridors provide opportunities and competitiveness for real estate companies (IMTJ, 2015).

On the other hand, growth in the municipality of Tlajomulco in terms of housing is constantly increasing every year. In 2010, there were a total of 101,811 homes with all services, but by 2020, there were a total of 208,758 homes (IIEG, 2023). The predominant materials used are masonry, cement-sand blocks, reinforced or unreinforced brick walls, reinforced concrete slabs, brick or wedge vaults, the most commonly used reinforced concrete structural elements (dalas or castillos), and occasionally Armex.

Background

The city of Guadalajara had its first Building Regulations in 1988, which were amended in 1997 and are still in force today. No updates have been made to date, despite the fact that the state of Jalisco has high seismicity and buildings constructed before 1993 have lower resistance than they should be designed for (Pérez, 2018)..

The concept of resilience has become increasingly relevant in recent years. In the 1970s, this concept began to be used in

Figure 2. Route of the ALG macro-bypass

Source: www.publimetro.com.mx

Location	Population 2010	Population 2020
Hacienda Santa Fe	86,935	139,174
San Agustín	30,424	49,402
Tlajomulco Center	30,273	44,103
Lomas del Sur	19,413	37,146
Santa Cruz del Valle	26,866	30,849
Tlajomulco de Zúñiga	416,626	727,750

Table 1. Population census of the municipality of Tlajomulco de Zúñiga

Source: IIEG, INEGI, 2020

fields of knowledge such as psychology and sociology, as well as environmental engineering and economics, to name a few.

In the field of seismic engineering, Bruneau (2003) was the first to adapt the concept of resilience to reduce the vulnerability of community infrastructure to seismic events. The goal of seismic resilience is to minimize the loss of human life, the number of injuries, economic losses, and in general any aspect that affects the quality of life caused by earthquakes.

The Jalisco block

The Jalisco block is the structure under which the Rivera plate subducts. The threat is located between the Rivera and North American tectonic plates, as well as the convergence between the Cocos and North American plates and the Rivera plate, causing severe damage in cities such as Colima (seismic zone D) and Guadalajara (seismic zone C) and in the states of Michoacán and Mexico (Urrutia, 2022), as shown in Figure 3.

State of the Art. Development of the Theoretical Framework

The structural concept

The general process of activities leading to a structural project involves a series of work stages that require a sequence and, at the same time, interdependence. These stages can be divided into four basic activities.

a) Structural design

b) Load analysis

c) Structural analysis

d) Dimensioning

Once the objectives of the structure have been defined and in accordance with its purpose, the designer, who is presumably already familiar with the problem to be solved and has studied the available information, begins the stage of designing the structure, that is, forming an idea or concept of it with suitable structural elements in terms of

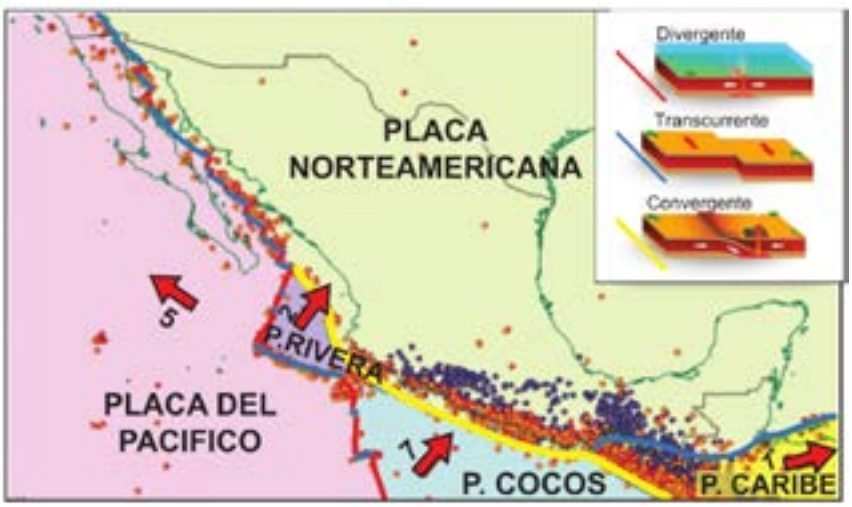

Figure 3. Map of the tectonic plates that interact in Mexico

Source: González, 2019

materials, shapes, proportions, and their arrangement, based on various alternatives so that the final solution meets certain requirements of strength, economy, and aesthetics.

The structural design will be the result of the experience, imagination, but above all the skill of the designer, but this professional intuition can only be developed with good academic support and constant, up-to-date professional practice. With these elements, the aim is to guide the design of the structures and not limit oneself to their calculation (Gómez, 2009).

In the case of urban construction, the structural design is developed simultaneously with the architectural project, seeking to materialize clear forms and ideas that solve the problem of adapting spaces. The architect has primary responsibility for this important structural phase, which will be decisive in terms of costs and the proper performance of the system *(ibid).*

Since the response of a building to seismic actions does not depend solely on the resistance capacity of the elements that make up the system, but also to a large extent on its shape, volumetric proportion, symmetry, regularity, etc.

