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Seismic Vulnerability Assessment Using FEMA P-154 and Welded Mesh Reinforcement in Informal Settlements in Peru

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Abstract **-** The main objective of this study is to evaluate the seismic vulnerability of 30 self-built houses in the Juan Pablo II human settlement in San Juan de Lurigancho, Lima, Peru, which, due to their informal construction and the use of low-quality materials, present a high risk of seismic events; To do so, the FEMA-P154 methodology will be used, revealing that 31% have a risk of collapse greater than 50%. Likewise, the results of this research will allow us to identify the main structural deficiencies and propose appropriate reinforcement solutions, thus contributing to improving the safety of the inhabitants of the area and reducing human and material losses in the event of an earthquake. This study evaluates the alternative of welded mesh as a reinforcement proposal to improve the seismic behavior of the houses, which will be evaluated through dynamic and pushover analysis, using tools such as AutoCAD and Etabs to perform structural analysis.

Keywords**:** Seismic vulnerability, Pushover analysis, electrowelded mesh, self-built homes, human settlements, structural reinforcement, FEMA P-154, reinforcement material

1. Introduction

In the research work of [1] it is understood that there is a large part of the population of Latin America, especially those who suffer from scarce economic resources, who build their own houses without following the standards stipulated for the construction sector, which serve to guarantee the safety and comfort of the inhabitants of said houses. Likewise, there are millions of people who dream of having their own home at a certain economic level, for which they choose to carry out unregulated processes and without the help of specialized professionals. This creates informal settlements with housing in a precarious state and without the basic conditions for a decent life. On the other hand, the emergence and increase of said settlements or informal housing around Latin American cities is related to urban growth and the increase in social and economic inequalities, so much so that urban development has become an existing poverty as well as in rural areas, which shows that it is necessary to understand and act appropriately to face reality, where seismic movements are a problem that is experienced today. Likewise, this often affects the population, causing them to be left without a place to live and even lose their lives, either due to a failure in the structure due to seismic intensity called seismic vulnerability [2].

That is why there are comprehensive design standards to regulate construction practices in Peru, since the population being constantly growing creates a greater demand for housing. However, this has also increased self-construction practices without due compliance with the principles of structural engineering, which has generated deficient housing in precarious conditions, a fact that is closely related to greater seismic vulnerability, where the consequences are serious and high risk [3].

On the other hand, in the research work of [4], we are informed that, in San Juan de Lurigancho, there are various AA. HH. due to the population growth rate that migrate to these sectors due to the need to procure land or a house. A clear example is the AA. HH. Juan Pablo II, the inhabitants have a variety of self-constructions according to their economic possibilities, location of the land, acquisition of low-quality construction materials. In addition, they are located in peripheral areas, where the structure can fail in the event of a seismic event. Such is the fact that, with cheap constructions, the seismic behavior is not as expected, which leads to structural damage and human losses. The most notable are confined masonry, mixed structures with concrete frames and masonry walls, which are built by non-professionals.

2. State of the Art

A. Seismic vulnerability in human settlements

In the research work of [4], we are informed that, in San Juan de Lurigancho, there are various AA. HH. due to the population growth rate that migrate to these sectors due to the need to obtain land or a house. A clear example is the AA. HH. Juan Pablo II, the inhabitants have a variety of self-constructions according to their economic possibilities, location of the land, acquisition of low quality construction materials. In addition, they are located in peripheral areas, where the structure can fail in the event of any seismic event. Such is the fact that, with cheap constructions, the seismic behavior is not as expected, which leads to structural damage and human losses. The most notable are confined masonry, mixed structure with concrete porticoes with masonry walls, which are made by non-professionals. Methods for assessing seismic vulnerability

[5] also emphasizes that over time and due to the climatic changes to which they are subjected, these homes have suffered deterioration in walls, roofs, beams, and columns. So much so that they present cracks, structural failures, and water leaks. However, even though their homes are vulnerable to these natural events, many people do not reinforce or maintain their homes due to the high cost and time required to do so. Consequently, they do not realize that they cause long-term problems, mainly such as the inclination, sinking, or collapse of their home.

