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Tesis

Self-Built Houses in a Peruvian Andean City: Seismic Vulnerability and Seismic Behavior

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David Anderson Flores Rojas
Jose Luis Nizama Mallqui
Albert Jorddy Valenzuela Inga
Juan Gabriel Benito Zuñiga
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Self-Built Houses in a Peruvian Andean City: Seismic Vulnerability and Seismic Behavior

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Abstract The Mantaro Valley in Peru has experienced a seismic silence lasting 54 years, indicating a significant likelihood of a major seismic event occurring. Moreover, the rapid increase in the problematic practice of self-construction, mainly using clay frame structures with infill masonry walls materials, has rendered the area highly susceptible to a seismic disaster, raising concerns specifically for the Huancán district. Thus, the main aim of this study was to assess the seismic vulnerability of 30 houses in the Huancán district by employing a questionnaire based on the INDECI methodology. The structural program (ETABS) was employed. Additionally, the seismic behavior of each house was evaluated through analytical analysis using structural calculation software. The findings revealed that 40% of the houses exhibited a very high vulnerability, 50% demonstrated an increased exposure, and 10% displayed a moderate vulnerability. The most influential factors contributing to this vulnerability were irregularities in the floor plan, height, and mass distribution of the houses. Furthermore, it was observed that the homes suffered from inadequate wall density in the X direction, negatively impacting compliance with standards related to wall density, maximum axial stress, crack control, and inter-story drift. Ultimately, the Huancán district exhibits a 90% vulnerability level classified as "high" and "very high", highlighting significant structural deficiencies such as house wall flexibility. It underscores the urgent need for authorities to implement preventive measures, including structural reinforcements and enhanced control in risk management practices.

Keywords Seismic Vulnerability, Seismic Behavior, Self-Construction, Seismic Risk of Destruction, Frame Structures with Infill Masonry Walls, Self-Built Houses

1. Introduction

Studying tectonic plates and their implications for seismic disasters is a significant concern. When these plates interact, they create faults that can trigger earthquakes, leading to devastating consequences such as loss of life and economic damage [1]. Research conducted by the Institute of Geology and Mining on significant earthquakes in Peru between 1513 and 1974 revealed 216 major earthquakes. These seismic events were primarily caused by the interaction between the South American and Nazca plates [2]. The most recent intense earthquake in the Huancayo area occurred in 1969, resulting in significant human and material losses. Remarkably, the Mantaro Valley has experienced a seismic lull for 54 years, but the possibility of future seismic activity remains [3]. Consequently, comprehensive design standards have been established to regulate construction practices throughout Peru [4].

The population continues to grow steadily, with the

National Institute of Statistics and Informatics reporting a population of 33,396,700 inhabitants in 2022 [5]. This population growth has created a heightened demand for housing, leading to a surge in self-construction practices without proper adherence to structural engineering principles. This increase in substandard construction practices is closely associated with heightened seismic vulnerability, and the consequences can be severe when the risk is high [6].

Therefore, to mitigate various catastrophic events and safeguard human lives during future earthquakes, it is crucial to assess the seismic vulnerability of informal housing as a primary component of seismic disaster management [7]. A study was conducted in the district of Huancán, which is currently experiencing a boom in construction activity and population growth. Confined frame structures with infill masonry walls have emerged as the most prevalent structural system due to their affordability and ease of implementation [8].

This research's primary focus is to investigate structures' vulnerability to seismic events using a modified approach based on the INDECI methodology. This method enables us to evaluate the susceptibility of buildings through a visual inspection process supported by a checklist that includes minimum requirements following national building regulations. Additionally, a structural analysis is conducted to ensure an accurate understanding of how the building will behave during seismic events. This analysis involves measuring and processing data from critical structural elements, particularly assessing story drift as a significant indicator [9].

One of the significant concerns in various regions of Peru is the high risk of structural failure in houses constructed with clay frame structures with infill masonry walls. This construction material is widely used, making it particularly vulnerable to seismic activity [6].

To address this issue, various potential alternatives center around risk prevention, as it is more cost-effective to implement preventive measures rather than deal with the consequences of repairing load-bearing walls in self-constructed houses. By determining the seismic vulnerability in the study area, this research serves as a crucial warning and precedent for future seismic disasters that may occur. It underscores the importance of proactive measures to mitigate the potential impact [10].

Hence, the main objective of this study is to assess the level of seismic vulnerability and understand the seismic behavior of self-constructed houses primarily built with clay frame structures with infill masonry walls materials in the district of Huancán. This will help to recommend the methods/technologies for urgent strengthening of the considered vulnerable buildings.

2. Literature Review

Over several years, numerous research studies have been conducted globally to assess seismic vulnerability and prevent future disasters. Below are the detailed findings of some of these studies.

One study [11] employed the Italian vulnerability method, which establishes a vulnerability index correlating the intensity of seismic activity with the anticipated structural damage. The index is based on class assignments ranging from A to D, representing high to low quality. Notably, no buildings were classified as class A. The following percentages for classes B, C, and D were 40.20%, 50.00%, and 9.8%, respectively. The researchers concluded that the absence of seismic design led to significant damage to the structures. Furthermore, vulnerability index values exceeding 70% indicated a high level of seismic risk and inadequate resistance in the buildings within the study area.

Another example is the city of Timisoara, Romania [12], where a rapid vulnerability assessment methodology was employed. It involved using the Vulnerability Index method and a mechanical approach based on pushover analysis with Tremuri software. The results indicated a moderate level of vulnerability with a low probability of collapse, approximately 5% for the historical area of Josefin and 4% for the historical size of Fabric.

In a different study [13], the Rick-UE vulnerability index method was utilized to determine the seismic quality of buildings. This index considers the specific structural typology and characteristics that can influence the seismic response of each structure. The findings revealed that frame structures with infill masonry walls buildings had the highest vulnerability indices, with a significant occurrence (55.2%) above a ground acceleration threshold of 0.8 degrees, predominantly belonging to classes A and B. On the other hand, buildings constructed with reinforced concrete and steel exhibited lower vulnerability indices, below 0.77 degrees of maximum ground acceleration, mainly falling into classes B, C, and occasionally type D. The researchers concluded that residential buildings located in the "El Cabanyal" Zero Zone need to enhance their seismic response to minimize losses in the event of an earthquake and safeguard the historical heritage.

Another research contribution [14] applied the Seismic Assessment of the Vulnerability of Vernacular Architecture Structures (SAVVAS) methodology to assess seismic vulnerability in the historic center of Vila Real de Santo António (VRSA) city. This simplified and accelerated approach enables a primary seismic safety evaluation through visual inspection alone. The results indicated that the buildings in the historic center exhibited good construction quality and regularity, resulting in notably low overall vulnerability (considering the historical configuration). Notably, since most buildings in the historic center are single-story houses, the researchers concluded that the study provides valuable insights into large-scale seismic vulnerability assessment, aiding seismic risk management and decision-making regarding rehabilitation strategies for older urban areas. The applicability of the innovative SAVVAS method for this particular subject was confirmed [14].

Furthermore, Stefano de Santis [15] proposes a method for assessing seismic vulnerability in unreinforced frame structures with infill masonry walls houses, conducted under the supervision of the National Group for Seismic Protection and the Special Office for the Reconstruction of L'Aquila. This method visually examines the structural characteristics, geometry, construction methods, materials used, and other factors. The study highlights a relatively high variability between the estimated vulnerability and the assessed damage, primarily due to the expedited nature of the method, which relies on limited information. It is acknowledged that a complementary approach to this assessment method would be the structural analysis of each building. However, the large sample size makes conducting such an analysis impractical.

In a separate study by Abdullah Ansari [16], an analysis was conducted on buildings in Jammu and Kashmir, predominantly occupied by families. The analysis considered factors such as population, density based on the demographic framework, building height, age, and materials used according to structural specifications for construction.

