STRUCTURAL (PHYSICAL–TECHNICAL) VULNERABILITY OF LOW-INCOME HOUSING IN THE FACE OF SUBSIDENCE IN URBAN AREAS: CASE STUDY OF THE ERMITA ZARAGOZA NEIGHBORHOOD, IZTAPALAPA DISTRICT, MEXICO CITY, MEXICO

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ABSTRACT

This article is based on a case study in the Iztapalapa municipality in Mexico City. The purpose of the research was to analyze the structural vulnerability of housing of social interest in order to identify the susceptibility to the impact caused by the gradual subsidence of the soil, and the occurrence of earthquakes that are frequent in the city. A mixed approach was applied based on the use of geographic information systems, the description of subsidence zones and the identification of original housing typologies by means of cartographic techniques. Besides, the evaluation of structural vulnerability was documented, as well as the knowledge that the inhabitants have about their dwellings at the moment of occupation. The results focused on two aspects, the first was a representative sample of dwellings directly affected by the subsidence or cracking caused by the desiccation of the subsoil due to the development of subsidence. The second aspect identified the factors that determine structural vulnerability based on the three-dimensional modelling of the housing and its current state, with the aim of identifying the level of structural vulnerability. It was determined that a house may present three levels of structural vulnerability; high, medium and low, and based on indicators of structure, maintenance and accumulated damage in the dwelling, it was possible to assess the dwellings that present a greater susceptibility to being vulnerable. This leads us to generate intervention strategies to reduce damage presented by the structural elements of housing and formulate prevention strategies for the inhabitants to mitigate damage.
Keywords: structural vulnerability, housing, subsidence, Mexico City.

1 INTRODUCTION

Soil subsidence in its simplest sense refers to subsidence of the earth's crust and has either a natural origin or one induced by human activity in the subsoil [1].

In Mexico City, the appearance of this phenomenon and its exacerbation is attributed to overexploitation of aquifers because of the lack of surface water supply sources, with the main effect on the surface of a gradual vertical deformation of soil, extending across areas as wide as entire neighbourhoods [2], which is why this is also known as regional sinking.

Subsidence is more notable in urban areas, where apart from the sinking itself, there is soil cracking or fracturing, a stage that is considered subsequent to sinking [3] and it is also linked to a subsoil desiccation process because of the extraction of water, which produces stress that causes greater damage to urban infrastructure.

Based on the Mexico City Risk Atlas [4], one of the neighbourhoods most affected by subsidence since 2014, because of soil subsidence and cracking has been the Unidad Habitacional Ermita Zaragoza neighbourhood, located to the east of the city in the Iztapalapa district (see Fig. 1).

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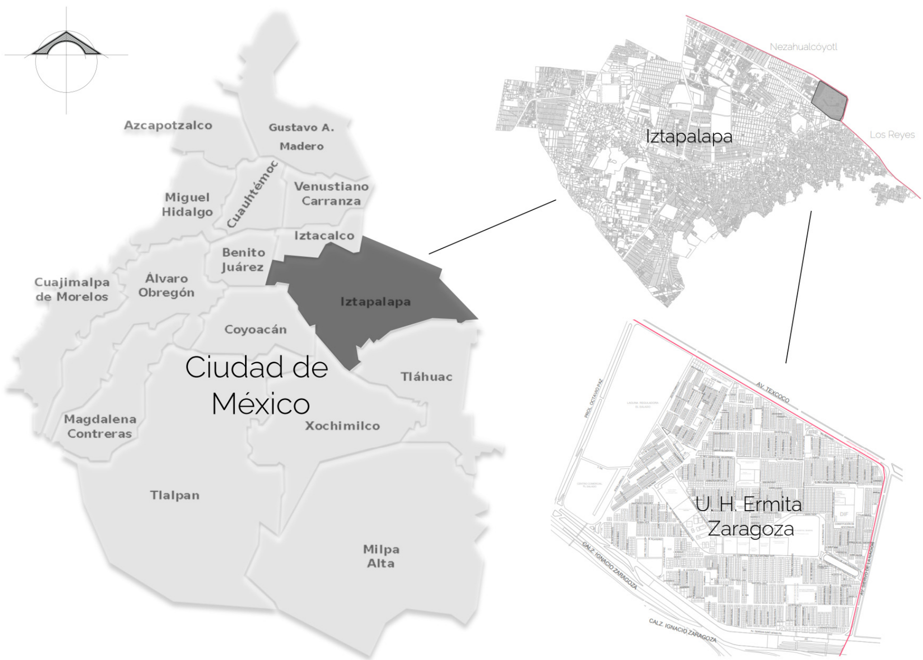