Both civil engineers and architects must be made aware of the problem from their academic training, for which it is necessary to provide sufficient information on the attributes or qualities that structures must have in terms of their shape, the arrangement of vertical earthquake-resistant elements, mezzanine systems, etc. can lead to the design of a building that performs satisfactorily under the effects of an earthquake (*ibid).*

On the other hand, the state of Jalisco has pending tasks in the area of earthquakes, such as in the culture of risks and disasters, as well as in infrastructure in terms of structural safety and updating its building regulations, in addition to the lack of implementation of both seismological and accelerographic networks.

The only way to prevent risks caused by natural hazards is through their characterization and study, which allows for preventive measures or, where appropriate, mitigation measures for possible disaster scenarios (Núñez, 2011). As a first step toward assessing seismic hazard, it is necessary to study historical seismicity and correlate it with recent information. Unfortunately, there is no local seismic network.

Jalisco is one of the areas with the highest seismicity in Mexico and, as a result, the seismic hazard is very high, as it is not only associated with the subduction processes of the Rivera plate under the North American plate, but also with other continental structures that have generated large earthquakes, some capable of generating tsunamis, such as the earthquake on October 9, 1995, with its epicenter in Manzanillo, Colima (Cruz, 2013).

Materials and methods

Seismic protection in reinforced masonry constructions is an issue that has gained momentum in recent years, not only nationally but also globally. However, in the AMG, the Complementary Technical Standards for Seismic Design have not been updated since 1997. The main difficulties stem from the heterogeneity of the materials and their seismic behavior, as their tensile strength has not been designed.

The framework for seismic risk management in buildings consists of assessing seismic vulnerability and the measures necessary to reduce it. The susceptibility of a structure to damage is determined by the seismic threat and the vulnerability of the structure itself. In other words, structures under the action of an earthquake are subject to a cycle of action and effect, where the action is the earthquake and the effect is the damage to the structure.

All these factors combined—seismic zone, frequency content, fundamental vibration periods, and site effects—make seismic assessment and diagnosis in this type of construction (unreinforced masonry) a complex task. Therefore, the objective of this work is to satisfactorily assess the seismic risk in homes in both San Juan and San Lucas Evangelista, as well as to diagnose the preventative and corrective measures to reduce the risks. This is because the seismic risk of a masonry structure is determined by the seismic threat and its structural vulnerability.

To analyze the susceptibility of unreinforced masonry buildings to suffer damage or collapse in the event of an earthquake, it is necessary to assess the seismic vulnerability of unreinforced masonry houses in the aforementioned towns, since both towns are located in zone C and are classified as having high seismic hazard.

Probabilistic seismic performance assessment scheme

The most robust tool for evaluating structural performance in probabilistic terms is the scheme developed by the Pacific Earthquake Engineering Research Center (Cornell & Krawinkler, 2000). This scheme consists of four probabilistic analyses: seismic hazard analysis, structural analysis, damage analysis, and damage consequence analysis, as shown in Figure 1.

The concept of resilience has many aspects and fields of application. The most relevant contributions in the field of structural engineering focus on aspects such as the assessment of loss of functionality or the estimation of recovery time. The innovation of this methodology is associated with a series of events that define the stages for recovering the functionality of buildings.

On the other hand, Burton (2016) proposes a three-phase recovery function: occupiable and functional, occupiable and

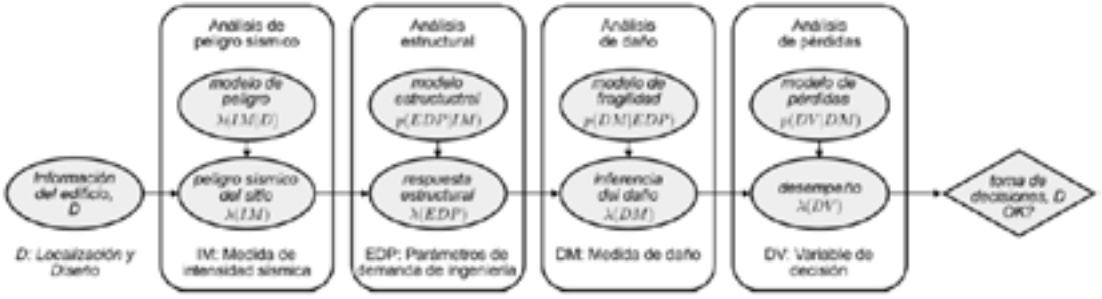

Figure 1. PEER assessment methodology framework.

Source: Cornell & Krawinkler, 2013.

non-functional, and unoccupiable and non--functional. The result is the obtaining of functionality recovery curves conditioned by the degree of seismic hazard.

The methodology to be implemented in this work will help us determine the costs and recovery time, as well as the functionality time and number of workers needed to carry out recovery work on a building damaged by the effects of a potentially destructive earthquake (Gutiérrez, 2022).