B. Seismic vulnerability assessment method

First, the method that qualitatively ensures the collection of information for the identification of seismic vulnerability in housing in human settlements in our article is the FEMA-P154 method, since it can be observed that authors such as [6], who focused on the seismic vulnerability of confined masonry housing in the district of La Encañada, identified a high risk due to informal construction and the use of low-quality materials. To address this problem, qualitative techniques such as standardized interviews and questionnaires, as well as structural analysis based on the FEMA-154 method, were used. The results revealed that 20% of masonry housing typology presents a high seismic risk, 66.67% of respondents showing a medium vulnerability and 13.33% low NVS level, which underlines the urgent need to implement mitigation measures and technical advice in construction.

Similarly, it is worth highlighting that [7] addresses the problem of how to assess the seismic vulnerability of homes in sector 5 of Anconcito, Ecuador, where a high percentage of structural deterioration was identified. To do so, data collection techniques were used through visual inspection and analysis methods such as FEMA P-154 and AIS, which allowed a systematic evaluation of the conditions of the buildings. The results revealed that of the 78% of homes with masonry typology, 17% of the homes present a high seismic risk, 59% of the respondents showed a medium vulnerability and 2% a low level of NVS, which underlines the urgent need to implement mitigation measures and technical advice in construction.

C. Seismic reinforcement in masonry structures

The author [8] addresses the structural behavior of two informally built semi-detached houses, identifying problems such as knocking, short columns and column discontinuity. Likewise, the methodology included on-site information gathering, material testing and analysis using mathematical models, finding that the structures did not present adequate behavior, with 30% of deficiencies in structural resistance. In addition, a reinforcement was proposed by means of masonry coating with welded mesh and mortar, optimizing costs and improving the stability of the buildings. It should be noted that the inelastic drifts obtained with the reinforcement were less than 1% allowed by the Ecuadorian Construction Standard (NEC SE-SD), and it was shown that the resistance of the system exceeded 100% of its weight in lateral load tests. In addition, it was reported that a rehabilitated wall resisted 1.35 times more than an original one, and the reinforcement system increased lateral stiffness, decreasing the deterioration rate by 354%.

In addition, [9] seeks to solve the problem of how to determine the seismic vulnerability of self-built 1, 2 and 3-story houses located on S3 soil on the west coast of South America, which are exposed to constant earthquakes due to the subduction of the Nazca plate into the South American plate. Likewise, it can also be seen that the informality in the construction of these houses and the irregular structural configuration make them highly vulnerable, putting the integrity of the inhabitants at risk. To do so, the author includes the determination of models of self-built confined masonry houses on S3 soil, the case study of 1, 2 and 3-story houses, the analysis of the resistance and lateral deformation of walls with reinforcing mesh, and the evaluation of the mechanical behavior of the AR fiberglass mesh in masonry walls. The critical parameter that significantly influenced the evaluation of the strengthening techniques was the resistance to shear forces, where the AR fiberglass mesh stood out compared to the electro-welded mesh in terms of resistance to shear forces and ductility. As a result, in the X direction, the electro-welded mesh increased the resistance to shear forces by 47.08% and the AR fiberglass mesh by 82.25%.

3. Contribution: Reinforcement Material

Firstly, welded mesh has been positioned as an effective and versatile solution for the seismic reinforcement of structures, especially in masonry buildings. Its application has spread due to various advantages that make it attractive for both engineers and owners. That is why the proposal for reinforcement with welded mesh for self-built homes in the Juan Pablo II Human Settlement is presented as a viable and economic solution to significantly improve the seismic resistance of these structures.

4. Methodology

In order to carry out the study on the houses, it had to be divided into 3 phases. First, the characterization of the self-built houses; that is, data was collected in terms of predominant construction materials, typology, construction techniques and their state of conservation. Secondly, the Fema P-154 method was used to quickly determine the level of vulnerability through scores (Vertical and plan irregularity, Pre-code, Post-year, Soil Type according to the method). Finally, by selecting a pair of highly vulnerable houses, considering the most frequent characteristics, a reinforcement technique is proposed to improve the seismic behavior of the houses. This reinforcement will be evaluated for its effectiveness by calculating the contribution to the shear force in the walls and the pushover analysis in ETABS.