Figure 1: Location of the UH Ermita Zaragoza neighbourhood in the Iztapalapa district.

Although subsidence does not cause fatalities, it does have important economic repercussions for the inhabitants in this neighbourhood due the damage caused to their houses, because apart from soil deformation, these houses have been transformed and extended throughout their useful life posing greater structural vulnerability against subsidence itself and other risks, such as earthquakes and floods.

This was identified in the transformation brought about to low-income housing as presented in the case studies. Guzmán Ramírez and Bravo Patiño state that low-income housing models developed by real estate companies are unable to satisfy all needs of the people who will be inhabit them [5]. These conditions are reflected in house extensions completed as a result of family dynamics and economic income evolutions that are translated into alterations and transformations of the space inside and outside the house.

Housing transformation, as observed in the Unidad Habitacional Ermita Zaragoza neighbourhood in the form of expansions, is distinguished based on the transforming stages of low-income housing proposed by Guzmán Ramírez and Bravo Patiño [5]. Broadly speaking, houses can go through four "states" or "phases" that refer to the changes taking place in it (see Fig. 2). In particular, this transformation is identified with stages A, B, C, D and E, which refer to separate phases a house goes through starts from the moment it is purchased until it is fully altered with a loss of its original features.

Of these four stages, the original house is the one with all its original characteristics, that is, as designed at the end of construction and as purchased by buyer.

There are three stages to the house undergoing transformation: stage A "identification" is minimum changes to the house and is characterized by the fact that the owner changes its

Figure 2: Transformation of low-income housing. *(Source: Picture 1 – López Parcero [12]; Pictures 2 to 4 – Alonso Baca, 2020.)*

colour and/or façade finishes as a form of "owning" the house; stage B, "demarcation and extension", refers to lot demarcation by building fences for security and privacy purposes, since those fences are not available at purchase. In this stage it is common for the garden areas to be lost. Furthermore, it has been found that in the UH Ermita Zaragoza neighbourhood the property is also extended by building fences beyond the lot limits. Stage C or "alternate uses" is the one where the change of use in the original spaces of the house takes place, in this way it can give way to the setting up of a business inside the house.

Modified housing involves major architectural and structural changes. In this type of house, it has been identified that stage D that of "extension and aesthetic transformation" has been completed, characterized by the development of the first major changes to the house. In this stage, new rooms are being constructed, which involves a structural intervention to the house because of its growth, first horizontally until all free space available on the ground floor has been used, continuing with vertical growth until the needs of the inhabitant have been satisfied. At the end of this stage, the original characteristics of the house will have been lost.

Lastly, if the house continues to be extended vertically for more than two storeys, it is considered a consolidated house and it is identified with transforming stage E, which bears the same name: "consolidation". After the new rooms are built to accommodate new inhabitants and that meant losing the original characteristics of the house, new spaces continue to be constructed that respond more to convenience and comfort for the inhabitants than to necessity, such as the appearance of terraces or entertainment areas.

Low-income housing in the UH Ermita Zaragoza neighbourhood, the future expansion was contemplated in its design. Although this was only because there was free space for this purpose, considering that the original house had space at the front of the property and was built with the minimum dimensions for daily activities, making it affordable.

The lack of flexibility in housing within the neighbourhood is a problem that continues to be found in the new horizontal developments built in the city, and it is because of this, that changes are made to the original construction to adapt the construction for extension in consideration of the reduced dimensions of the initial spaces.

