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Comparison of Seismic Performance Levels of Five-Story Limited Ductility and Confined Masonry Structures, Lima, Perú

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Abstract - This study evaluates the seismic behavior of a five-story multifamily building by comparing two structural systems: Limited Ductility Walls (LDW) and Confined Masonry Walls (CMW). The structural models were developed using Estera 3D software, and the analysis was carried out exclusively through nonlinear static analysis (pushover). Four levels of seismic demand were considered: frequent, occasional, design, and maximum earthquakes. Both systems achieved the same structural performance levels according to code-based criteria: full operation for the frequent earthquake; operation with minor damage for the occasional and design earthquakes; and life safety for the maximum earthquake. However, quantitative results show better performance for the LDW system. For the design earthquake, the LDW system exhibited a maximum base shear of 1141.36 tons and a top-level displacement of 7.098 cm, while the CMW system reached 2371.63 tons and 2.9696 cm, respectively. In terms of spectral acceleration, LDW registered 935.20 gal compared to 1098 gal for CMW. For the maximum earthquake, the LDW system reached a displacement of 10.68 cm and a base shear of 1272.15 tons, whereas the CMW system reached 8.0686 cm and 2291.71 tons. These results indicate that, although both systems meet the established performance objectives, the LDW system demonstrates more efficient structural behavior and greater energy dissipation capacity under severe seismic events.

***Keywords*:** Pushover analysis, seismic behavior, limited ductility walls, confined masonry walls, structural performance, Estera 3D, base shear, spectral displacement.

1. Introduction

The seismic behavior of a building depends on its stiffness, ductility, and the adopted structural system. In cities like Metropolitan Lima, where mid-rise multifamily buildings are predominant in high seismic hazard zones, it is essential to evaluate structural alternatives that ensure safety, economic efficiency, and good performance during severe earthquakes.

Confined masonry (CMW) has been widely used in Peru due to its low cost and ease of construction. However, it presents limitations in terms of ductility and energy dissipation capacity. In contrast, limited ductility walls (LDW), mainly used in reinforced concrete buildings, have recently been evaluated as a viable alternative for low-cost housing, offering a combination of stiffness and moderate deformability.

Several studies have addressed the structural analysis of these systems. Loa et al. [1] conducted a numerical study on LDW using finite element models and concluded that these walls exhibit drifts below the limits established by the Peruvian Technical Standard E.030, although their strength is compromised when those drifts are exceeded. Ortega et al. [2] also analyzed LDW and highlighted their ability to resist lateral and axial loads even without confining elements, associating the onset of failure with the drift level reached.

For confined masonry, Borah et al. [3] used empirical methods to determine the lateral behavior of the walls, observing that stiffness and compressive stresses significantly influence cracking. Acharya et al. [4], using finite element models, confirmed that CMW meets drift limits established by the codes, making it a technically and economically viable solution. Additionally, Borah et al. [5] evaluated the nonlinear behavior of the confining elements and found that steel yielding occurs at drift levels close to 0.5%.

In this context, the objective of the present study is to compare the seismic performance levels of a five-story multifamily building, using limited ductility walls and confined masonry walls as the primary structural systems. Unlike previous studies focused on linear or modal analyses, this research employs nonlinear static analysis (pushover) using STERA 3D software, which enables the generation of capacity-demand curves, performance levels, and failure mechanisms. This approach provides a more realistic understanding of structural behavior under severe seismic events and allows for the identification of advantages and limitations of each system for social housing buildings in Metropolitan Lima.

2. Tools and Method

2.1. Tools

The structural modeling and analysis were carried out using STERA 3D software. This program allows accurate simulation of structures and provides key data for seismic analysis, such as period, spectral acceleration, spectral displacement, participation factor, modal mass, and effective mass ratio.

2.2. Method

The methodology followed for determining the performance point included the following steps:

- Detailed nonlinear modeling in ESTERA 3D, incorporating the actual mechanical properties of the materials and the geometry of the wall. See Fig 1 and Fig 2.