5. Tools

A. Data collection form

High seismicity sheet according to the Fema P-154 manual that was used to obtain field data necessary for the evaluation of each parameter of the methodology

B. AutoCAD and Etabs

In order to carry out a rigorous structural analysis, AutoCAD was used to generate the plans of the houses. These plans were imported into Etabs to develop a three-dimensional structural model. Using this model, static and dynamic analyses (spectral modal) were performed in accordance with the requirements of Standard E 0.30. A non-linear pushover analysis was also performed, simplifying the load-bearing walls as frame-type elements to evaluate the deformation capacity of the structure under lateral loads.

C. Excel

In order to visualize and analyze the results more effectively, the Excel program will be used to generate graphs and perform statistical calculations.

6. Results

A. Vulnerability study using FEMA P-154 methodology

After carrying out a detailed vulnerability assessment using the FEMA P-154 method on 30 homes, it was determined that 7% have a collapse percentage of 63.10%, and 28% have a 19.95% prone to collapse, as shown in Fig. 1. In addition, Fig. 2 and Fig. 3 show the characteristic value of the most influential factor of the homes in each parameter.

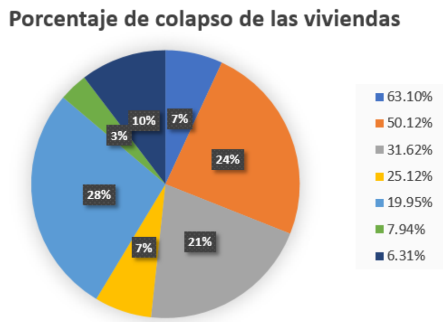

Fig. 1: Percentage of housing collapses in the study.

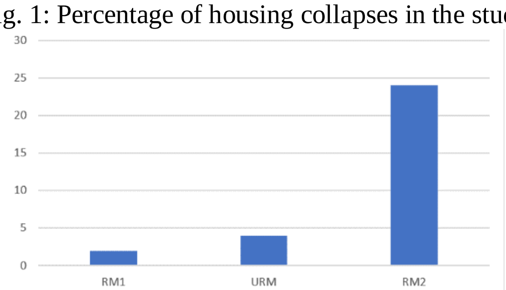

Fig. 2: Structural system according to FEMA.

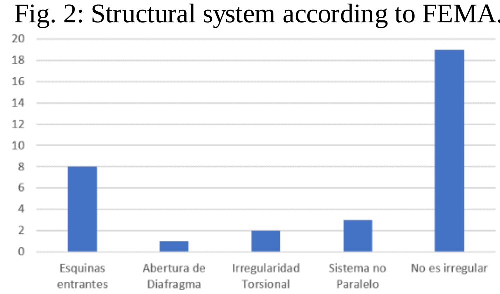

Fig. 3: Classification of the homes under study by irregularity in the floor plan.

By evaluating the most predominant characteristics in the 30 houses collected, showing more incidents in each parameter evaluated. The 22nd and 16th houses were selected to be modeled, and the reinforcement proposal was applied. To do this, the factors indicated above were taken into account, their representative level of vulnerability and the number of floors of each house to see which houses were most affected by the collapse due to the characterization of parameters.

B. Static and dynamic modal spectral analysis according to E.030 of the RNE

After performing a seismic analysis according to the E.030 standard, as shown in Table 1, it was determined that the house is regular, the coefficient that corresponds to it is 3 to study the response of a confined masonry system in the event of a severe earthquake. Finally, the dynamic shears do not need a scale factor as they are within the range of being greater than 80% of the static shear.

Table 1: Classification of the homes under study by parameter of the FEMA P-154 method.