Possible changes to the original construction without affecting supports are limited. Indeed, the structure needs to be modified (changing load-bearing walls, beams, slabs, etc.), removing elements and building them again in a rearrangement determined by the new construction. However, unlike the formality with which the original house was built, most of these processes are conducted by way of self-construction and without the permits or construction licenses required by government agencies in the city. These new structures do not justify the choice of reinforcements used and do not consider the effects already caused due to subsidence and cracking of the soil, so they adversely affect the structural vulnerability of property (see Fig. 3).

Figure 3: Affectation of soil cracking in modified housing. Loss of verticality. UH Ermita Zaragoza neighbourhood. *(Source: Alonso Baca, 2021.)*

There are studies for the assessment of the structural vulnerability of buildings and houses not only in Mexico but also in countries such as Colombia.

In Mexico City, one of the main risks of urban infrastructure is earthquakes and a variety of studies have been conducted to assess structure vulnerability from the effects of the 1985 earthquake that had numerous effects on buildings and houses in the country's capital, apart from a considerable number of human losses [6]. However, vulnerability to subsidence of these structures has been studied to a lesser degree and since their development can be so slow [1] the damage is overlooked or perceived as slight by city dwellers.

Structural vulnerability can be understood as the predisposition of a structure to suffer damage in the face of a certain situation resulting from a phenomenon, and whose susceptibility to affectation is associated with the processes that intervene from conception, design, construction, operation, and maintenance that are intrinsic to the structure analyzed [7].

For this research, different studies were reviewed that made an evaluation on the vulnerability of the structures, identifying the criteria of the structure considered and those before the risk under study – seismic features in Mexico and mass removal in Colombia. This last study is of cases of low-income housing (see Table 1).

Based on the previous studies, it has been determined that the structural vulnerability of a building or dwelling is associated, regardless of the risk to which it is exposed, to its own characteristics regarding its construction and preservation during the time it has been occupied. Similarly, the damages to the structure will have to be related to the magnitude of the phenomenon they have endured.

The characteristics determined and shared between these studies and that have been taken into consideration to assess the vulnerability in structures of low-income housing in the UH Ermita Zaragoza neighbourhood can be divided into three groups: those describing its structure, those referring to the maintenance given during its useful life and those produced by the damages associated with the risk under study.

Table 1: Criteria considered from several authors – Structural vulnerability assessment before various risks, 2021.

Author	Study	Year	Country
Páez Moreno and Hernández Delgadillo [7]	Methodology for the study of the structural vulnerability of buildings	2005	Colombia
Maldonado Rondón and Chio Cho [8]	Structural vulnerability index to the effects of mass removal in masonry buildings based on fuzzy sets	2012	Colombia
Iglesias [9]	Evaluation of concrete buildings in Mexico City	1989	Mexico
Pan-American Health Organization [10]	Analysis of structural vulnerability in health facilities	2004	AL and Caribbean

As for the information on the characteristics describing the structure of low-income housing, this refers to those of the antecedents from design and construction to the damage due to earthquakes that have affected the structure.

2 METHOD DESCRIPTION

An explanatory mixed approach research was developed. The structural vulnerability of six study cases has been assessed quantitatively, and its impact because of soil subsidence has been deepened qualitatively, as well as the expansion practiced on each of the cases, apart from the risks to which they are exposed: earthquakes and floods.

The work is based on the identification of areas most affected by both soil subsidence and cracking in the neighbourhood based on the information available from the Risk Atlas in Mexico City and the Iztapalapa district, creating maps supported with Geographic Information Systems over the risk of subsidence on the urban layout within the neighbourhood.

Fig. 4 shows soil cracks indicated by the risk atlas in Mexico City [11]. Blue polygons specify the areas with concentrations of these cracks and that apart from the fact that they are easily visible from the roads, they represent a greater affectation to the houses.