The proposed approach is based on the PERT methodology, which is a recursive process, i.e., the initial problem is divided into smaller, easier-to-solve problems. Within this evaluation scheme, key elements for the repair of damaged buildings are introduced, as well as a number of crews to repair a specific state of damage.

Results and Discussion

Assessment of repair costs and recovery time

To determine the recovery time of a building that has been damaged by an earthquake, it can be discretized into two time intervals called rational and irrational (Comerio, 2006). The first is associated with the time consumed in structural and non-structural repairs, while the second analyzes events such as seismic inspection, structural review and/or redesign, repair planning, obtaining financing to carry out reconstruction tasks, as well as permits from public works to be able to intervene in the building.

For example, if a building sustains minor damage, it is likely that only a quick inspection will be necessary (ATC; 1989), whereas if the building sustains severe damage, a detailed inspection will most likely be required to determine the type of repairs needed.

The number of trained personnel cannot be determined arbitrarily. Due to the number of damaged homes, the number of workers is likely to increase, thereby delaying the recovery not only of a single home, but of a group of homes.

Figure 2 illustrates the generic flowchart proposed in this paper for recovery assessment. This diagram contains the hypothetical sequence of factors involved in the recovery of a damaged home. Determining

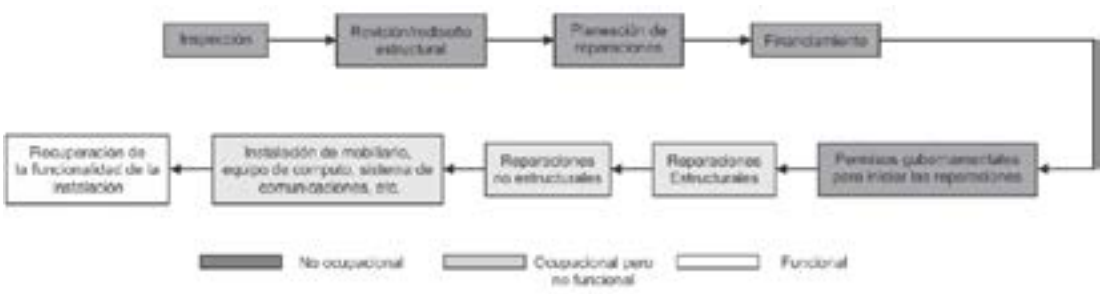

Figure 2. Generic sequence of factors influencing the time required to restore a home to functionality

Source: Gutiérrez, 2022

these factors and the chronological order in which they are represented is a complex task, as there are variables involved with a high degree of uncertainty and factors that cannot be taken into account due to the very nature of the problem (Gutiérrez, *et al.* 2019).

Conditions for generating the PERT diagram

As noted above, the recovery time for each damaged element was estimated within each performance group, while the following criteria were used for the construction of activities:

1. Propose the number of crews within each discrete damage repair activity.
2. Assign each crew the same proportion of elements that developed the same damage status.
3. The activities to be carried out must be performed sequentially by each corresponding crew, since the first activity contains x elements to be repaired, while the second contains **y** elements, associated with plants *q* and *r*, respectively.
4. Repairs will begin with activities involving the most severe damage. Once these are completed, activities involving less severe damage will begin, and so on.
5. Schedule activities in parallel to be carried out by two or more different crews, provided that the repairs to the elements are in the same damage state and correspond to the same performance group.

Conclusions

Tlajomulco de Zúñiga, a municipality that includes the towns of San Juan and San Lucas Evangelista, is of utmost importance to the AMG because Miguel Hidalgo International Airport is located just a few kilometers away, in addition to being home to the Franciscan route, which is considered a treasure from the colonial era, as we mentioned earlier.

The state of Jalisco, including Tlajomulco, is located in a highly seismic area, which puts homes built with unreinforced masonry at risk of damage or collapse in the event of an earthquake.

The proposed methodology can be useful not only for civil engineers but also for decision-makers such as investors, insurers, etc. Engineers can use it to assess the seismic resilience of buildings that have already been constructed or are under construction. The information generated will help us increase the resilience of buildings, which can translate into reduced vulnerability, and decision-makers can benefit from it when determining the most appropriate course of action after an earthquake damages a building.

Recommendations

Although the results of the assessment of the building under analysis appear acceptable, it is recommended that research be conducted in Mexico on the development of probability distribution functions for damage, costs, and repair times using information generated by Mexican institutions, such as the National Center for Disaster Prevention of the UNAM Institute of

Engineering, to name just a few. As is well known, the frequency, duration, and intensity of earthquakes that characterize seismicity in Mexico are different from the seismic characterization of the United States.

With regard to the number of workers and crews used, it is also advisable that these be prescribed based on the experience of Mexican engineers engaged in the seismic rehabilitation of buildings, and therefore it is recommended that the factors preventing the start of repairs be analyzed.

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