The findings revealed that buildings located near the river exhibited extreme vulnerability. Urgent measures were proposed to ensure the population's safety, including implementing urban planning policies aimed at reducing seismic damage in the event of a future earthquake.

3. Materials and Methods

In this study, the researchers applied theoretical knowledge about the variables they wanted to investigate [17]. They established a cause-and-effect relationship between the independent variables, self-constructed houses, and the dependent variables, including seismic vulnerability and behavior [18].

To gather data about the population, the researchers relied on reports from the urban cadastral office of the Huancán district. These reports indicated that there were 900 self-constructed houses in the area, mainly constructed using clay frame structures with infill masonry walls. For this research, a sample of 30 self-constructed homes was selected, explicitly focusing on places with more than two levels as shown in Figure 1 [19]. The researchers believed these selected houses shared similar characteristics with the entire population of homes in the district based on their professional experience. This approach aimed to minimize bias and ensure that the findings could be generalized to the study district.

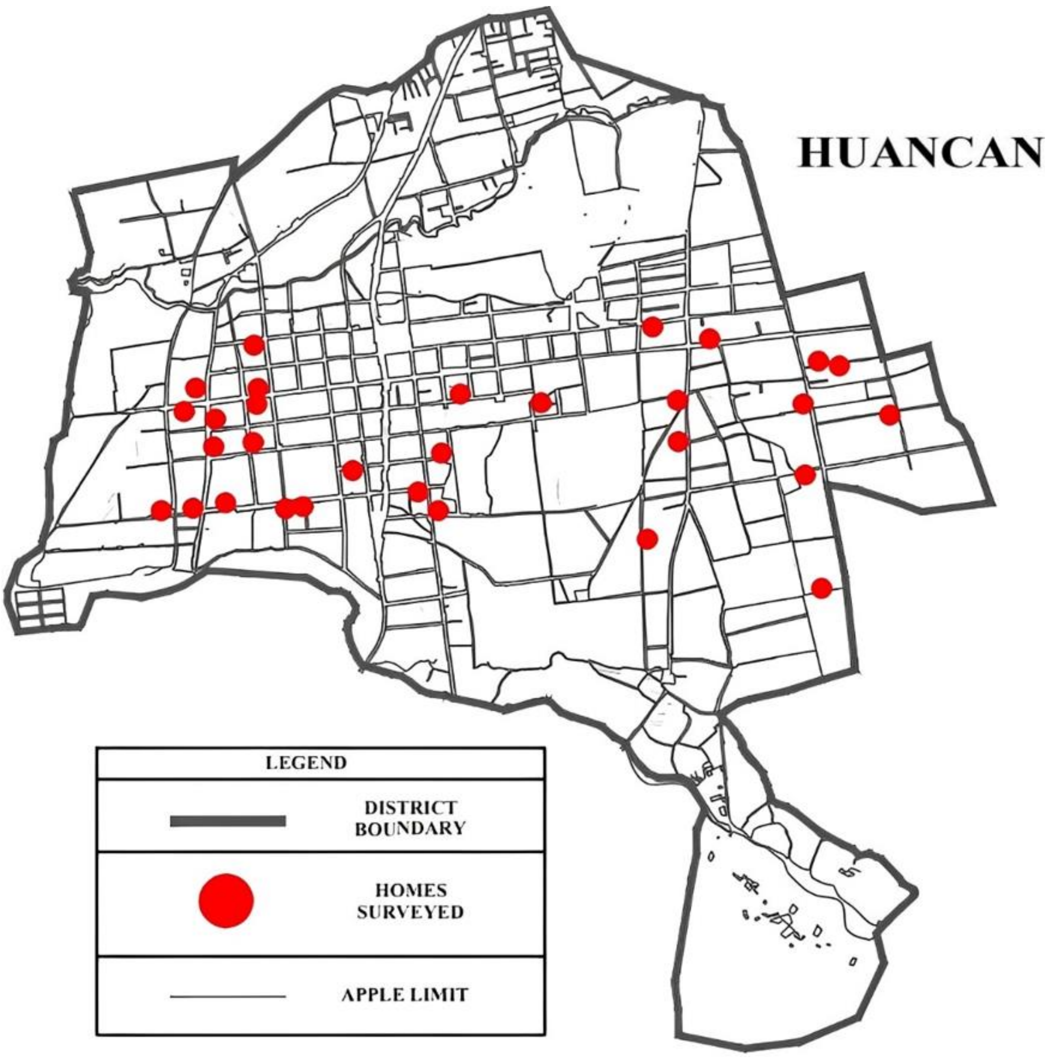


Figure 1. Surveyed areas in Huancan

3.1. Indeci Method

This methodology was developed in 2010 in accordance with the structural provisions and construction processes outlined in the National Building Regulations of Peru [20]. To conduct the assessment, verification survey forms were utilized [21,22], as depicted in Figure 2, and these forms were approved by experienced engineers specializing in structural analysis. The methodology was refined to account for the specific characteristics of house construction in the Huancán district, where many houses are self-constructed through empirical methods [23]. As part of the adaptation process, five additional questions were introduced to assess the visual inspection of the studied structural system, which predominantly involved frame structures with infill masonry walls, aligning with the relevant provisions outlined in the National Building Code of Peru.

C.- Building characteristics

1. PREDOMINANT MATERIAL OF THE DWELLINGS											
Characteristics		Value	Caracteristicas		Value	Caracteristicas		Value	Caracteristicas		Value
1 Adobe	( )	4	2. Precarious masonry	( )	3	3. Masonry	(X)	2	4. Confined masonry or Reinforced concrete	( )	1

2. The building had the participation of a civil engineer in the design and/or construction											
Characteristics		Value	Characteristics		Value	Characteristics		Value	Characteristics		Value
1. No	(X)	4	2. Only building	( )	3	3. Only design	( )	2	4. Yes, totally	( )	1

3. Edification years											
Characteristics		Value	Characteristics		Value	Characteristics		Value	Characteristics		Value
1. > 50 years	( )	4	2. 20 to 49 years	( )	3	3. 3 to 19 years	(X)	2	4. 0 to 2 years	( )	1

4. Soil type											
Characteristics		Value	Characteristics		Value	Characteristics		Value	Characteristics		Value
1 Soft Soil (S3)	( )	4	2. Intermediate Soil (S2)	(X)	3	3. Too rigid soil (S1)	( )	2	1. Hard rock (S0)	( )	1

5. Housing soil topography											
Very High		Value	High		Value	Moderate		Value	Plain		Value
1. > 45%	( )	4	2. 20% to 45%	( )	3	3. 10% to 20%	( )	2	4. Till 10%	(X)	1

6. Topography of the terrain adjacent to the dwelling and/or in the surrounding area											
Very High		Value	High		Value	Moderate		Value	Plain		Value
1. > 45%	( )	4	2. 20% to 45%	( )	3	3. 10% to 20%	( )	2	4. Till 10%	(X)	1

7. Plant geometric configuration						8. Geometric configuration in elevation					
Characteristics		Value	Characteristics		Value	Characteristics		Value	Characteristics		Value
1. Irregular	( )	4	2. Regular	(X)	1	1. Irregular	(X)	4	2. Regular	( )	1

9. There are seismic joints with neighboring structures						10. There is mass irregularity					
Characteristics		Value	Characteristics		Value	Characteristics		Value	Characteristics		Value
1. No	( )	4	2. Si	(X)	1	1. SI	( )	4	2. No	(X)	1

11. The load-bearing walls have confinement elements											
Characteristics		Value	Characteristics		Value	Characteristics		Value	Characteristics		Value
1. 0% - 25%	( )	4	2. 26% - 50%	( )	3	3. 51% - 75%	( )	2	4. 76% - 100%	(X)	1