Similarly, from the neighbourhood topography, depression zones were located that refer to those zones where the vertical soil deformation occurs due to subsidence. However, in this case, the topographically low zones could not be confirmed to indeed refer to those most affected by soil subsidence in the neighbourhood because of the COVID-19 pandemic lockdown that took place during the investigation.

Although Risk Atlases in Mexico City and the Iztapalapa district hold information on soil subsidence, in both cases this information specifies the estimated vertical soil deformation only, which for the UH Ermita Zaragoza neighbourhood ranges from 2 to 10 cm per year [11]. This information does not represent the soil deformation operating in the neighbourhood nor does it specify the points most affected by this phenomenon.

The original typologies were identified as built by the General Office of Popular Housing for the neighbourhood at construction and inauguration in 1974 [12] based on historical research and interviews with one of the neighbourhood representatives. This information is necessary to understand the features and initial dimensions of houses and to measure transformation in the form of the extensions as described in the stages of this process.

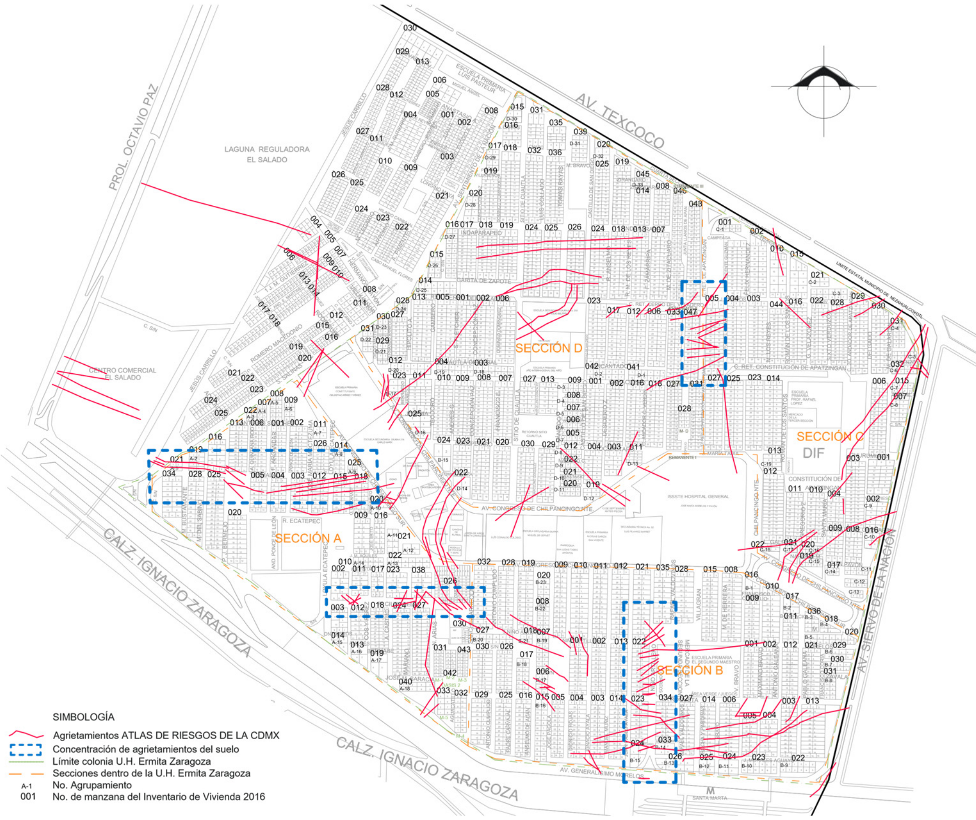

Figure 4: Identification of areas affected by soil cracking. UH Ermita Zaragoza neighbourhood. *(Source: Prepared by Alonso Baca based on the Risk Atlas in Mexico City [11].)*

We proceeded to locate these typologies in the neighbourhood layout to measure the transformation sustained by each of them and identified the current stages in each house through Google Earth tours in the neighbourhood because of the pandemic.