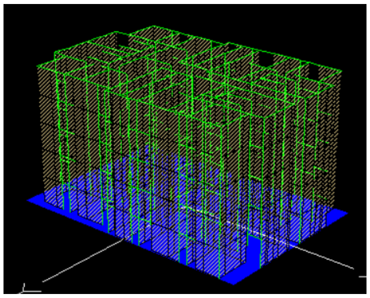

Fig. 1: CMW 3D model in STERA 3D

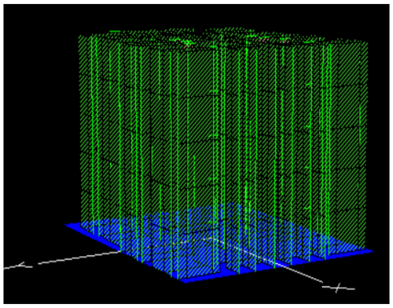

Fig. 2: LDW 3D model in STERA 3D

- Extraction of the model capacity curve (Sa vs. Sd). See Fig 3 and Fig 4.

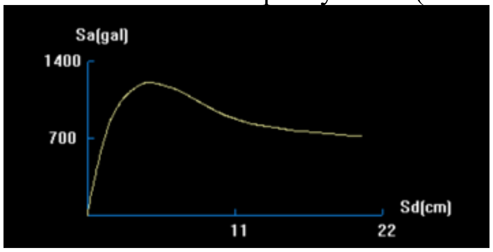

Fig. 3: STERA 3D CMW capacity curve

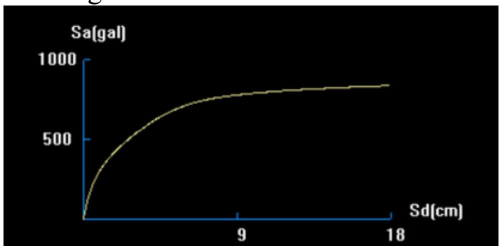

Fig. 4: STERA 3D LDW capacity curve

- Conversion of the capacity curve to spectral format (base shear vs. displacement) in the Acceleration - Displacement Response Spectrum (ADRS) format. See Fig 5.

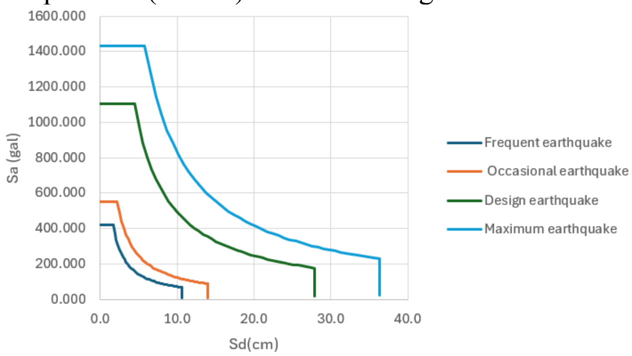

Fig. 5: Elastic response spectra - ADRS (R=1)

- Intersection with the capacity curve and the seismic spectra, whether frequent, occasional, design and maximum.

- Identification of the performance point, recording the displacement, shear force, and seismic performance level values.

3. Results and analysis of results

In this section, the results obtained from the structural analyses applying the nonlinear pushover analysis , according to the ATC 40 procedure [6] are presented. The data show the behavior of the modeled structural systems under seismic loading conditions, allowing to compare the responses between the different models.

3.1. CONFINED MASONRY STRUCTURAL SYSTEM

For the CMN system, there is the intersection of the demand spectrum and the capacity curve in ADRS format with the frequent, occasional, design and maximum period earthquakes, as shown in Fig 6.