12. There is continuity of load-bearing walls											
Characteristics		Value	Characteristics		Value	Characteristics		Value	Characteristics		Value
1. 0% - 25%	( )	4	2. 26% - 50%	( )	3	3. 51% - 75%	( )	2	4. 76% - 100%	(X)	1

13. The non-load-bearing walls are braced											
Characteristics		Value	Characteristics		Value	Characteristics		Value	Characteristics		Value
1. 0% - 25%	(X)	4	2. 26% - 50%	( )	3	3. 51% - 75%	( )	2	4. 76% - 100%	( )	1

14. The beams are connected to the columns with moment connections											
Characteristics		Value	Characteristics		Value	Characteristics		Value	Characteristics		Value
1. 0% - 25%	( )	4	2. 26% - 50%	(X)	3	3. 51% - 75%	( )	2	4. 76% - 100%	( )	1

15. In the main structural elements, the following can be observed ...											
15.1. They do not exist		Value	15.2. Humidity in		Value	15.3. Regular		Value	15.4. Good		Value
1. Columns	( )	4	1. Columns	( )	3	1. Columns	(X)	2	1. Columns	( )	1
2. Walls	( )		2. Walls	( )		2. Walls	(X)		2. Walls	( )	
3. Beams	( )		3. Beams	( )		3. Beams	(X)		3. Beams	( )	
4. Ceilings	( )		4. Ceilings	( )		4. Ceilings	(X)		4. Ceilings	( )	

16.The supports of the elevated tank ...						17. There are expansions without criteria ...					
Characteristics		Value	Characteristics		Value	Characteristics		Value	Characteristics		Value
1. Inexistent	(X)	4	2. Flexibles	( )	3	1. Existent	(X)	4	2. Inexistent	( )	1
3. Rigid supports or without elevated tank				( )	1						

D.- Vulnerability calculation

Vulnerability level	Σ	1	2	3	4	5	6	7	8	9	10	11	12	13	14
		2	4	2	3	1	1	1	4	1	1	1	1	4	3

15	16	17		TOTAL
2	4	4	=	39

Figure 2. Survey form in frame structures with infill masonry walls houses.

The first question in the survey focused on visually assessing the geometric configuration of the houses, both in terms of their floor plan and height, as illustrated in Figure 3 and Figure 4. Mass irregularity was also detected in some areas, as shown in Figure 5. Subsequently, the presence of an embedded connection between the beam and the column was examined. To ensure structural integrity, the steel reinforcement in the beams needed an appropriate development length based on factors such as steel diameter, steel strength, and concrete compressive strength [24].

Figure 3. Irregularity in a floor plan

Figure 4. Irregularity in height

Table 1. Vulnerability level score scale

Vulnerability level	Value	Description
High	> 34	Under current conditions, accessing a Safety Zone within the building is impossible.
Very High	Between 27 and 33	Under the current conditions, it is NOT possible to access a Safety Zone within the building; significant changes to the structure are required.
Moderated	Between 20 and 26	Reinforcement is required in the potential Internal Safety Zone
Low	<19	It is possible to access a Safety Zone within the building in the current conditions.

Figure 5. Mass irregularity

To determine the level of seismic vulnerability, the verification survey form employed scales outlined in Table 1. The scale for low exposure indicated values below 19, the moderate scale encompassed values between 20 and 26, the high level corresponded to values between 27 and 33, and the very high-level denoted values exceeding 34.

An additional inquiry incorporated into the study pertains to the specifications outlined in the E070 frame structures with infill masonry walls design standard [25]. According to this standard, a structural wall must be enclosed on all four sides, maintain an aspect ratio of width to a height below 2m, and exhibit appropriate slenderness relative to size.

3.2. Seismic Behavior

The seismic performance was assessed by examining the specialized plans submitted by homeowners for their respective houses. In cases where these plans were unavailable, a survey was conducted to identify the primary structural elements.

Design loads, including dead loads (the physical components of the building) and live loads (temporary loads affecting the structure), were considered. These loads were evaluated for each building environment based on the specified occupancy density outlined in Normative E020 [26].

Additionally, an essential aspect of the analysis was the determination of the base shear of the building, which relied on the seismic design standard E030. This standard facilitated the calculation of the shear force acting on the building, considering factors such as its location, designated use, and soil type, as soil characteristics significantly influence the reception and impact of seismic waves on the studied superstructure. This value results from the interaction between the building's location (Z) as shown in Figure 6 and the type of soil present (S) as shown in Table 2.

Figure 6. Seismic zonation map of Peru

Table 2. Soil types

Profiles	Features
Type S0	Hard rock
Type S1	Rock or Very Stiff Soils
Type S2	Intermediate Soils
Type S3	Soft Soils
Type S4	Exceptionally flexible soils and sites where geological and/or topographical conditions are particularly unfavorable.

The Peruvian market classifies a variety of handmade and industrial bricks with dimensions ranging from 23x9x21 cm (side-width-side), generally composed of clay (alumina) and sand (silica). These bricks are classified as solid, solid with hollow, honeycomb and tubular, as shown in Figure 7. Solid brick and hollow brick are the most recommended for construction based on confined frame structures with infill masonry walls, since they have the capacity to distribute vertical loads in load-bearing walls [27], as shown in Figure 8. We could infer the structural system utilized by examining the configuration and dimensions of the structural elements within the houses. The predominant system identified in most homes studied was confined frame structures with infill masonry walls. The value provided by the standard regarding the structural design indicates its capacity to mitigate seismic forces acting on the building and whether the structure exhibits elastic or rigid behavior [28].

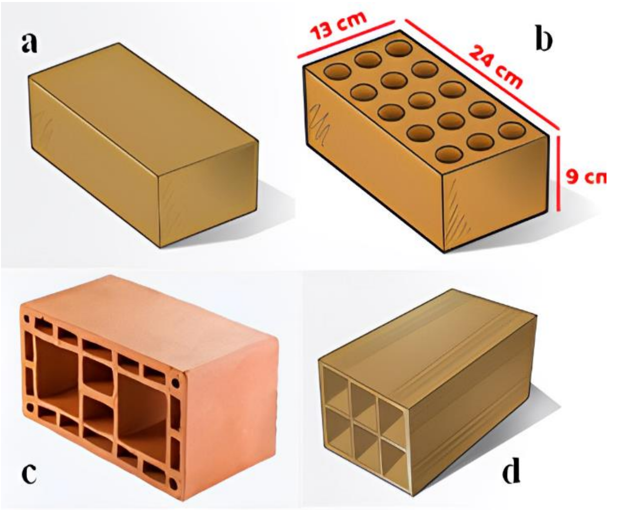


Figure 7. Types of bricks: a) Solid brick, b) Hollow brick, c) Hollow bricks, d) Tubular bricks

The calculated outcome was subsequently employed to determine the inter-story drifts. In cases where walls were constructed with brick types not covered by the E070 frame structures with infill masonry walls standard, the compressive strength values provided by the Peruvian-Japanese Center for Seismic Research and Disaster Mitigation [25] were utilized. Table 3 presents the corresponding values for compressive and shear strength of walls constructed using industrial and artisanal bricks.