To collect field information, observation checklists were prepared and detailed over those homes with greatest observable physical damage.

Analysis of the collected information made it possible to identify factors determining susceptibility to damage in each case study, i.e., apart from the influence of soil subsidence, to identify those factors that increase vulnerability.

Finally, structural vulnerability of housing was assessed quantitatively from weighting the identified factors, grouping them by their characteristics, obtaining three values of structural vulnerability, one for the description of the structure, one for maintenance and another for damage observable in each house.

3 RESULTS

3.1 Typologies and degree of transformation within the neighbourhood.

Based on the initial composition of the neighbourhood, it was possible to identify the originally designed typologies and construction in the 1970s, with a total of 4 typologies that, based on the physical characteristics of spaces and the dimensions of lots, were identified as Type 1, Type 1A, Type 1B, and Type 2 (see Fig. 5).

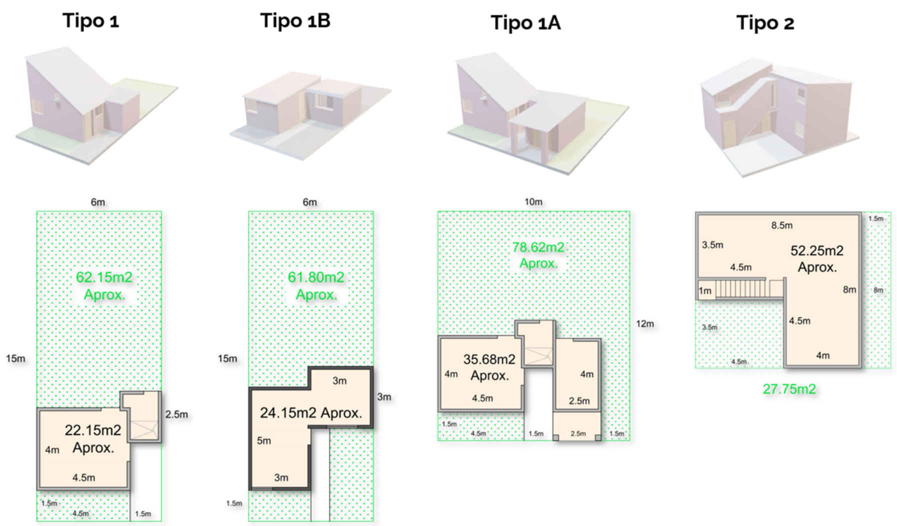

Figure 5: Models of original houses in the UH Ermita Zaragoza neighbourhood, Iztapalapa, Mexico City, 2021. *(Source: Prepared by Alonso Baca based on López Parcero [12] and field work, 2021.)*

Typologies 1 and 1A share features, such as a loft space designed to adjust to the lifestyles of inhabitants coming from other states in the country. Such features give an architecturally distinctive appearance to the neighbourhood against other low-income housing in the city.

Among the similarities between type 1 and type 1B are lot dimensions, and that both types have a ground floor comprised by the bathroom area, kitchen area and a main area used as a hall and a bedroom.

The fourth type of housing identified as Type 2 is the only one that had two built stories from the start and did not have space available for expansion. It had a patio in front of the house instead. It included three bedrooms and a bathroom on the upper story and a kitchen, living–dining room, and bathroom on the ground floor. The four typologies were modelled and the dimensions of both the house and the space available for expansion were estimated.

The distribution of the neighbourhood was mapped based on the original typologies. In the year 1980 (6 years after inauguration), there were a total of 4,926 properties in the neighbourhood and, it was found that two new typologies emerged other that the four original typologies with the purpose of giving a greater accommodation capacity.

At present, no house stands that can be considered totally original in the neighbourhood. The minimum change observed is at least the change of façade colour.

39% of type 1 and type 1B houses have been completely transformed, 27% of them have had their lot newly delimited or extended, and 15% of houses are in the process of consolidation, i.e., they are houses 3 or more stories high. Conversely, stages less present are stage “A” or identification, with less than 1%, and stage “D” or expansion, either horizontally and/or vertically, but they maintain the original features making it possible to distinguish the original house typology.