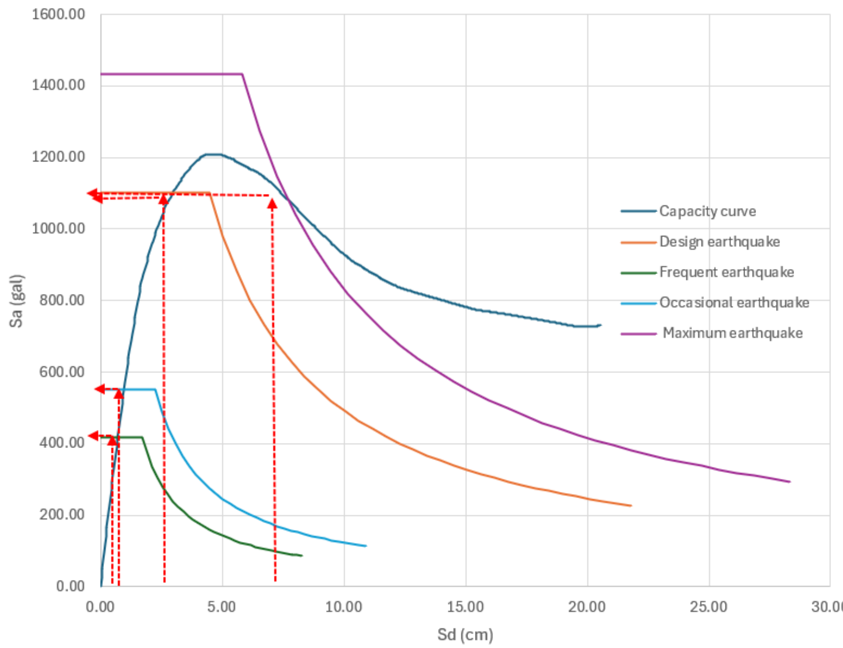

Fig. 6: Capacity curve and demand spectrum

With these intersections the performance point is determined, in terms of spectral displacement (cm) and spectral acceleration (gal), as shown in Table 1.

Table 1: CMW performance points

	Performance point	
Earthquakes	**Sd(cm)**	**Sa(gal)**
Frequent	0.700	413.300
Occasional	0.960	549.100
Design	2.938	1098.000
Maximum	7.990	1061.000

These points represent the structure's spectral response to different seismic demands. The Sa value (spectral acceleration) increases up to the design earthquake, and then decreases slightly at the peak earthquake, consistent with post-peak behavior where stiffness degradation predominates.

To estimate the structural displacements, the capacity curve expressed in terms of base shear and displacement is used. This procedure is based on the following formulas:

$$Sd = \frac{\Delta\, n}{\beta \times \emptyset_{1,n}} \qquad y \qquad Sa = \frac{Vo}{\propto}$$

Where:

- Sd= spectral shift (cm)
- Sa= pseudo acceleration (gal)
- β= modal participation factor
- ∝= modal mass
- $\emptyset_{1,n}$ = Amplitude at level n

Substituting the values into the indicated expressions, the capacity curve is obtained as a function of base shear and displacement. This relationship is presented in Fig 7.