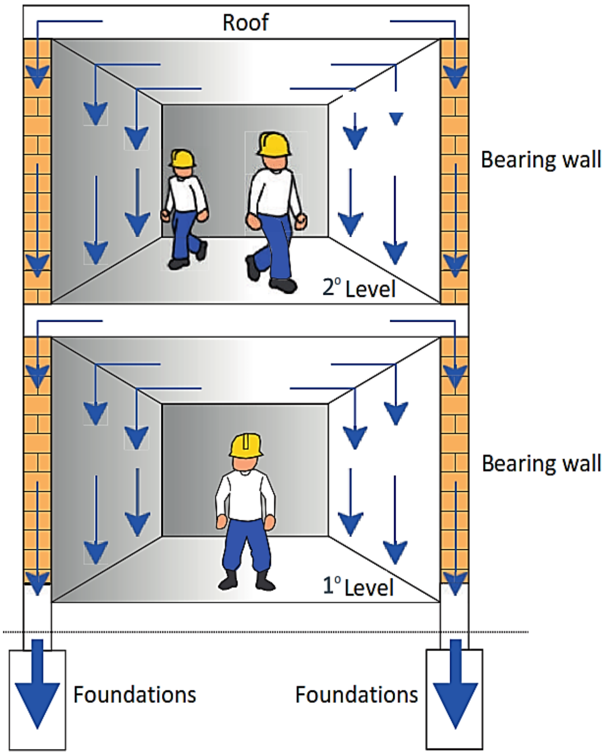


Figure 8. Load distribution of load-bearing wall [27]

Table 3. Compressive strength in masonry walls by brick type

Brick Type	Mean Axial compressive strength of the brick (Kg/cm2)	Mean Masonry shear strength (Kg/Cm2)
Industrial	22.1	6.7
Handmade	33.2	9.6

Similarly, the assessment mandated by Standard E070 is computed utilizing formula (1), which entails the determination of wall density.

$$(\sum L.T) = \frac{(Z)(U)(S)(N)}{56} xAP \quad \textbf{(1)}$$

Z = Zone Factor

U =Use Factor

S = Soil Factor

N = Stories number

L = Wall Length

T = Effective Wall Thickness

Ap = Plan Area

After, a subsequent step involved conducting a thorough assessment of the maximum axial stress by utilizing the data generated from the engineering software known as Extended Three-Dimensional Analysis of Building Systems (ETABS), this verification process, which involved employing formula (2), was undertaken explicitly to scrutinize the structural integrity of the walls and determine their ability to endure the highest possible levels of axial stress.

$$\sigma m = \frac{Pm}{(L)(t)} \quad \textbf{(2)}$$

σm = Maximum axial stress

Pm = Maximum gravity load

L = Wall Length

t = Wall Thickness

Besides, the maximum axial stress derived from the walls must adhere to the prescribed limits outlined in equation (3) and equation (4) as stipulated by the E070 standard.

$$\sigma m \leq 0.2(f'm)x[1-\left(\frac{h}{35t}\right)^2] \quad \textbf{(3)}$$

$$\sigma m \leq 0.15xf'm \quad \textbf{(4)}$$

Pm = Maximum gravity load

L = Wall length

σm = Esfuerzo axial máximo

h = Clear height between bracings

t = Wall thickness

$f'm =$ Brick axial compression strength

The assessment of crack control in the walls was conducted by applying equation (5) as outlined in the E070 standard.

$$\text{Ve} \leq 0.55\text{Vm} = \text{Allowable shear force} \quad \textbf{(5)}$$

Ve = Shear force induced by a moderate earthquake

Vm = Shear pressure associated with diagonal cracking of frame structures with infill masonry walls.

Furthermore, the frame structures with infill masonry walls' shear strength "Vm" on each floor was assessed by applying the following method, as defined by equation (6).

$$\text{V'm} \leq 0.50 \ (\text{V'm})(\alpha)(\text{t})(\text{L}) + 0.23(\text{Pg}) \quad \textbf{(6)}$$

V'm = Frame structures with infill masonry walls shear strength

Pg = Total permanent load

t = Effective wall thickness

L = Wall length

α = Strength reduction factor

After determining frame structures with infill masonry walls shear strength values, a thorough assessment was conducted, comparing the building's shear strength to the shear force induced by intense seismic activity. This rigorous analysis aimed to guarantee the structure's optimal rigidity and strength, as illustrated by equation (7).

$$\sum \text{Vmi} \geq \text{VEi} \quad \textbf{(7)}$$

$\sum$Vmi = Contribution of load-bearing walls

VEi = Interstory shear force by a severe earthquake

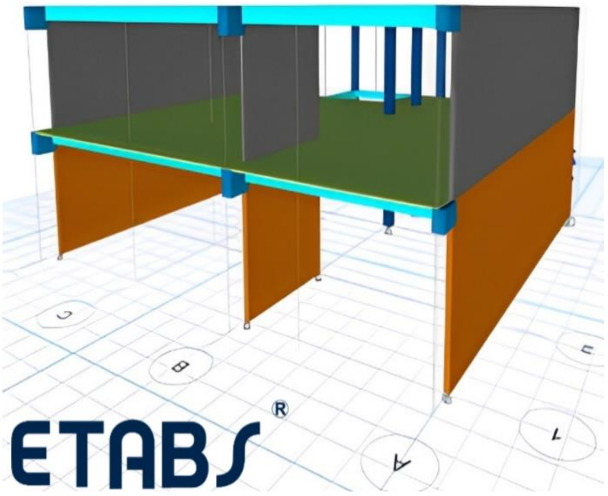


Figure 9. Structural analysis in frame structures with infill masonry walls houses

After obtaining the results from the dynamic seismic structural analysis, as presented in Figure 9, the maximum relative inter-story displacements are calculated. It is essential to ensure that these displacements do not exceed the limits specified in the E030 seismic design standard [29], as demonstrated in Table 4. It is crucial to adhere to these guidelines to guarantee the building's structural integrity and seismic resistance.

Table 4. Floor limit lateral displacement

Floor limit lateral displacement - These limits do not apply to industrial warehouses-	
Predominant material	(A1/he1)
Reinforced concrete	0.007
Steel	0.010
Frame structures with infill masonry walls	0.005
Wood	0.010

A flowchart, presented in Figure 10, was created to visually represent the sequential process involved in establishing the goals. The steps are as follows: A comprehensive survey of the district was conducted, utilizing the cadastral map provided by the District Municipality of Huancán as a navigational aid. With the homeowners' consent, extensive surveys of individual houses were carried out to assess the present condition of each property. Architectural and structural plans of the houses were procured to obtain a comprehensive understanding of their design and construction. The collected survey data was meticulously processed and analyzed, enabling the determination of the seismic vulnerability level for each house. For accurate structural analysis, the renowned software ETABS was employed, leveraging its capabilities to assess the structural integrity and stability of the buildings. As an additional tool, we developed bespoke Excel spreadsheets to facilitate the evaluation of irregularities, adherence to minimum structural requirements, structural analysis, and inter-story drifts. This comprehensive approach, combining field surveys, data analysis, structural modeling software, and custom tools, ensures a thorough assessment of the seismic vulnerability of the houses under investigation.