In type 1A houses located at the ends of blocks, 37% of houses have been transformed in the form of stage “B”, i.e., delimitation and extension, followed by 22% of houses in stage “D” or horizontal and/or vertical expansion, and 22% of houses have been fully transformed but still limited to two stories. Just as with the previous typologies, stage “A”, identification, is least present in this type of houses.

In the case of type 2 houses, a lower degree of transformation was generally found if compared to the other original typologies. The most predominating stage is stage “B”, i.e., delimitation and extension of the house in 75% of cases, followed by the stage of expansion and aesthetic transformation in just under 20% of houses. Dwellings of this type accounted to almost 2% of the total.

The lower degree of transformation in type 2 houses is attributed not only to the unavailability of free space for extension, but also to the fact that the rooms available since purchase better met the needs of occupants than the rest of the typologies over time.

3.2 Study cases

To assess structural vulnerability, six cases were studied to which an observation certificate was applied. These houses were selected because of the access permit obtained thanks to the support of personnel from the Commission for the Reconstruction of Mexico City, who were conducting work in the neighbourhood during this part of the investigation.

The study cases were located in section “B” of the neighbourhood, which, the neighbourhood representative declared to be one of those areas with the lowest crime rates, which also facilitated field visits and access to houses for data collection (see Fig. 6).

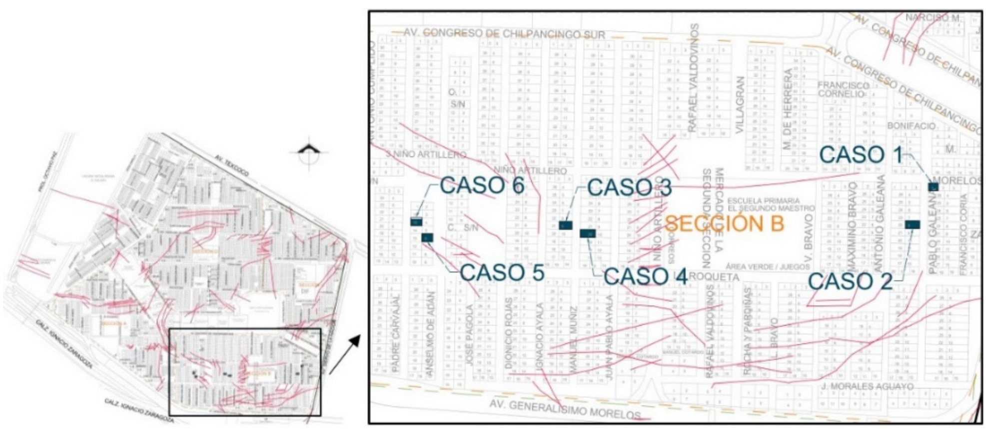

Figure 6: Location of case studies for assessment of structural vulnerability. *(Source: Prepared by Alonso Baca based on the Risk Atlas in Mexico City [11] and field work.)*

The typologies to which each study case belongs are type 1A for case 1, while cases 2, 3 and 4 are typology 1B, and in cases 5 and 6 are typology 2.

3.2.1 House extensions

The degree of transformation caused by extension of each case study was analyzed using 3D models with the support of Autodesk Revit design software. Fig. 7 shows each 3D model for each study case. The blue section is the part of the construction that has been added to the original house and representing an expansion.

