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EVALUATION OF THE SEISMIC VULNERABILITY OF TYPICAL BUILDINGS IN THE URBAN AREA OF CUENCA BY MEANS OF SIMULATION AND MULTIVARIATE TECHNIQUES

EVALUACIÓN DE LA VULNERABILIDAD SÍSMICA DE EDIFICIOS TIPO EN EL CASCO URBANO DE CUENCA MEDIANTE TÉCNICAS DE SIMULACIÓN Y MULTIVARIANTES

Luis Octavio Avila Guamán
Universidad Estatal de Milagro, Ecuador

Delia Narcisa Bueno Pulla
Instituto Superior Universitario Tecnológico del Azuay, Ecuador

Ávila Guamán James Andrés
Instituto Tecnológico Sudamericano, Ecuador

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Evaluation of the Seismic Vulnerability of Typical Buildings in the Urban Area of Cuenca by Means of Simulation and Multivariate Techniques

Luis Octavio Avila Guamán[1]
lavilag2@unemi.edu.ec
https://orcid.org/0009-0007-6770-2575.
Universidad Estatal de Milagro
Ecuador

Delia Narcisa Bueno Pulla
dely27a@gmail.com
https://orcid.org/0009-0000-1891-0588
Instituto Superior Universitario Tecnológico del Azuay.
Ecuador

Ávila Guamán James Andrés
andresavilaua@gmail.com
https://orcid.org/0009-0009-0473-4419.
Instituto Tecnológico Sudamericano
Ecuador

ABSTRACT

The study uses simulation techniques and multivariate analysis to evaluate the seismic vulnerability of typical buildings in the urban area of Cuenca, Ecuador. Located in an area of rich cultural heritage and high seismic activity, it highlights the need to implement mitigation strategies to preserve the architectural heritage and ensure the safety of its occupants. The structural response to earthquakes is evaluated through the modeling of representative prototypes and the application of specific models for confined and unreinforced masonry. The results show significant differences in the resistance of materials such as adobe and brick, with a considerable portion of buildings prone to collapse in medium-high intensity seismic events. The research shows the relevance of incorporating holistic approaches in urban planning and construction practices, taking into account the socioeconomic and cultural dynamics of the population, in addition to seismic standards. This analysis offers a valuable perspective for future research and the formulation of seismic risk prevention policies, bringing an innovative approach to the field of the relationship between seismic intensity and structural deformation.

Keywords: seismic vulnerability, Ecuador basin, risk mitigation, multivariate techniques

[1] Autor principal.
Correspondencia: lavilag2@unemi.edu.ec

Evaluación de la Vulnerabilidad Sísmica de Edificios Tipo en el Casco Urbano de Cuenca Mediante Técnicas de Simulación y Multivariantes

RESUMEN

El estudio utiliza técnicas de simulación y análisis multivariante para evaluar la vulnerabilidad sísmica de edificios típicos de la zona urbana de Cuenca (Ecuador). Situada en una zona de rico patrimonio cultural y elevada actividad sísmica, pone de manifiesto la necesidad de aplicar estrategias de mitigación para preservar el patrimonio arquitectónico y garantizar la seguridad de sus ocupantes. La respuesta estructural ante terremotos se evalúa mediante la modelización de prototipos representativos y la aplicación de modelos específicos para mampostería confinada y no reforzada. Los resultados muestran diferencias significativas en la resistencia de materiales como el adobe y el ladrillo, con una parte considerable de edificios propensos al colapso en eventos sísmicos de intensidad media-alta. La investigación muestra la pertinencia de incorporar enfoques holísticos en la planificación urbana y las prácticas de construcción, teniendo en cuenta la dinámica socioeconómica y cultural de la población, además de las normas sísmicas. Este análisis ofrece una valiosa perspectiva para futuras investigaciones y la formulación de políticas de prevención del riesgo sísmico, aportando un enfoque innovador al campo de la relación entre intensidad sísmica y deformación estructural.