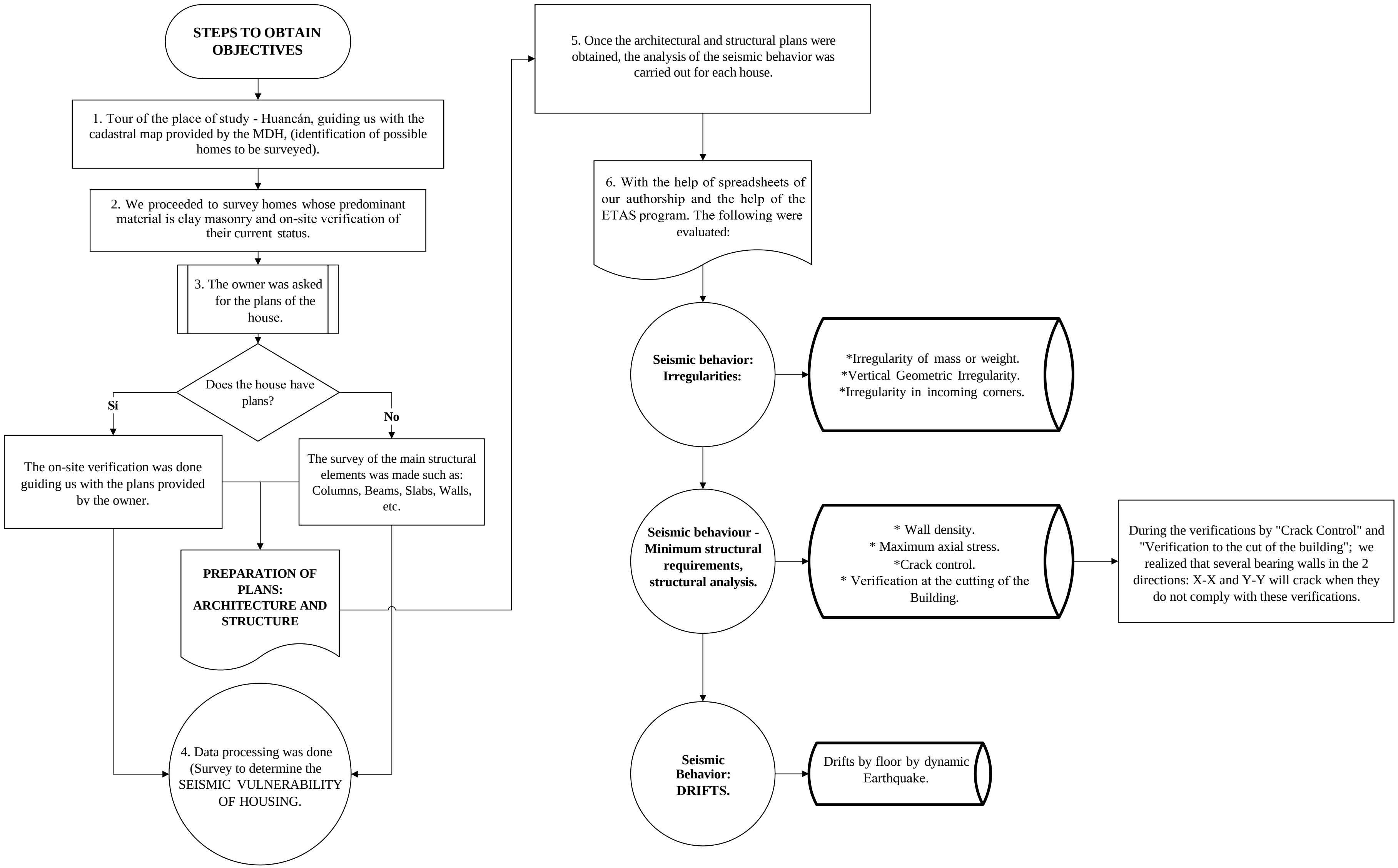


Figure 10. Process flowchart

4. Results

4.1. INDECI Method

Upon analyzing the data collected through the data collection form and conducting the necessary processing, a set of quantitative outcomes was derived, as depicted in Figure 11. The figure provides a comprehensive overview, indicating that among the self-constructed residences in the Huancán district, approximately 10% are characterized by a moderate level of vulnerability, while around 50% display a high level of exposure. Additionally, it is noteworthy that about 40% of these houses are identified as possessing a significantly elevated level of vulnerability.

Furthermore, worrisome findings were identified during the analysis of the data obtained from the verification survey form. These findings are a cause for concern due to the significant disparity in the involvement of a qualified professional in the housing project. Specifically, it was discovered that the participation of a responsible professional was reported to be as high as 96.67% during the design stage. However, this involvement drastically decreased to 3.33% during the execution stage. These alarming statistics are graphically represented in Figure 12.

The primary objective of the research was to assess the seismic vulnerability of the studied structures.

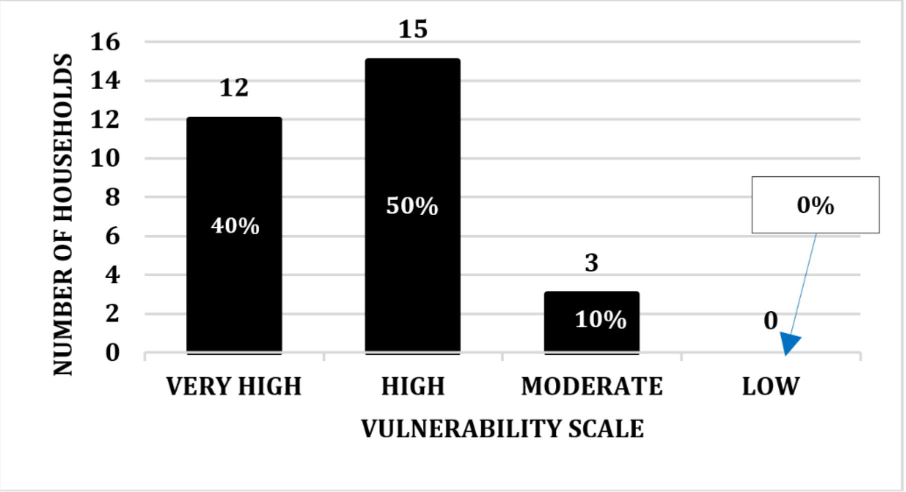


Figure 11. Seismic vulnerability in frame structures with infill masonry walls houses

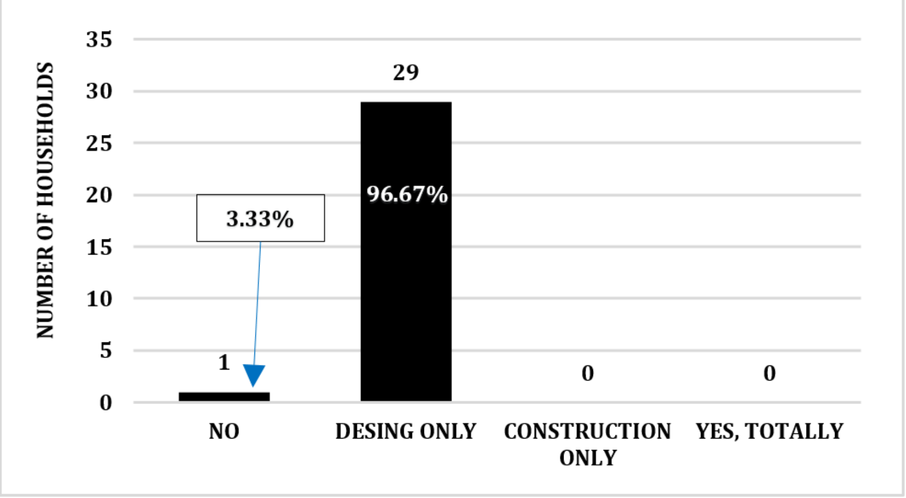


Figure 12. Participation of professionals in housing construction.

A significant aspect of the verification process involved examining the presence of confined load-bearing walls in the houses. The following outcomes, as illustrated in Figure 13, were obtained through thorough analysis. It was determined that none of the places had load-bearing walls lacking confinement. In contrast, a small percentage of houses, precisely 3.33%, exhibited walls with confinement levels ranging from 26% to 59%. Furthermore, a substantial portion, constituting 30% of the houses, possessed walls with confinement levels between 51% and 75%. Most homes, comprising 66.67% of the total, featured walls with high confinement levels ranging from 76% to 100%. These findings provide valuable insights into the extent of confinement and its potential impact on the seismic resilience of the structures.

4.2. Seismic Behavior

The seismic behavior analysis revealed significant findings, as depicted in Figure 14. The figure highlights that a considerable proportion of self-built houses, precisely 36.67%, show irregularities in the X-X direction at the floor plan, while 26.67% exhibit irregularities in the Y-Y direction, primarily caused by recessed corners. Moreover, 10.0% of the houses display irregularities in height within the X-X direction, and 16.67% manifest irregularities in the Y-Y direction, which can be attributed to vertical geometric anomalies. Lastly, a notable observation is that 3.33% of the houses exhibit irregular mass distribution.