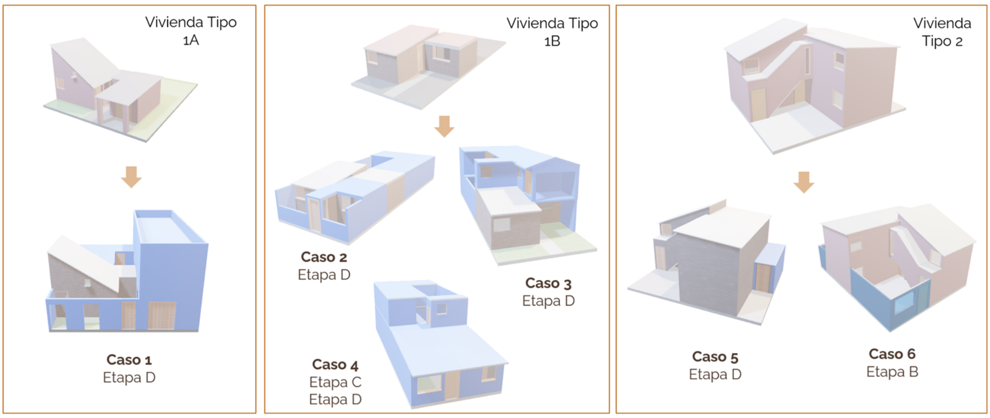

Figure 7: Original typology and expansion of the house in case studies. *(Source: Prepared by Alonso Baca based on field work, 2021.)*

For case 1, the transformation stage refers to stage "D" of expansion and aesthetic transformation, still distinguishing part of the original house.

For cases 2, 3 and 4 the transformation corresponds to stage "D" of enlargement with different dimensions, while in case 2 it has been limited in the horizontal direction only. In case 3, it has also been conducted in the vertical direction. In case 4, the house is the only one that has lost its original typology by expanding horizontally towards the front, which is why it is considered a completely transformed house.

For cases 5 and 6 of typology 2, they have a lower degree of transformation, unlike all the previous cases. In case 5, the expansion was limited to a utility room at the back of the lot (stage D) and in case 6, occupants only delimited the façade and the back of the house with a perimeter fence (stage B).

As regards the growth of the constructed area, it was found that this was greater in type 1A houses (case 1), going from 35.68 m^2 to 146.46m^2. This is the typology with the largest available area for expansion. Typology 1B houses (cases 2, 3 and 4) show high growth, especially when the extension reaches the vertical direction, in cases 3 and 4 the area went from 24.15 m^2 to 83.25 m^2 and 85.05 m^2 respectively, while in case 2 this came only to 41.10 m^2.

Typology 2 house is the house with the least extension, although stage "D" is identified in case 5, this is due to the construction of a small room in the small free space representing an additional area of 5.00 m^2 against the original area of 104.50 m^2. The house in case 6 was not expanded but was in stage "B" with only the delimitation of the lot with a fence.

3.2.2 Structural vulnerability

Assessment of structural vulnerability was conducted for each of the study cases with the information collected on site. Three vulnerability values were obtained over the categories of structure description, maintenance, and damage in the house.

These values were obtained by weighting the characteristics of each of the sections based on the most unfavourable condition in any of the case studies.

As regards the description of the structure, high vulnerability percentages were obtained, since house extensions are conducted with unconfined masonry and solid slabs with reinforcements set on original reinforcements. They show irregularities on foundations and height, and they were conducted by informal construction processes, not to mention that the original houses have structures more than 40 years old and therefore, use design methods and practices common before the 1985 earthquake.

Based on maintenance, there are values of medium and high vulnerability in houses. It is high vulnerability in cases where the lack of maintenance, which starts from the lack of waterproofing in roof slabs, has caused the detachment of coatings with exposure of reinforcing steel in slabs, and beams, and the presence of moisture in walls.

Structural vulnerability from the damage presented to these houses ranges from low to high depending on the damage associated with soil subsidence (sinking and cracking) and damage to walls and concrete elements due to the earthquakes of 1985, 2017 and 2021.

A global vulnerability value was obtained by averaging each value obtained for each case study. This value shows that vulnerability was medium for 5 study cases and only one was of high vulnerability (see Table 2).

Table 2: Identification of structural vulnerability in houses – UH Ermita Zaragoza neighbourhood, Mexico City, 2021.