Palabras clave: vulnerabilidad sísmica, cuenca del ecuador, mitigación de riesgos, técnicas multivariantes

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INTRODUCCIÓN

The city of Cuenca, located in the heart of Ecuador, stands as an outstanding example of colonial urban settlements, whose unique architecture and cultural richness have attracted the attention of scholars for its significant heritage value. However, this historical heritage is under constant threat due to Cuenca's geographic location in an area prone to seismic activity. This historical and geographical context underscores the urgent need to assess the seismic vulnerability of its buildings in order to implement mitigation strategies that preserve both its architectural heritage and the safety of its inhabitants [1].

In Cuenca, urban challenges such as insufficient planning, concentration of population and resources in high-risk areas, social segregation and the presence of informal habitats highlight the complexity of managing seismic vulnerability in densely populated and socially diversified urban areas. These factors highlight the need to adopt an inclusive and comprehensive approach that considers both the physical and constructive characteristics of the building and the socioeconomic and cultural dynamics of the affected population [2].

The challenge lies in developing building and urban planning policies and practices that not only meet seismic standards, but also promote equity and access to essential resources and services, thus ensuring greater community resilience in the face of the inevitable challenges presented by earthquakes. This integrative approach is proposed as essential to strengthen Cuenca's adaptive and resilience capacities, charting a path toward seismic risk management that effectively protects both the architectural heritage and the integrity and well-being of its inhabitants [3].

Seismic Vulnerability Assessment (SVA) of buildings in urban areas is a critical tool with multifaceted applications, notably in the development of seismic damage scenarios, emergency planning, and risk mitigation strategies [4]. The importance of these applications lies in their ability to inform and enhance urban resilience against seismic events. By predicting potential damage and identifying vulnerable structures, SVA aids in the preparation and implementation of effective emergency response plans, thus minimizing human and economic losses during earthquakes. Furthermore, by guiding the development of long-term risk mitigation strategies, SVA contributes to the creation of safer urban environments.

This vulnerability, according to Zamora et al., [5], is approached from a holistic perspective that integrates geophysical, environmental, sociopolitical and architectural factors, which is essential to capture the inherent complexity of risk assessment and the formulation of effective mitigation strategies. This multidimensional approach highlights the importance of understanding vulnerability not only as the capacity of systems or populations to withstand adverse events, but also in their ability to recover and adapt to such circumstances. Specifically, in the urban setting, special emphasis is placed on the specific conditions that affect cities and their inhabitants, highlighting how urban configuration and dynamics can significantly influence a community's ability to cope with and overcome seismic challenges [1].

SVA methodologies frequently incorporate Geographic Information Systems (GIS) to manage and analyze multisource data, culminating in georeferenced building databases that are instrumental for large-scale assessments [6]. The integration of GIS allows for a comprehensive spatial analysis of seismic vulnerability across extensive urban areas, enabling detailed mapping and visualization of risk levels. This capability is particularly valuable in urban planning and development, as it allows for the identification of high-risk zones and prioritization of retrofitting or reinforcement efforts. Moreover, GIS-based SVA supports dynamic updates and real-time monitoring, which are crucial for adaptive risk management.

The application of SVA methodologies ranges from individual buildings to entire urban districts, providing qualitative vulnerability indices that facilitate comparative assessments [7]. By categorizing buildings based on vulnerability indices, these methodologies help in assessing and prioritizing structures that require immediate attention or intervention. Simplified procedures for evaluating the seismic vulnerability of urban centers have been developed, taking into account various factors such as building typologies, construction periods, and structural systems [4]. These streamlined approaches enable rapid assessments, which are essential for timely decision-making in both pre- and post-earthquake scenarios.

Recent research in seismic vulnerability assessment of urban buildings focuses on improving accuracy and efficiency. Diana et al., [8] proposed using typological curves and modified N2 method for more reliable damage prediction. Likewise, Pilipović et al. [9] conducted a risk-based assessment of a typical masonry building in Zagreb, deriving fragility curves and vulnerability curves using incremental dynamic analysis. Asadi et al. [10] developed a framework combining Rough Set theory and weighted linear combination to assess seismic vulnerability under various earthquake scenarios, considering both physical and human factors.