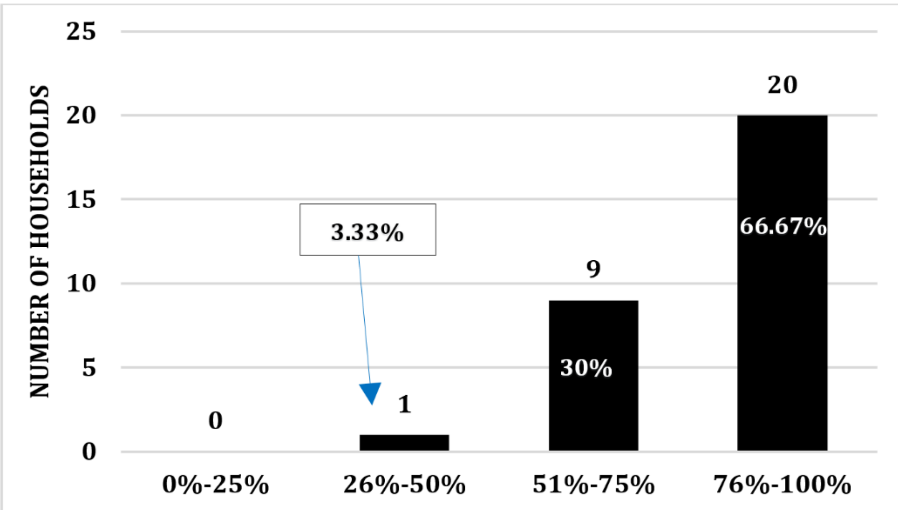


Figure 13. Seismic vulnerability in frame structures with infill masonry walls houses

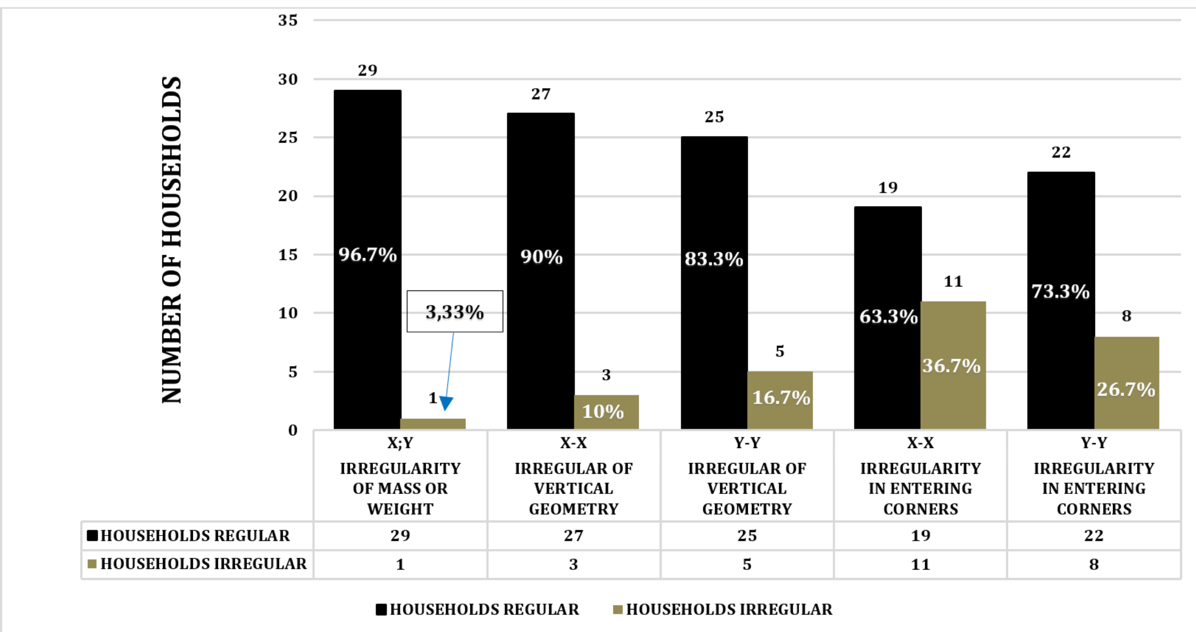


Figure 14. Irregularities in floor plan, height, and mass in frame structures with infill masonry walls house

Similarly, the additional verifications have produced the findings depicted in Figure 15. The results indicate that most of these verifications, precisely 86.67%, do not satisfy the prescribed minimum wall density criterion in the X-X direction. Similarly, in the Y-Y direction, a notable portion, accounting for 13.33%, fails to meet the exact requirement. Moreover, upon closer examination, it has been determined that 36.67% of the walls do not adhere to the maximum axial stress threshold in the X-X direction, while 40.00% exhibit non-compliance in the Y-Y direction.

Additionally, it was discovered that a significant majority, precisely 96.67%, of self-constructed dwellings do not fulfill the verification criteria for effectively controlling the deformation of load-bearing walls in the X-X direction. Similarly, a considerable proportion of 80.00% fails to comply with the corresponding requirements in the Y-Y direction. Moreover, the analysis highlights that an overwhelming majority, again 96.67%, of self-built houses do not meet the specified criteria for shear verification along the X-X axis. Furthermore, it is notable that a significant portion, 30.00%, fails to satisfy the verification standards along the Y-Y axis, as depicted in Figure 16.