Features	Housing 22	Housing 16
Weight (tonf)	74.451	156.342
Height (m)	5	7.65
Fundamental Periods of Vibration (s)	0.090	0.085
Shear Force (tonf)	30.71	64.49

Direction	X	Y	X	Y
Static Displacements X and Y (mm)	Piso 2: 1.339	0.618	Piso 3: 0.724	0.155
	Piso 1: 0.805	0.389	Piso 2: 0.479	0.116
			Piso 1: 0.200	0.059
Dynamic Displacements X and Y (mm)	Piso 2: 2.308	0.724	Piso 3: 1.594	0.204
	Piso 1: 1.285	0.479	Piso 2: 1.112	0.157
			Piso 1: 1.285	0.008

To continue with the control of wall cracking, it can be seen in Fig. 4 how the walls were named at each level of the houses. In addition, the shear forces to be used for the subsequent analysis will be when the house is in a dynamic state, since there is a greater demand for work to be resisted by the walls.

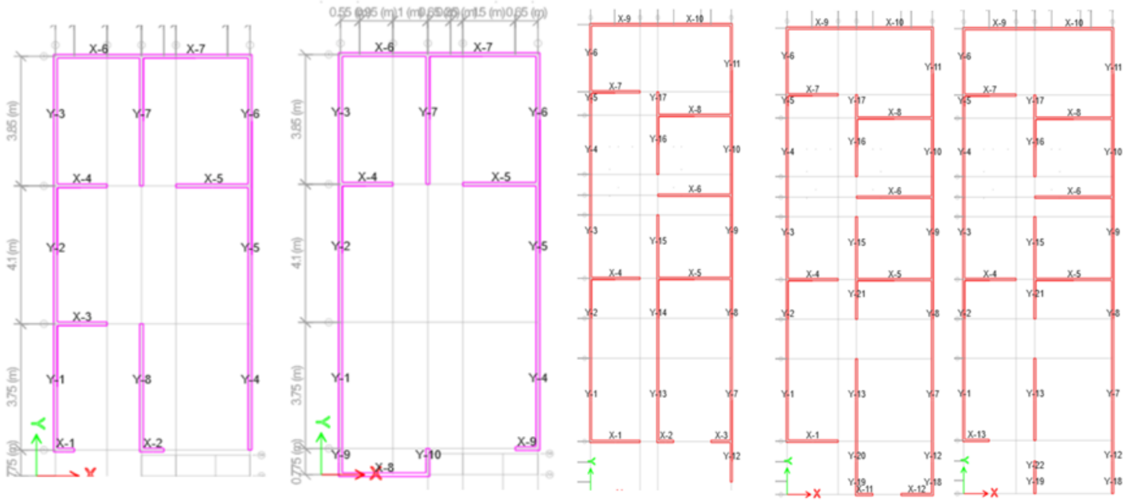

Fig. 4: Floor plan of the levels of housing 22 and 16.

C. Crack control and proposed strengthening technique

According to the E. 070 standard for masonry walls confined with clay bricks, the shear strength of the walls was determined, which through the ETABS will be compared if the wall can support the load demand attributed to it without cracking. Those walls that do not meet the criterion will be reinforced with electro-welded mesh, with which, according to [11], it is possible to calculate the contribution to shear in the walls and thus be able to determine if the reinforcement is feasible as shown in Table 2 and Table 3.

Table 2: Calculation of reinforcement contribution in the walls of the house 22.

	Muro	L m	VmR tnf	Fr	h/L	n	Ko	ph	k1	η	VsR tonf	Vrequerido tonf	Criterio
	X-2	0.5	0.57	0.70	5.00	1.00	1.00	0.001919	0.57	0.43	1.64	1.05	Cumple
PISO 1	X-6	2.2	6.10	0.70	0.66	1.00	1.30	0.001919	0.57	0.40	6.70	1.01	Cumple
	X-7	2.85	7.92	0.70	0.70	1.00	1.30	0.001919	0.57	0.40	8.67	1.10	Cumple

Table 3: Calculation of reinforcement contribution in the walls of the house 16.