The importance of this analysis lies in the ability to accurately discern the specific physical and constructive characteristics of buildings in Cuenca. This makes it possible to identify those areas most susceptible to earthquake damage, thus facilitating informed decision making aimed at strengthening the safety and resilience of the region. Through this approach, we seek not only to protect the historical legacy of Cuenca, but also to safeguard the lives of its residents from the inevitable seismic risks [11].

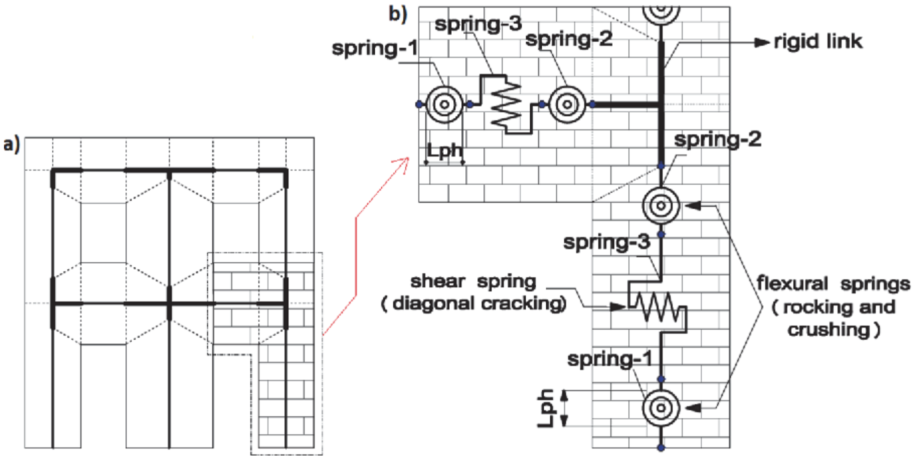
The methodological challenges of this study are considerable, given the complexity involved in modeling and analyzing the constructive variability of buildings in the basin. The integration of geospatial, topographic, geotectonic and climatic data plays a crucial role in the development of a reliable model that can faithfully reflect the seismic reality of the city, as mentioned by Menéndez-Navarro et al., [12]. In addition, the adoption of multivariate techniques introduces an innovative perspective to address seismic vulnerability, allowing to examine the interactions between multiple variables and their impact on the structural resistance to earthquakes.

Thus, the city of Cuenca faces the significant challenge of preserving its rich cultural and architectural heritage in the face of the constant threat of seismic activity, a task that demands a holistic and integrative approach [13]. The assessment of seismic vulnerability in this colonial urban context not only underscores the importance of protecting the heritage and safety of the inhabitants, but also highlights the need for conscious planning and construction that addresses both seismic standards and the socioeconomic and cultural dynamics of the population. The integration of multivariate analyses and the consideration of geophysical, environmental, sociopolitical, and architectural factors are fundamental to developing effective mitigation strategies that ensure the long-term resilience and sustainability of Cuenca [14].

METODOLOGÍA

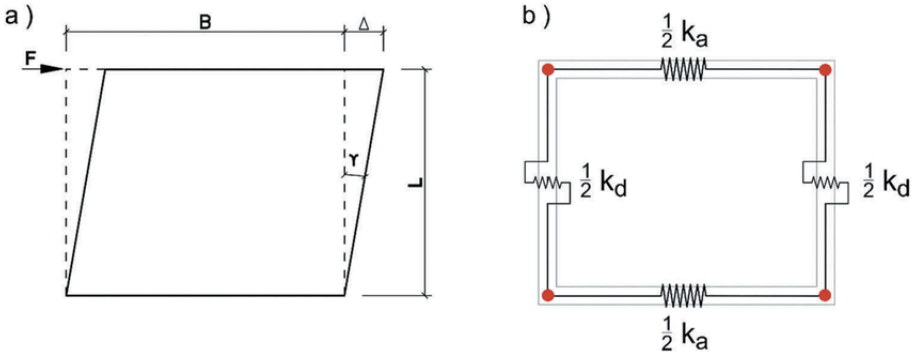
Methods and materials: This study began with the modeling of prototypes of the most representative buildings in the urban area of the city of Cuenca. A detailed approach was employed for both unreinforced and confined masonry, using specific models that reflected the predominant construction characteristics of the region. For unreinforced masonry buildings, static forces equivalent to shear axis models were applied based on specific portal frame and span geometries. In the case of confined masonry, the equivalent portal frame model was used, supplemented with elements such as horizontal reinforced concrete chains, according to the typology of the buildings as shown in the figure below [15].