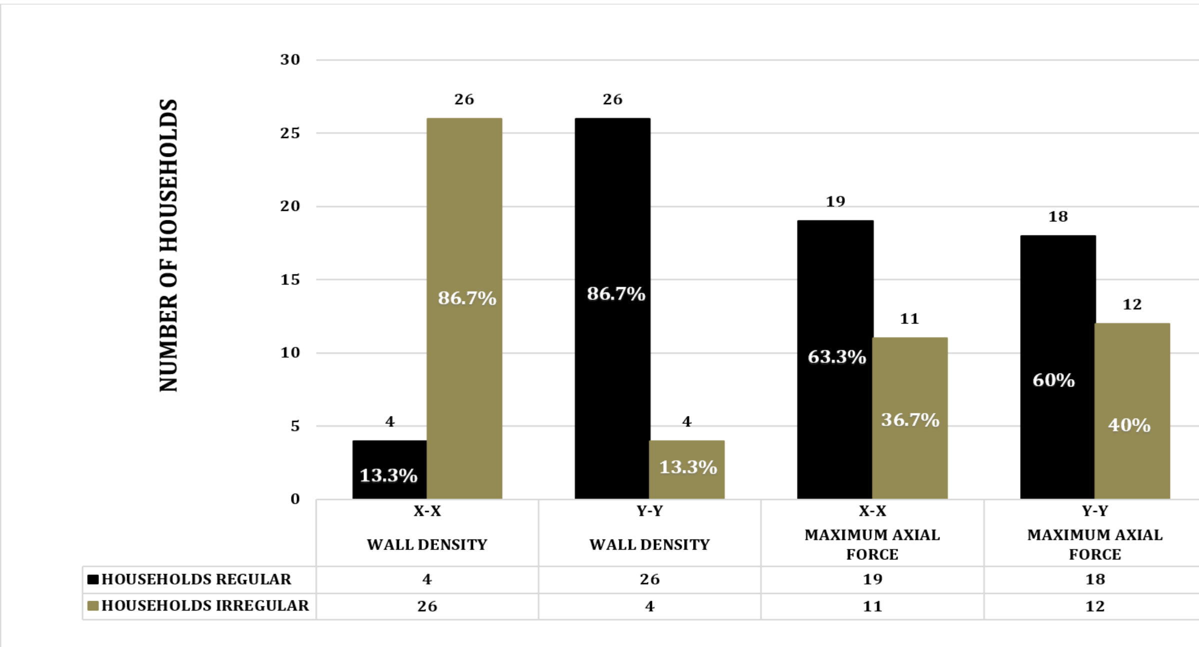


Figure 15. Wall density and axial stress

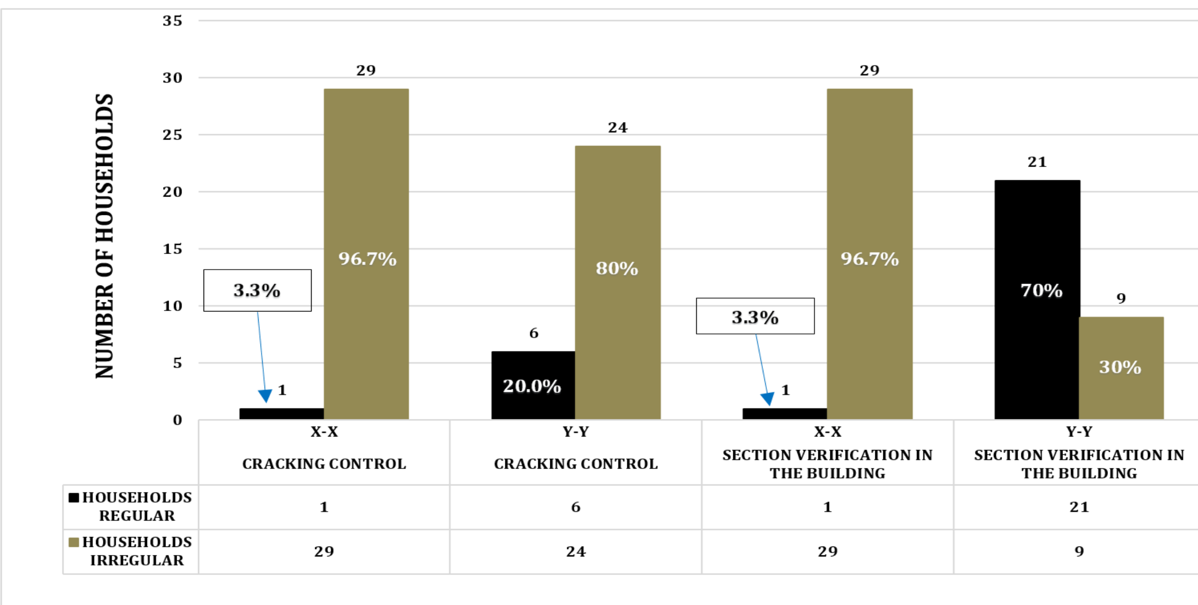
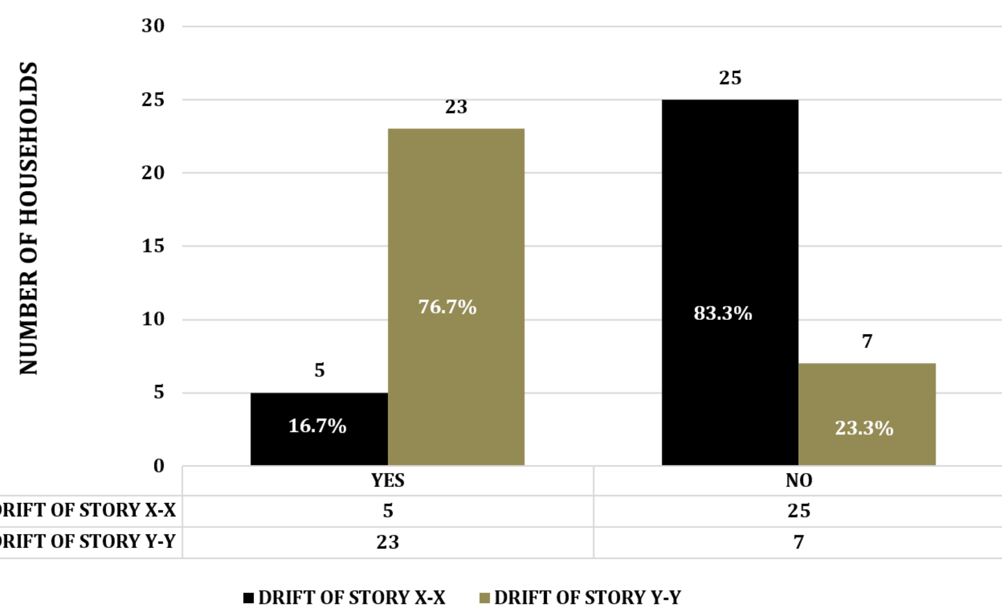


Figure 16. Crack control and shear verification

The results indicate that a significant majority, precisely 83.3% of these houses, do not satisfy the prescribed drift limits along the X-X axes. Similarly, 23.3% of the homes fail to meet the required drift criteria along the Y-Y axes, as illustrated in Figure 17.

The findings regarding displacement during the seismic analysis of the modeled and analyzed house using the ETABS simulator are depicted in Figure 18.



	YES	NO
■ DRIFT OF STORY X-X	5	25
■ DRIFT OF STORY Y-Y	23	7

Figure 17. Interstory drifts in frame structures with infill masonry walls house

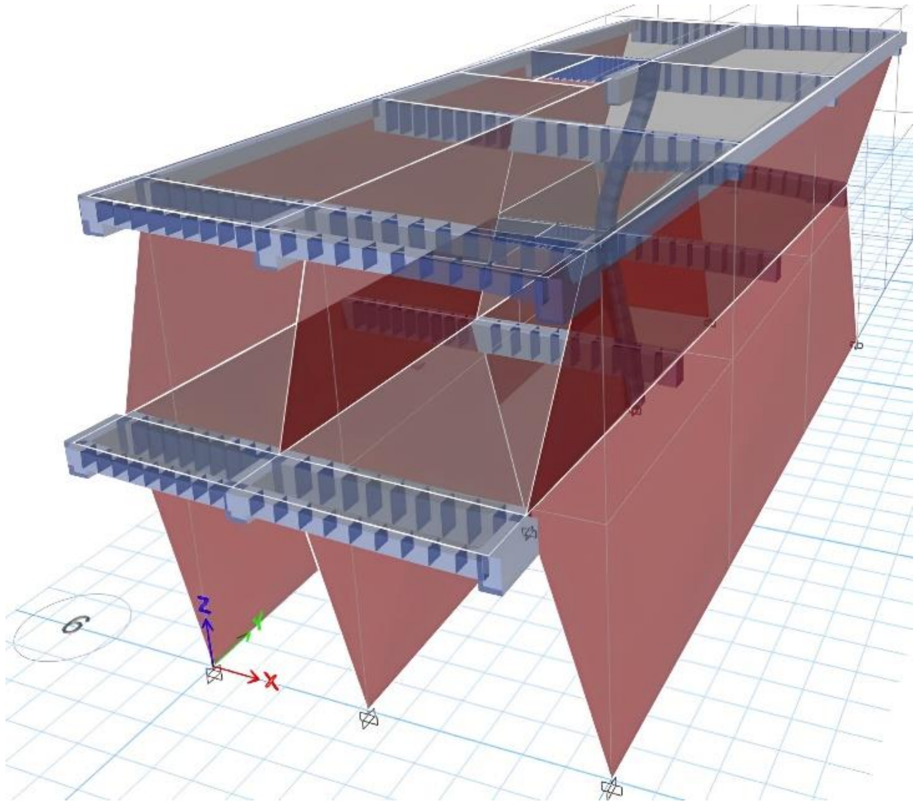


Figure 18. 3D view of the analysis of House 8 – ETABS

5. Discussions

The assessment of seismic vulnerability in frame structures with infill masonry walls houses in the Huancán district using the INDECI methodology has revealed that 40% of the homes fall into the category of very high exposure, while 50% are classified as having an increased vulnerability. Interestingly, these findings align closely with the research conducted by Hassan [11], who employed the Italian method and identified houses as moderately vulnerable (50%) and highly vulnerable (40.20%) under classes B and C, respectively. This similarity suggests that both methodologies utilize interconnected parameters to determine the vulnerability of houses. It is worth noting that in Huancán and throughout Peru, a significant portion of construction has been carried out without the supervision of qualified professionals and without adhering to the existing regulations. A similar situation can be observed in the capital of Egypt, where constructions, like those in Huancán, lack earthquake-resistant design. In Peru, major cities exhibit informal housing constructions characterized by exaggerated and unsafe methods [30].