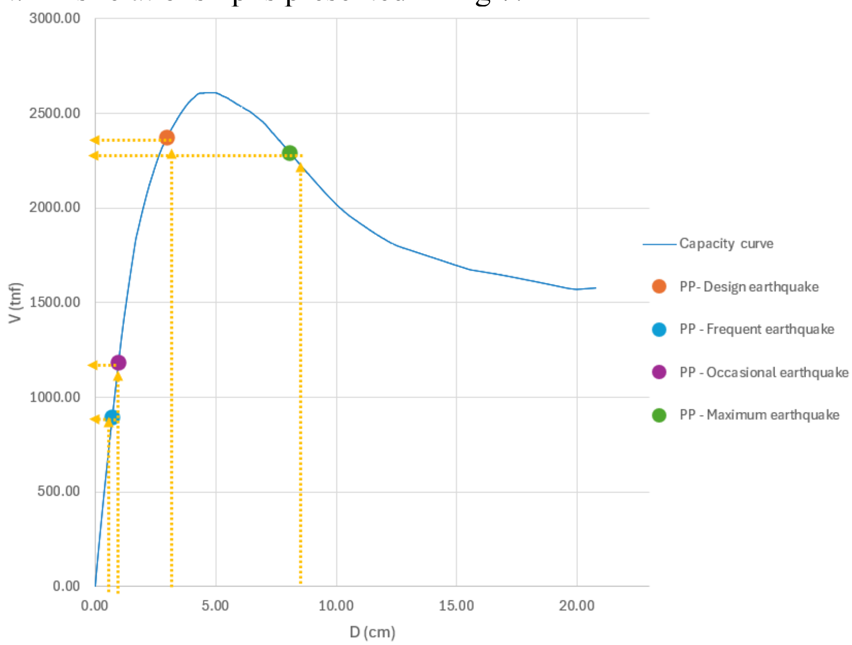

Fig. 7: Capacity curve and CMW performance point

Table 2 shows the displacement values at the top level of the structure (cm) and shear (ton).

Table 2: CMW performance points

	Performance point			
Earthquakes	**Sd(cm)**	**Sa(gal)**	**Δni (cm)**	**Voi (tonf)**
Frequent	0.700	413.300	70.688	892.711
Occasional	0.960	549.100	96.944	1186.033
Design	2.938	1098.000	296.689	2371.635
Maximum	7.990	1061.000	806.856	2291.716

As the severity of the earthquake increases, the displacement on the roof increases considerably, as expected. The maximum base shear also occurs during the design earthquake. Subsequently, for the maximum earthquake, although the displacement continues to increase, the shear decreases slightly, indicating inelastic behavior with a loss of load-bearing capacity.

The performance limits are then determined using the bilinear graph obtained using the equivalent area method. Table 3 presents the limit points corresponding to the different performance levels, as established by the SEAOC Vision 2000 document. The graphical representation of these levels is shown in Fig 8.

Table 3: Points for performance levels and distances on the CMW X axis

Zone	Range (cm)
Complete Operation	0.000- 0.849
Minor Damage Operation	0.849 - 6.823
Life Safety	6.823 - 12.797
Collapse Protection	12.797 -16.779
Collapse	16.779 - 20.762