	Muro	L m	VmR tnf	Fr	h/L	n	Ko	ph	k1	η	VsR tonf	Vrequerido tonf	Vrequerido<=VsR
PISO 3	X-5	3.8	10.37	0.7	0.6711	1	1.3	0.001919	0.57	0.41	11.61	1.79	Cumple
PISO 2	X-1	2.6	8.55	0.7	0.9808	1	1.3	0.001919	0.57	0.39	7.56	1.55	Cumple
	X-5	3.8	10.38	0.7	0.6711	1	1.3	0.001919	0.57	0.41	11.60	7.82	Cumple
	X-9	3.45	9.88	0.7	0.7391	1	1.3	0.001919	0.57	0.40	10.42	0.72	Cumple
	X-10	3.8	10.90	0.7	0.6711	1	1.3	0.001919	0.57	0.40	11.47	0.83	Cumple
PISO 1	X-1	2.6	11.68	0.7	0.9808	1	1.3	0.001919	0.57	0.34	6.74	4.29	Cumple
	X-2	0.75	2.01	0.7	3.4000	1	1	0.001919	0.57	0.35	1.96	0.73	Cumple
	X-3	1	3.35	0.7	2.5500	1	1	0.001919	0.57	0.31	2.32	1.09	Cumple
	X-5	3.8	10.47	0.7	0.6711	1	1.3	0.001919	0.57	0.40	11.58	7.55	Cumple
	X-9	3.45	10.46	0.7	0.7391	1	1.3	0.001919	0.57	0.39	10.26	2.12	Cumple
	X-10	3.8	11.48	0.7	0.6711	1	1.3	0.001919	0.57	0.40	11.32	2.36	Cumple

D. Pushover Analysis

For the analysis, it is necessary to have the non-linear conditions of a conventional masonry wall and one reinforced with welded mesh calibrated against an experimental model. For the hinges of the masonry walls and with the reinforcement in non-linear conditions, those proposed by [9] were used. Accordingly, the capacity curve is determined as shown in Fig. 5, both As built and reinforced with welded mesh in both houses in both directions.

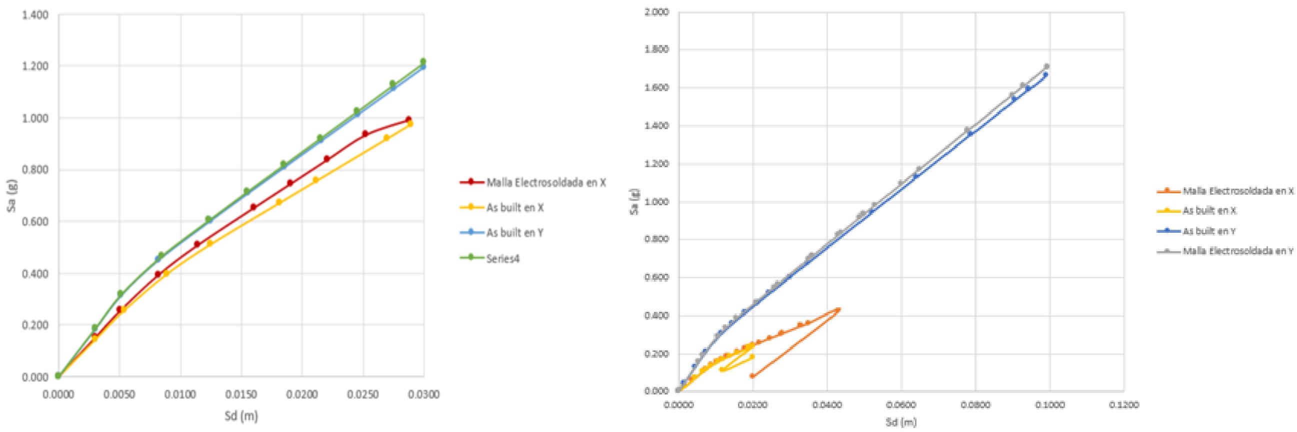

Fig. 5: Capacity curve on X and Y axis of housing 22 and 16

Once the capacity and demand curves have been obtained in ADRS format, the curves are superimposed to obtain Fig. 6 and Fig. 7. The objective of this is to find the performance points that would be the intersections of the capacity-demand spectra.