Figure 1. Equivalent gantry model



In addition, a specific model was considered for the floor system, representing small floor diaphragms, suitable for the typical constructions of the study area as presented in figure 2. This model was based on the composition and arrangement of wood beams and planks, following the recommendations of previous studies for a reliable representation of structural conditions [15].

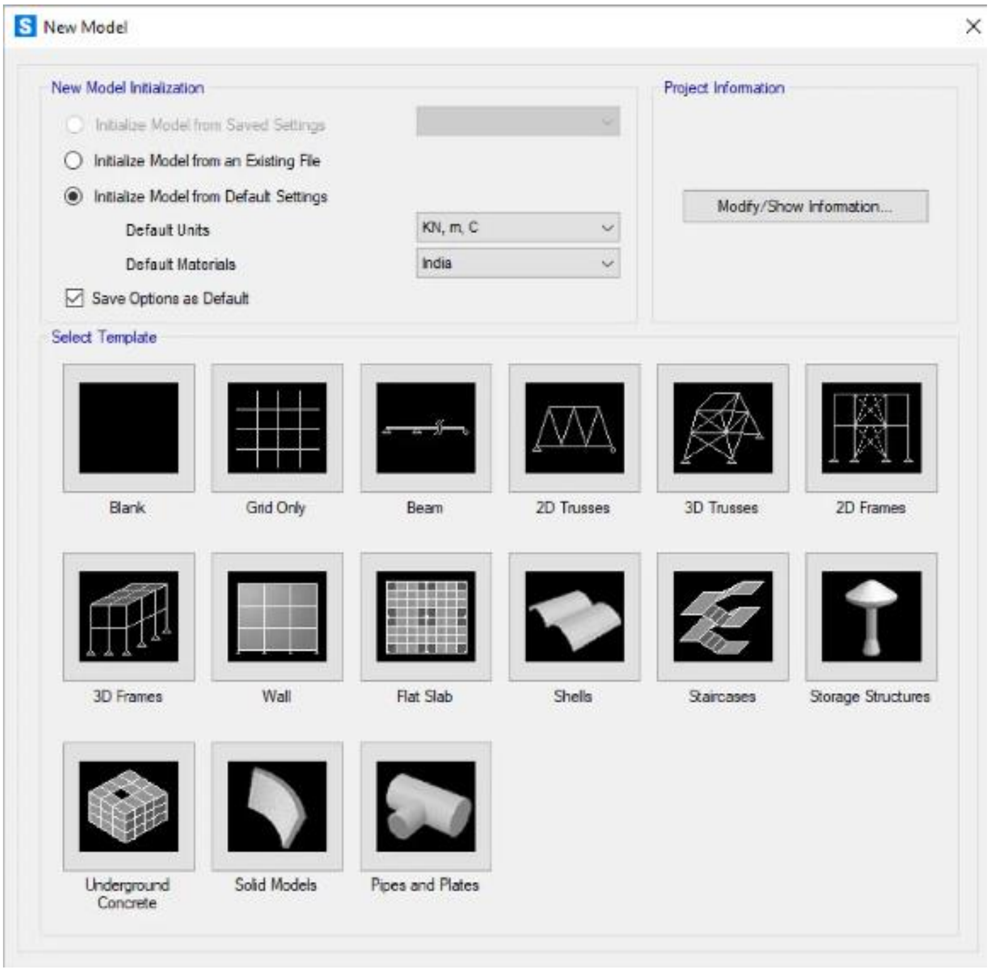
Figure 2. Floor diaphragm



The methodology included a multivariate statistical analysis, with a focus on multiple linear regression to explore the relationship between seismic intensities and structural deformations that could lead to building collapse. This mathematical approach to structural analysis allowed for an innovative interpretation of seismic vulnerability, differing from previous studies by incorporating techniques not used in this context [16].