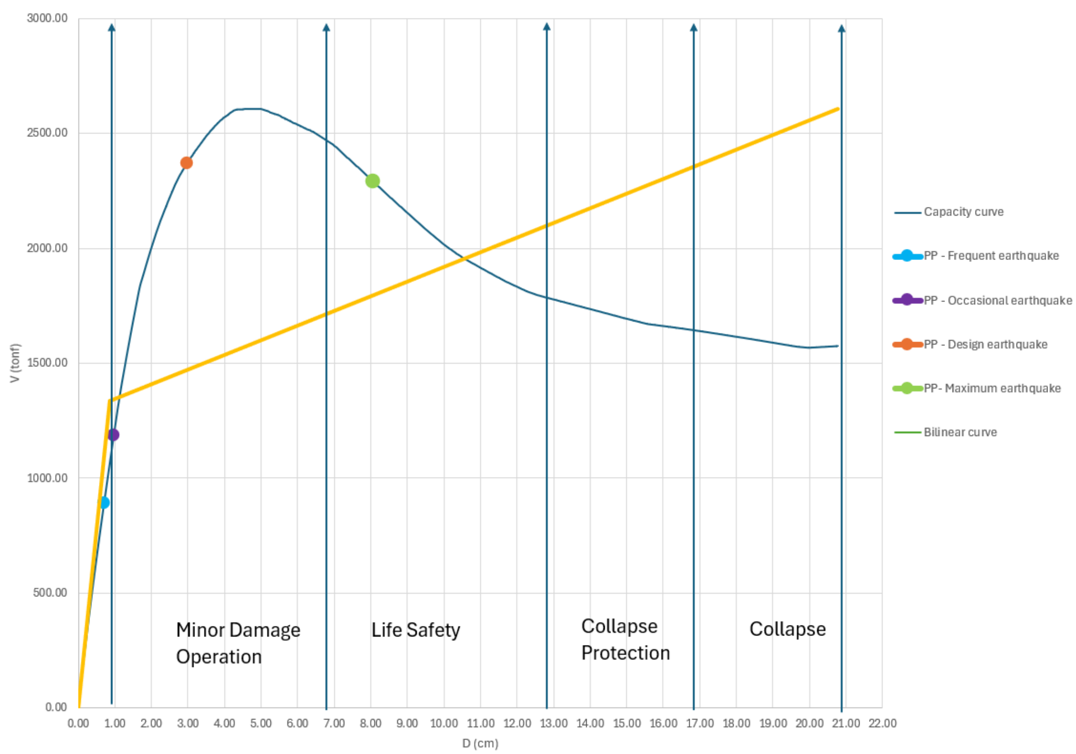

Fig. 8: SEAOC CMW performance limits

Based on the performance limits and seismic response points obtained, the performance levels corresponding to each seismic intensity level for the CMW are identified. The results are presented in Table 4.

Table 4: Building performance according to CMW seismic intensity

Earthquake	Complete operation	Minor damage operation	Life protection	Collapse protection	Performance objective
Frequent	X				OK
Occasional		X			OK
Design		X			OK
Maximum			X		OK

The CMW system meets the minimum performance objective required for each seismic level, according to Vision 2000. No structural collapse was observed under any seismic level. Furthermore, the transition between levels is progressive and expected, indicating acceptable ductile behavior despite the CMW system's inherent limitations under high demands.

3.2. LIMITED DUCTILITY WALLS

For the LDW system, after obtaining both the demand spectrum and the capacity curve in the ADRS (Acceleration-Displacement Response Spectrum) format, the two curves are superimposed. The point where they intersect corresponds to the structural performance point, which represents the limit state reached by the structure under the seismic action considered. This calculation is shown in Fig 9.

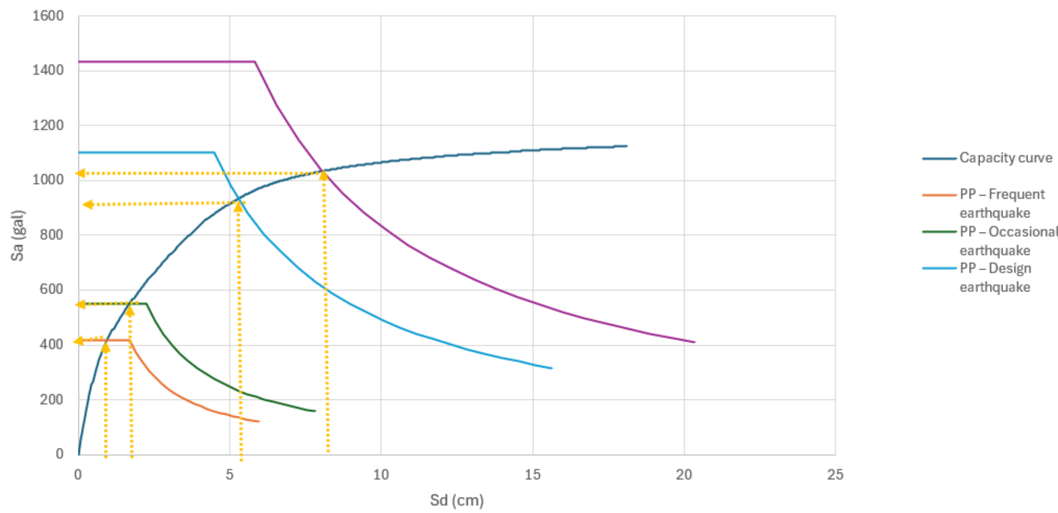

Fig. 9: Capacity curve and demand spectrum LDW

The performance points for each type of earthquake in terms of spectral displacement, indicating the maximum expected lateral displacement, and the spectral acceleration corresponding to the effective acceleration in that state, as shown in Table 5.