Section	Case 1	Case 2	**Case 3**	Case 4	Case 5	Case 6
	T-1A	T-1B	**T-1B**	T-1B	T-2	T-2
Structure	75.0%	75.0%	**75.0%**	62.5%	75.0%	62.5%
Maintenance	62.5%	50.0%	**75.0%**	37.5%	12.5%	37.5%
Damage	54.0%	16.7%	**70.6%**	49.9%	49.9%	54.0%
Total	64.0%	47.0%	**74.0%**	50.0%	46.0%	51.0%
Note: Low vulnerability:0–33%, medium vulnerability: 34–66%, high vulnerability: 67–100%						

Case study 3 has been the most structurally vulnerable as it has a greater affectation in its structure. This was the case because the expansion followed the dimensions of the original house as regards concrete and masonry elements. No maintenance was found on the waterproofing of slabs. Therefore, there is humidity, detachment of coatings and exposure of reinforcements. Due to the subsidence in the neighbourhood and the earthquakes of 2017 and 2021, part of the drainage inside the house has collapsed, as well as part of the exposed electrical installation.

The structural vulnerability in case study 3 is also high because the damage to the two stories is considered serious, with openings in masonry walls and failure in connections of concrete elements for confinement, and although initially the damage was due to subsidence, this has increased due to recent earthquakes in Mexico City.

It was also found that the structural vulnerability in the neighbourhood houses has increased due to their expansion. This process, apart from representing a greater load on the original house, it also means the construction of new structures that are only superficially attached to the walls on the ground floor or upper floor, beams, and slabs, but not in the foundations. This produces a differential subsidence.

The informal expansion of houses also affects its structural vulnerability by exposing it to damage when its construction extends over public areas causing subsidence and/or cracking. This phenomenon is the result of land appropriation as has been practiced in the neighbourhood.

Extensions, age, and lack of maintenance are factors favouring the structural vulnerability of houses because although the concrete elements show only natural deterioration due to the passage of time, this increases if houses are not properly maintained. Lack of maintenance or deficient maintenance are directly related to the economic situation of owners because their lack of means gives them no opportunity to make any proper maintenance.

The neighbourhood urban design is a factor that has influenced structural vulnerability, particularly in the case of extensions, because walkways are so narrow and the vegetation so present in the area, that it is impossible to use machinery, even light machinery for the construction of concrete elements.

In the neighbourhood, houses were affected by the earthquakes on 19 Sept. 1985, 7 Sept. 2017 and 19 Sept. 2017 and 7 Sept. 2021, and floods that are also the product of soil subsidence. Both risks increase their structural vulnerability by intensifying the damage already caused to houses.

4 CONCLUSIONS

The structural vulnerability of houses, although it is induced by the susceptibility of the soil to subsidence and cracking, has increased by expansions conducted under informal construction processes and by the lack of necessary maintenance to preserve the original structures.

During the extensions practiced on houses, the use of inadequate structuring predominates in an area that has been identified to have a subsidence risk and highly compressible clay soils. Furthermore, they have unconfined masonry for walls, characterized by irregularities both in its foundation and in elevation of the structural elements for each of the built stories, which also makes them more vulnerable to effects such as tilting and cracking, especially in older sections.

Based on the original typologies studied, those with the highest degree of transformation and therefore the greatest expansions are the ones that initially had the greatest free areas: types 1, 1A and 1B; and the only one where growth was reduced was type 2 houses, because apart from the fact that they did not have space open for growth, they originally had a greater number of rooms that better covered the needs of occupants.

It was also concluded that typology 2 houses were the least structurally vulnerable as they have been the object of fewer interventions because they are the least expanded houses in the neighbourhood.

Based on the results in the assessment of the vulnerability of the houses studied, this research can be directed to the development of policies for the design, construction, and designation of free areas in low-income housing, and for their expansion in the medium and long term to reduce the effects of soil subsidence and cracking that is increasing in urban areas because of groundwater extraction.

In future research, it is possible to delve into the integration of the structural design of low-income housing against the development of soil subsidence for new real estate developments, and to consider the feasibility for occupants to follow strategies to reduce vulnerability in the extensions they practice on their properties with the application of essential structure maintenance.

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