For the analysis of seismic vulnerability, overstress indices were determined for each structural element, comparing the seismic stress demand and resistance capacity. This process culminated in obtaining a general flexibility index of the structure, representing its deformation and collapse potential. The modeling of the buildings was carried out using the SAP 2000, version 23 structural calculation program as seen in figure 3. The geometry of the typical buildings studied was configured as equivalent frames, assigning constraint parameters and force combinations adequate to simulate the impact of seismic events

Figure 3. New model options in SAP 2000 version 23



This methodological approach, which combined detailed structural modeling techniques with multivariate statistical analysis, represented a significant contribution to the study of seismic vulnerability. It allowed a deeper understanding of how different seismic intensities affected structures in the urban area of Cuenca, with potential applications to improve the seismic resistance of buildings in the region.

RESULTS AND DISCUSSION

When simulating the seismic events using the equivalent frames of the typical buildings, the deformation suffered by the structure is obtained as a result for our study. This deformation, in turn, was analyzed in relation to two types of materials: adobe and brick. The experiment focused on the comparison of the damage of these materials in porches of different spans and floors. It was possible to observe some differences between the resistance of both types of materials, although, in general terms, they presented similar damage.

In the case of adobe masonry, a mean deformation of 0.3059% was found, with a standard deviation of 0.15871% and after running a total of 90 simulations. The measurements were made with a seismic intensity of 5.5 degrees on the Richter scale, with a standard deviation of 0.8704 and using a Pearson correlation of 0.994. As a summary, this represents an approximate one-toone relationship, i.e., a strong correlation between the parameters compared. On the other hand, in the case of brick masonry, the mean deformation was 0.2348% with a standard deviation of 0.13716% after running a total of 90 simulations. The measurements were made with the same mean seismic intensity (5.5 degrees) and standard deviation as for the adobe masonry (0.8704), using a Pearson correlation of 0.991. In this case there was also an approximate one-to-one relationship and a strong correlation between the comparator parameters, although slightly lower than in the adobe masonry.

Regarding the damage that seismic events could cause in a given group of structures, we can see that, in the case of adobe, 32% of the buildings would collapse with an event of 5 to 6 degrees on the Richter scale; while, with events of 6 to 7 degrees on the Richter scale, 100% of the buildings would theoretically collapse (i.e., those considered in our sample). In the case of brick, we see that 13% of the buildings would collapse with intensities of 5 to 6 degrees on the Richter scale, and, as with adobe, 100% of the theoretical number of buildings would collapse with intensities of 6 to 7 degrees on the same scale. As we can see, these data show that, in general, the city of Cuenca is not yet sufficiently prepared to face seismic events of medium to high magnitude.

The findings of this study highlight the significant seismic vulnerability of typical buildings in Cuenca, Ecuador, reflecting an urgent need to integrate more robust mitigation strategies and to adapt construction and urban planning practices. The comparison between adobe and brick materials, while revealing greater strength in brick, does not minimize the concern for adobe, especially considering its prevalence in the city's historic architecture (Jiménez et al., 2018).. These results are consistent with previous studies that also highlight the structural vulnerability of traditional buildings to earthquakes in Cuenca [3,11].

The understanding of vulnerability in Cuenca based on our data can be approached through a comparison with other studies in the same city or country, or through a contrast with studies in other parts of the world. In the specific context of Cuenca, Jiménez [2] highlights the high seismic hazard in the city of the city, focusing also on the establishment of a catalog of typical adobe and brick buildings in the Historic Center. Like the present study, it took variables related to concrete architectural structures, (considering structure sizes, floor heights, wall thickness, among other criteria) and highlights the vulnerability they suffer. Another similar example is the work of Zamora and Aguirre [5], who emphasize the Church of El Sagrario (Old Cathedral). The authors point out critical aspects in this historic construction, such as the absence of trusses or reinforcements in the roofs and the unfavorable seismic behavior of the earthen structures. It should be noted that these studies consider buildings with similar architectural characteristics, using variables of different types. Therefore, we can say that seismic vulnerability in the historic areas of Cuenca has been studied using different methods and fronts, which provides consistency and validity to the results obtained.