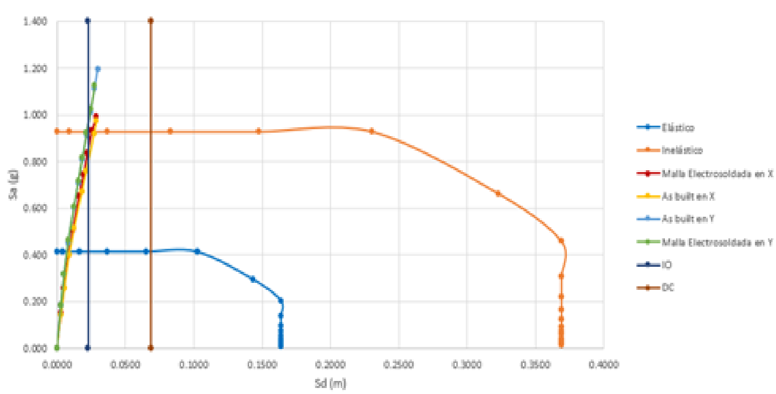

Fig. 6: Capacity Spectrum – Housing Demand 22

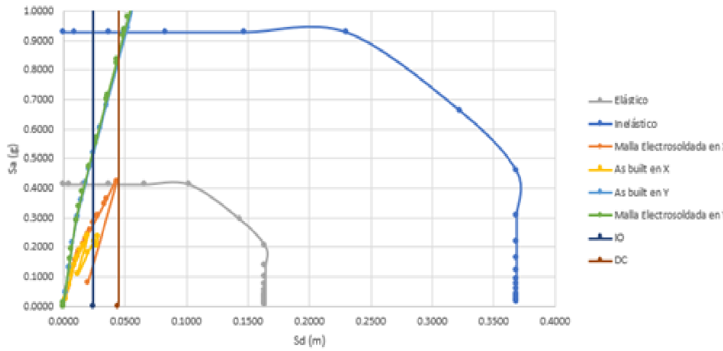

Fig. 7: Capacity Spectrum – Housing Demand 16

With the data obtained above for each dwelling, the performance level is determined for each point according to the ATC-40, which establishes the performance limits. These results can be observed in Table 4 and Table 5.

Table 4: Performance level on housing performance points 16.

Punto de Desempeño	Sd (m)	deriva (m)	Step	Nivel de desempeño
EN DIRECCIÓN X				
P.D.1. NTP E.030 Elástico - As built	0.0093	0.0018	3	Ocupación Inmediata
P.D.2. NTP E.030 Elástico - Malla Electrosoldada	0.0087	0.0017	3	Ocupación Inmediata
P.D.3. NTP E.030 Inelástico - As built	0.0273	0.0060	7	Control de Daños
P.D.4. NTP E.030 inelástico - Malla Electrosoldada	0.0250	0.0055	8	Control de Daños
EN DIRECCIÓN Y				
P.D.5. NTP E.030 Elástico - As built	0.0073	0.0025	4	Ocupación Inmediata
P.D.6. NTP E.030 Elástico - Malla Electrosoldada	0.0072	0.0017	3	Ocupación Inmediata
P.D.7. NTP E.030 Inelástico - As built	0.0221	0.0043	7	Ocupación Inmediata
P.D.8. NTP E.030 inelástico - Malla Electrosoldada	0.0217	0.0043	7	Ocupación Inmediata

Table 5: Performance level on housing performance points 22.

Punto de Desempeño	Sd (m)	deriva (m)	Step	Nivel de desempeño
EN DIRECCIÓN X				
P.D.1. NTP E.030 Elástico - As built				
P.D.2. NTP E.030 Elástico - Malla Electrosoldada	0.0405	0.0169	7	Control de Daños
P.D.3. NTP E.030 Elástico - Malla Electrosoldada	0.0425	0.0191	8	Control de Daños
P.D.4. NTP E.030 Inelástico - As built				
P.D.5. NTP E.030 inelástico - Malla				
EN DIRECCIÓN Y				
P.D.6. NTP E.030 Elástico - As built	0.0178	0.0019	3	Ocupación Inmediata
P.D.7. NTP E.030 Elástico - Malla Electrosoldada	0.0173	0.0015	3	Ocupación Inmediata
P.D.8. NTP E.030 Inelástico - As built	0.0510	0.0067	7	Seguridad de Vida
P.D.9. NTP E.030 inelástico - Malla Electrosoldada	0.0500	0.0061	8	Seguridad de Vida