Table 5: LDW performance points

	Performance point	
Earthquakes	**Sd(cm)**	**Sa(gal)**
Frequent	0.955	418.950
Occasional	1.711	551.250
Design	5.310	935.200
Maximum	7.987	1042.364

A progressive increase in both parameters is observed with seismic severity, except at the maximum earthquake, where the acceleration stabilizes, which is consistent with a phase of inelastic response and possible structural degradation.

To calculate displacements in a structure with a LDW system, the capacity curve represented as a function of the base shear and displacement is used. To convert this information to the ADRS (Acceleration - Displacement Response Spectrum) format, the following equations are used:

$$Sd = \frac{\Delta\, n}{\beta \times\, \emptyset_{1,n}} \qquad y \qquad Sa = \frac{Vo}{\propto}$$

Where:

- Sd= spectral shift (cm)
- Sa= pseudo acceleration (gal)
- β= modal participation factor

- $\propto$= modal mass
- $\emptyset_{1,n}$ = Amplitude of the first vibration mode at level n
- Δn= Represents the displacement at the upper level of the structure (cm)
- Vo= Basal shear (Ton)

From this procedure, the capacity curve in terms of base shear and displacement is obtained, which is presented in Fig 10.

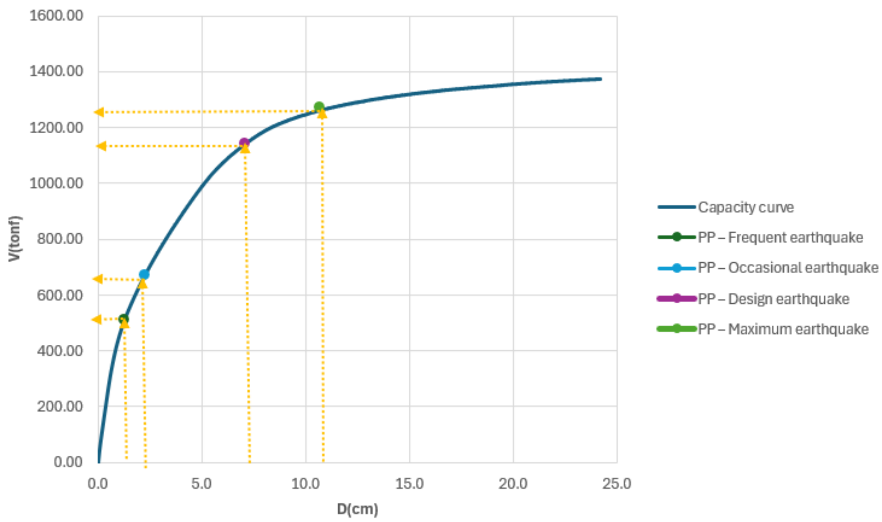

Fig. 10: Capacity curve and performance point LDW

By applying the previously described expressions, the performance point for the LDW system is obtained, resulting in a maximum displacement at the upper level of the structure of Δn = 7.0982 cm and a maximum base shear of Vo = 1141.36 tons, corresponding to the design earthquake. These values reflect, respectively, the maximum deformation reached at the top of the building and the maximum capacity of the system to resist lateral loads during said seismic event. The performance points associated with the different seismic intensities are summarized in Table 6.

Table 6: Displacement at the top level of the structure vs. shear in LDW

	Performance point			
Earthquakes	**Sd(cm)**	**Sa(gal)**	**Δni (cm)**	**Voi (tonf)**
Frequent	0.955	418.950	1.277	511.306
Occasional	1.711	551.250	2.287	672.771
Design	5.310	935.200	7.098	1141.362
Maximum	7.987	1042.364	10.677	1272.150

As seismic intensity increases, both the top displacement and the basal shear increase. The maximum basal shear is reached during the maximum earthquake, indicating greater lateral stress on the structural system. Furthermore, no significant loss of strength is observed, indicating good structural performance in the inelastic range.

The structural performance levels are defined below based on the bilinear curve constructed using the equivalent area method. Table 7 shows the threshold values for each performance level, in accordance with the criteria established by the SEAOC proposal in the Vision 2000 document. These thresholds are graphically represented in Fig11.