As we have seen, studies on this subject coincide in emphasizing the still poor preparedness of architectural structures to withstand seismic events. The correlation between seismic intensity and structural deformation found in this study provides a valuable perspective for understanding damage dynamics during seismic events, aligning with international research that advocates for more complex and detailed analyses in the assessment of seismic vulnerability [16]. In turn, this multidimensional approach, which considers geophysical, environmental, sociopolitical and architectural aspects [5], reinforces the need for a holistic paradigm in seismic risk management. However, a pending task in this regard is to consider even more varied constructions, in order to have a broader picture of seismic vulnerability in the country.

Also, although there are notable differences in strength between brick and adobe, it is essential to examine how construction practices and materials used in traditional construction can affect the seismic vulnerability of buildings [17]. It is evident that Cuenca's cultural heritage is reflected both in its architectural styles and in the construction methods that have been passed down from generation to generation. When linked to seismic risks, this cultural dimension presents an exclusive confrontation in relation to the preservation of architectural heritage, as can be evidenced in the Gothic style in Spain and its cultural buildings [18]. Consequently, any mitigation effort should take into account the importance of incorporating contemporary anti-seismic construction

techniques that respect and protect the historical and aesthetic value of buildings, fostering a dialogue between structural safety and heritage conservation [19].

In this regard, research shows that earthquake retaliatory building shows that the public needs to be more educated and aware of seismic hazards and preparedness and response measures. Despite technological advances in seismic vulnerability modeling and analysis, community engagement and adherence to safe building practices are important factors in the effectiveness of mitigation strategies [20]. It is essential that government, academic, and civil society institutions work together to develop education and training programs that promote a culture of disaster prevention and resilience. This holistic approach would not only help preserve Cuenca's architectural heritage but would also save lives and reduce the community's vulnerability to future disasters [21].

It is worth noting that the results of the present investigation present important conclusions regarding the resistance of the materials. As we could notice, the difference in seismic resistance is greater in brick buildings than in adobe buildings. However, it is striking that this difference is not very considerable, at least in the one or two-story buildings, which were chosen because they represent 84% of the sector. This could be due to the fact that adobe, not being a very rigid material, has the capacity to absorb seismic waves. On the other hand, it is also important to note that a very acceptable linear correlation was obtained between the seismic intensity and the deformation of these buildings.

CONCLUSIONS

This study provides crucial evidence on the seismic vulnerability of buildings in Cuenca, highlighting the significant difference in seismic resistance between adobe and brick constructions. The correlation between seismic intensity and structural deformation reveals that, despite the higher resistance observed in brick buildings, all constructions face considerable risk in moderate to high magnitude earthquakes.

The results emphasize the importance of considering the specific characteristics of building materials and structural techniques in the assessment of seismic vulnerability and underline the urgency of adopting mitigation measures aimed at protecting both architectural heritage and human life.

The major contribution achieved in the present study is to have presented the analysis of the correlation between seismic intensity and deformation (collapse) of buildings. In previous studies of seismic vulnerability, this statistical analysis has never been presented. Additionally, its contribution is to determine the number of buildings that will collapse for certain seismic intensities that may occur in the future in the Historic Center of the city of Cuenca. Seen from a broad perspective, these findings have important application possibilities in disciplines such as Civil Engineering, Architecture, Sociology, Geology and History. All these areas of knowledge, from their particular point of view, can contribute to implementing measures to prevent losses in the face of adverse natural events.

The present study may also open doors for future research on seismic vulnerability using multivariate statistical techniques. Investigations of this type can be implemented in different cases and contexts and serve as basic information inputs for risk prevention policy makers. It is important to emphasize at the outset that the results obtained are theoretical and calculated for specific geometries and materials. An interesting future study would be to study those buildings constructed with the anti-seismic materials common in modern buildings.

Finally, research is needed to explore the application of advanced technologies and innovative approaches in architectural design and urban planning to improve the seismic resilience of Cuenca. The integration of multidisciplinary approaches will be key in developing effective mitigation strategies that ensure the long-term sustainability and safety of historic urban areas from earthquake hazards.

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