7. Analysis of Results

The vulnerability assessment, carried out using the FEMA P-154 methodology, reveals a worrying picture regarding the seismic resistance of the homes analyzed. An alarming 31% of the buildings present a risk of collapse greater than 50% in the event of an earthquake, which classifies them as highly vulnerable structures. Likewise, an additional 28% exhibit a moderate risk of collapse, ranging between 20% and 50%. Only the remaining 41% show a low risk of collapse, less than 20%.

Based on the results obtained in the performance design of the houses studied, and the unit price referring to the application of welded mesh reinforcements, the Cost-Benefit analysis of the reinforcement technique is carried out. Regarding the lateral load capacity, in house 16 there was an improvement of at least 1.45% up to 42.30% in the walls in the X direction, which was the only reinforced direction. While, in house 22, there was an increase in the contribution of 9.82% up to 187.26% in the X direction.

In terms of ductility, the deformation capacity of the reinforcement is very similar to that of the As Built house. The reinforcement improves the shear resistance in the X direction of house 22 by 1.62%. While in the Y direction, it improves by 1.50%. On the other hand, in house 16, an increase in capacity of 1.34% was obtained in the X direction, while in the Y direction, 2.99% of its initial capacity

The static and dynamic spectral structural analyses carried out in houses 16 and 22 reveal poor seismic performance in both buildings. In the case of house 22, 3 walls are identified that, under seismic action, would be subjected to shear forces greater than their resistant capacity, which would cause them to crack. On the other hand, in house 16, this situation occurs in 11 walls. As a reinforcement measure, the addition of electro-welded mesh to one side of the walls was proposed. This solution was effective in ensuring the shear-resistant capacity of all the walls of houses 22 and 16.

As a reinforcement measure, the addition of electro-welded mesh to one side of the walls was proposed. This solution was effective in ensuring the shear-resistant capacity of all the walls of house 22. However, in house 16, despite the significant improvement in the resistance of most of the walls, 9.52% of them still do not fully meet the design requirements. In these particular cases, improvements in the resistant capacity of at least 57.70% (wall X-1, floor 1) and up to 135% (wall Y-1, floor 2) will be observed.

The structural analyses carried out in houses 16 and 22, using the pushover method and the comparison with demand spectra, allow their seismic performance to be evaluated and classified according to the damage levels established in the ATC-40 regulations. On the one hand, the structure of house 22 presents a performance level classified as Damage Control (DS) in the limit states of P.D.3 and P.D.4. This indicates that, in the event of a design earthquake, moderate to severe structural damage could be expected, without compromising the safety of people. However, the damage caused would require considerable repairs and could affect the habitability of the house. On the other hand, the results obtained for house 16 show a performance level classified as Life Safety (LS) in the limit states of P.D.8 and P.D.9. This level indicates that the structure could suffer very severe structural damage in the event of a design earthquake, which could put the lives of the occupants at risk and would require extensive repairs or even the demolition of the house.

When comparing the drifts obtained before and after reinforcement, a significant reduction is observed in both houses. This result confirms that the reinforcement measures implemented have considerably improved the seismic behaviour of the structures, reducing the risk of damage and collapse in the event of seismic events.

8. Conclusion

The study reveals that according to the FEMA P-154 methodology, an alarming 31% of buildings present a risk of collapse greater than 50% in the event of an earthquake.

The presence of geometric irregularities in plan and elevation, such as incoming corners and out-of-plane setbacks, generate stress concentrations that compromise the structural integrity of buildings. These irregularities are particularly dangerous in seismic zones, as they can trigger complex and difficult-to-predict failure mechanisms.

The reinforcement proposal has proven to be effective in reducing the seismic vulnerability of houses 22 and 16, which were identified as the most critical according to the evaluation criteria of Benedetti Petrini and FEMA P-154. The results obtained support the application of this same strategy to the remaining houses in the complex, with the aim of optimizing their performance in the event of seismic events.

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