Table 7: Points for performance levels and distances on the LDW X axis

Zone	Range (cm)
Complete Operation	0.000 - 1.348
Minor Damage Operation	1.348 - 8.198
Life Safety	8.198 - 15.048
Collapse Protection	15.048 - 19.615
Collapse	19.615 - 24.182

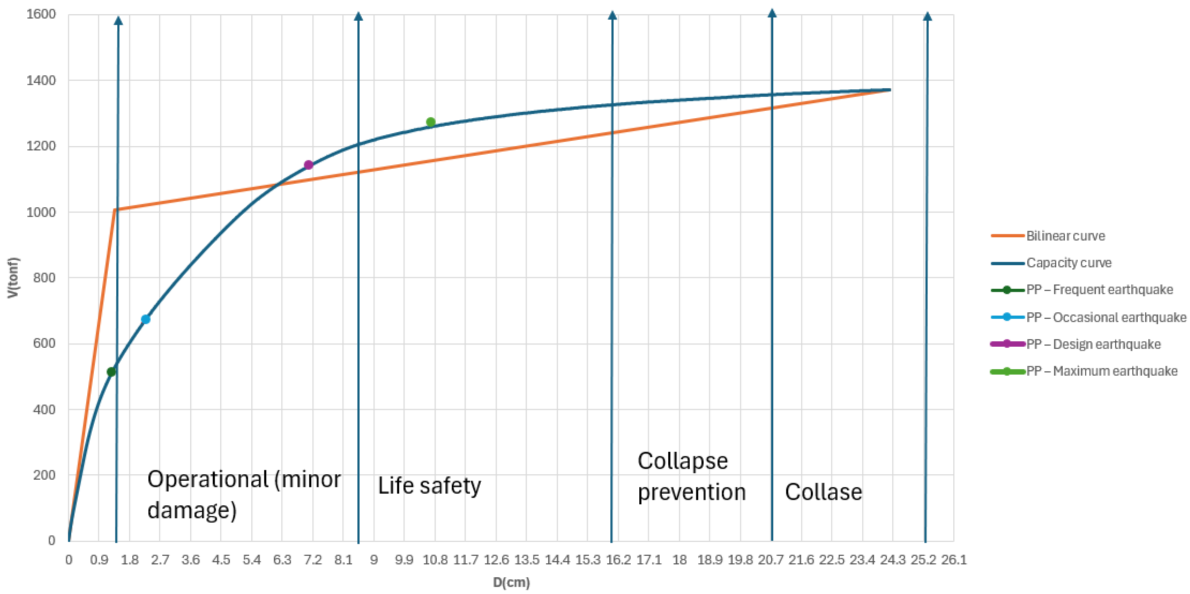

Fig. 11: SEAOC LDW performance limits

Based on the seismic performance points obtained and the limit values defined for each performance level, the behavior of the LDW structural system under different seismic intensities is evaluated. The results of this evaluation are detailed in Table 8.

Table 8: Building performance according to seismic intensity LDW

Earthquake	Complete operation	Minor damage operation	Life protection	Collapse protection	Performance objective
Frequent	X				OK
Occasional		X			OK
Design		X			OK
Maximum			X		OK

Building with the LDW system successfully meets the performance levels required by Vision 2000. No points of failure or collapse are identified under any seismic scenario. Furthermore, the progression between performance levels is consistent with a system that maintains its resilient capacity despite entering the nonlinear range.

3.3. Comparison of results analysis

The comparison between the structural systems of Limited Ductility Walls (LDW) and Confined Masonry (CMW) is based on the results obtained in the seismic performance analysis, considering the following main variables: spectral displacement (Sd), spectral acceleration (Sa), real displacement at the upper level (Δn), basal shear (Vo), and the level of damage reached according to the criteria of the Vision 2000 document [7], these comparisons are shown in Table (9),(10),(11).