Figure 19. Presence of openings in load-bearing walls.

Upon conducting the seismic vulnerability assessment of the examined dwellings, various construction process inadequacies were identified: The presence of openings in load-bearing walls compromising their rigidity in the constructed direction (Figure 19), utilization of tubular bricks instead of hollow-solid bricks, exceeding the maximum permissible thickness of the joint between tubular bricks prescribed by the Peruvian Standard E070 [31], presence of pipes within load-bearing walls impeding their confinement, and placement of sanitary installations in the ribbed slab adversely impacting the reduction of beam cross-sections. Furthermore, the results obtained through on-site observations using the data collection form, which assesses seismic vulnerability, closely resemble those found in countries experiencing population growth and utilizing similar construction materials.

These findings are consistent with the research by Stefano De Santis [15], who evaluated unreinforced frame structures with infill masonry walls houses using a method inspired by the Italian GNDT group and the USRA. On another note, the analysis of the seismic behavior of houses indicates that despite frame structures with infill masonry walls being the most cost-effective structural system for housing construction [32], individuals are not complying with verifications related to minimum wall density, maximum axial stress, crack control, and shear strength. Consequently, they construct houses without considering these factors, thus endangering their own lives. In his journal article [15], Stefano De Santis acknowledges that structural analysis of homes provides valuable information in assessing seismic behavior, but it is limited due to its high cost and the challenges of conducting large-scale studies without sufficient funding. Similarly, a critical parameter, inter-story drift, fails to meet the requirements on the X-axis for 83.3% of the houses and on the Y-axis for 23.3% of the homes. It suggests these houses would collapse in a severe earthquake, rendering them irreparable and non-functional [29].

Furthermore, it was observed that most of the examined dwellings exhibit tendencies towards crack formation in both directions and fall short of meeting shear verification at the first level of their frame structures with infill masonry walls. As a result, an alternative approach has been proposed, involving the reinforcement by utilizing welded wire meshes, as depicted in Figure 20. This method entails encasing 0.45 cm diameter steel rods spaced at 15 cm intervals with mortar, employing volumetric proportions of cement to sand 1:4. The implementation of this technique transforms diagonal cracks into minor fissures and elevates the lateral load resistance by 40% [33]. Conversely, the use of plastic meshes derived from cement bags, with 25 mm wide strips enwrapped around the frame structures with infill masonry walls and a plastering surface featuring a thickness of 1 cm using cement to sand proportions 1:4, results in a remarkable improvement of over 90% in compression and flexural strength. This approach imparts enhanced flexibility, resistance to corrosion, ease of execution, and cost-effectiveness [34].

Concerning the actions of the Local Government, when submitting building permits to municipalities, there is often an exclusive focus on evaluating architectural aspects, while other disciplines (structures, electrical installations, sanitary installations, etc.) are disregarded. This practice raises concern as the lack of evaluation poses risks to the occupants of these buildings. An additional problematic practice by municipalities is the collection of payments for the concept of 'Work Inspection,' a process seldom executed by the municipality, thereby contributing to informality within Peru's construction industry [36]. Moreover, inadequate supervision and control of construction projects foster the proliferation of informal constructions, wherein specifications indicated in approved construction plans by designers are not adhered to. Additionally, corruption and lack of transparency during construction are prevalent issues in Peru, with residents and supervisors permitting the utilization of substandard materials and prioritizing price over quality. All the aspects mentioned above should be integral components of the agenda of the country's principal authorities [37].

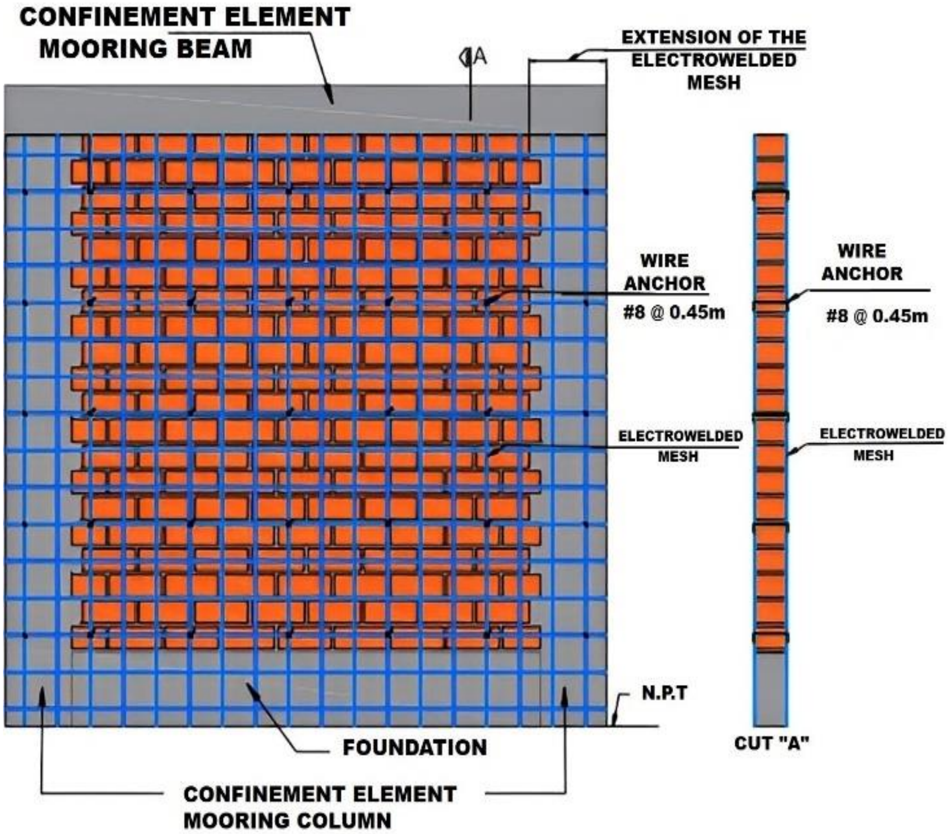


Figure 20. Welded mesh [35]

6. Conclusions

The implementation of the Indeci methodology proved to be a valuable approach for assessing seismic vulnerability and identifying construction deficiencies in the Huancan district. It facilitated a rapid structural evaluation of the dwellings, considering crucial criteria for these structures. Moreover, the analytical analysis conducted using engineering software ETABS provided a more accurate assessment of the vulnerability of these dwellings; nonetheless, this approach entails a considerable computational cost and demands expertise in modeling

Based on the findings, it can be deduced that frame structures with infill masonry walls houses in the Huancán district face considerable vulnerability, with 90% classified as "high" and "very high" in the event of an earthquake. These houses, predominantly constructed by individuals without professional assistance, display inadequate structural configurations that significantly compromise their seismic performance. Numerous deficiencies are observed throughout the construction process, exacerbating their vulnerability. Key factors contributing to this vulnerability include irregularities in the floor plan, height variations, and uneven mass distribution; this is due to the limited participation of specialists during the construction phase.

Despite having architectural and structural plans, these self-built houses fall short of meeting technical standards. The absence of proper technical supervision during construction and unauthorized alterations to the original design undermines the work of qualified professionals and compromises compliance with regulatory requirements.

A noteworthy observation is the limited wall density observed in the X-X direction, rendering the houses excessively flexible along that axis. While some walls are present in the Y-Y direction, the disruption caused by changes in room layout between floors disrupts structural continuity. Consequently, these deficiencies translate into an inadequate adherence to the recommended inter-story drift limits.

This information serves as a cautionary message to the responsible authorities, urging them to implement preventive measures through structural reinforcements. One cost-effective solution for enhancing wall strength is utilizing welded mesh, which can mitigate the vulnerability of houses and facilitate the implementation of a comprehensive seismic risk management plan.

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