3.3.1 Comparison of spectral shift (Sd) and spectral acceleration (Sa)

Table 9: Spectral shift and spectral acceleration in CMW and LDW

Earthquake	Sd LDW (cm)	Sd CMW (cm)	Sa LDW (gal)	Sa CMW (gal)
Frequent	0.96	0.7	418.95	413.3
Occasional	1.71	0.96	551.25	549.1
Design	5.31	2.94	935.2	1098.00
Maximum	7.99	7.99	1042.36	1061.00

The LDW system exhibits higher spectral displacements and accelerations, reflecting a greater capacity for deformation and energy dissipation, a characteristic typical of systems with more ductile behavior. The CMW system exhibits lower displacement demands, but this also reflects lower overall flexibility.

3.3. 2 Comparison of displacement at the upper level (∆n) and basal shear (Vo)

Table 10: Displacement at the top level and shear in CMN and LDW

Earthquake	∆n LDW (cm)	∆n CMW (cm)	Vo LDW (tonf)	Vo CMW (tonf)
Frequent	1.28	0.7069	511.31	892.7109
Occasional	2.29	0.9694	672.77	1186.0333
Design	7.1	2.9669	1141.36	2371.6347
Maximum	10.68	8.0686	1272.15	2291.7162

It is observed that buildings with a LDW system develop greater lateral displacements and higher base shear values, demonstrating its greater load-bearing capacity and ductility. In contrast, the CMW system presents lower displacements and stresses, which may be adequate for low-rise buildings, but reflects a more limited structural capacity in the event of severe seismic events.

3.3.2 Comparison of the level of performance achieved

Table 11: Performance level in CMW and LDW

Earthquake Level	Performance – LDW	Performance – CMW
Frequent	Completed Operation-	Completed Operation-
Occasional	Operation with Minor Damage	Operation with Minor Damage
Design	Operation with Minor Damage	Operation with Minor Damage
Maximum	Life Protection	Life Protection

Both the LDW and CMW structural systems meet the performance requirements established by the seismic performance-based approach (SEAOC Vision 2000) at all earthquake levels analyzed. However, although the performance levels are equivalent in name, the displacement, base shear, and strain values at the upper level show that the LDW system reaches these levels with greater resilience and structural reserve, while the CMW system operates closer to its resilience limits, especially at the maximum earthquake. This implies that:

- In an extreme earthquake scenario, the LDW system has additional leeway before compromising the overall stability of the structure.
- In contrast, the CMW system, while fulfilling its "life protection" objective, could experience greater material damage and require more significant interventions after a severe earthquake.

4. Conclusion

The analysis concludes that both structural systems, Limited Ductility Walls (LDW) and Confined Masonry (CMW), achieve the same level of structural performance under the four types of earthquakes considered. In both cases, the frequent earthquake corresponds to the full operational level; the occasional earthquake and the design earthquake correspond to operational levels with minor damage; and the maximum earthquake corresponds to life safety. This indicates that, from a regulatory perspective, both systems adequately meet the required safety levels.

However, when analyzing the quantitative results, it is evident that the CMW system presents higher basal shear values and lower displacements, reflecting greater stiffness, but also a lower energy dissipation capacity, which can translate into more fragile behavior.

For the design earthquake, the maximum base shear reached was 1,141.36 tons in the LDW system and 2,371.63 tons in the CMW system. Although the CMW system exhibits greater lateral resistance, the maximum displacement at the upper level was 7,098 cm in the LDW system and only 2,9696 cm in the CMW system, confirming its greater stiffness.

Regarding spectral displacement, in the design earthquake, the LDW system reached 5.31 cm, while the CMW system recorded 2.94 cm. Similarly, for spectral acceleration, the values were 935.20 gal for the LDW system and 1098 gal for the MAC, indicating that the LDW system has a better capacity to dampen the dynamic response.

For the maximum earthquake, the displacement at the upper level was 10.68 cm for the LDW system and 8.0686 cm for the CMW system. Regarding the base shear, the MDL system reached 1,272.15 tons, compared to 2,291.71 tons for the CMW system.

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