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Evaluation of Seismic Performance of Structural Concrete Walls through Linear Methods

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Abstract
The design of structural walls is an integral of the overall structural design process. Proper dimensioning and configuration play a crucial role in ensuring the strength and stability of a building, especially in regions with high seismic risk. Therefore, structural walls are widely employed in such countries. However, there are numerous methods to design and verify the behaviour of a structural wall, such the use of various calculation software applying pushover analysis, section cracking, equivalent inertia, and simulations. These methods are a better alternative than laboratory testing, they require less time and resources. The objective of this article is to provide design recommendations for different types of structural walls, following the guidelines outlined in the ACI 318 code. These wall types include concrete-steel composites, reinforced concrete, and veneer walls. The recommendations presented in this research article cover essential aspects such as material properties, reinforcement equivalences, and reduction factors. These factors are obtained through iterative structural analysis, ensuring reliable results, and preserving the structural integrity of the walls.

***Keywords*:** Seismic performance, structural concrete walls, seismic

1. Introduction

Structural concrete walls are widely used because they are capable of withstanding high seismic demands, preventing the collapse of buildings located in countries where earthquakes are common or those situated around the Pacific Ring of Fire. Countries such as Turkey, Chile, Mexico, Japan, the United States, Peru, Ecuador, among others, are recognized for their high seismic activity [1].

One of the aspects considered in the design of each structural wall is the seismic vulnerability to which the building is subjected, and in general, each wall must be capable of being ductile, avoiding a brittle failure. There are zones in the wall that dissipate the excess seismic energy, ensuring that the wall is not affected. Through current regulations, it is known which zones to place a reduced amount of steel, resulting in a reduction in the mechanical properties of the wall [2].

Nowadays, the design of a structural wall is very diverse, as are the calculation software used to verify and assess their performance. To guarantee reliable results from these programs, it is necessary to understand the correct data input methods, types of analysis, and correction factors that influence the mechanical properties of the materials used in reinforced concrete structures [3],[4].

Each test and contribution made emphasizes the importance of ductility in a structural wall. The lateral deflections of the wall must be controlled through good design, as this restricts the displacement of the building during an earthquake [5],[6],[7].

The objective of this research work is to analyse the seismic behaviour of different types of walls, particularly focusing on the influence of reinforcing steel distribution and the other related parameters. By employing structural evaluation software and conducting computational analysis, a comprehensive analysis of the lateral load-displacement response of each wall can be achieved.

2. Description Of Test Specimens

The following section describes the types of walls to be analyzed: Reinforced Concrete Wall (SW1) [8], Mixed Wall (SW2) [9] and Cladded Walls (SW3) [10].

All structural walls (SW)have a total width of 1 500 mm (including the headers) and a panel height that varies from 2 000 mm to 6 000 mm through iterations in 1 000 mm increments. However, SW1 and SW2 have a thickness of 150 mm, while wall 3 has a thickness of 80 mm without considering the thick concrete blocks for conservative analysis. In addition, a concrete strength $(f'c)$ of 22 MPa was considered, and for the calculation of the modulus of elasticity, the relationship $E = 12100\sqrt{(f'c)}\ [kg/cm^2]$ was used. For the reinforcing steel, a yield strength (fy) of 420 MPa was considered.

SW1 has concrete headers measuring 300x300mm with 8 rebars of 10 mm and a stirrup of 10 mm with a spacing of 60mm. It also has a core width of 900 mm with 2 longitudinal rebars of 8 mm spaced every 250 mm and 2 transverse rebars of 8 mm spaced every 270 mm. For lateral load distribution, a 300x300 mm beam is employed within the wall. For the reinforcing steel, a yield strength (fy) of 420 MPa was considered[8].

On the other hand, SW2 has metallic headers measuring 150x150x2 mm. Its core is confined with a longitudinal reinforcement of 4 rebars of 8 mm and stirrups of 8 mm spaced every 50 mm. Similarly, the rest of the core has a longitudinal reinforcement of 4 rebars of 8 mm and 2 transverse rebars of 8 mm spaced every 250 mm. For lateral load distribution, a metallic beam measuring 300x150x2 mm is employed within the wall [9].

Finally, SW3 has concrete headers measuring 200x200 mm, web thickness of 150mm including concrete block of 400x200x70mm, with 10 mm rebars and a stirrup of 8 mm spaced every 60 mm. For meshing, welded wire meshes measuring 150x150 mm with 4.5 mm rebars are used on both faces of the wall [10]. Fig. 1 shows the details of the cross section and Fig. 2 shows an elevation view, the dimensions are in milimeters. For the reinforcing steel, a yield strength (fy) of 600 MPa was considered.

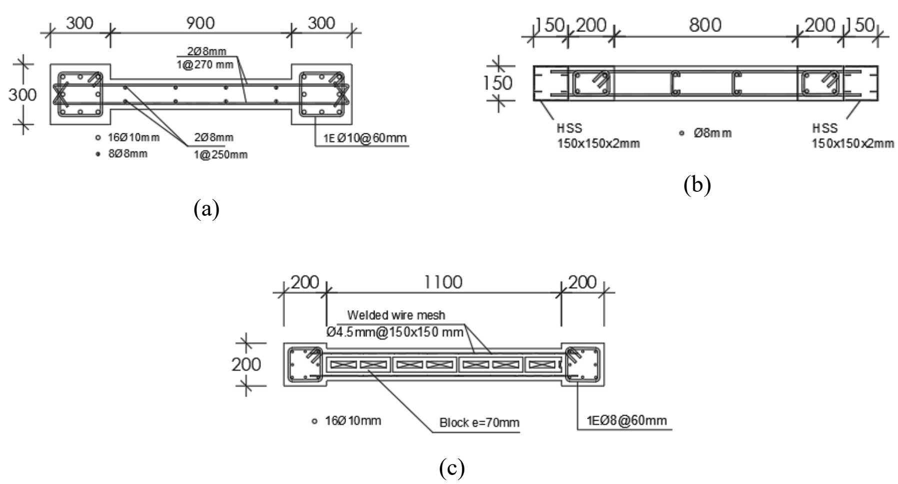


Fig. 1 Specimens cross section details: (a) SW1, (b) SW2, (c) SW3

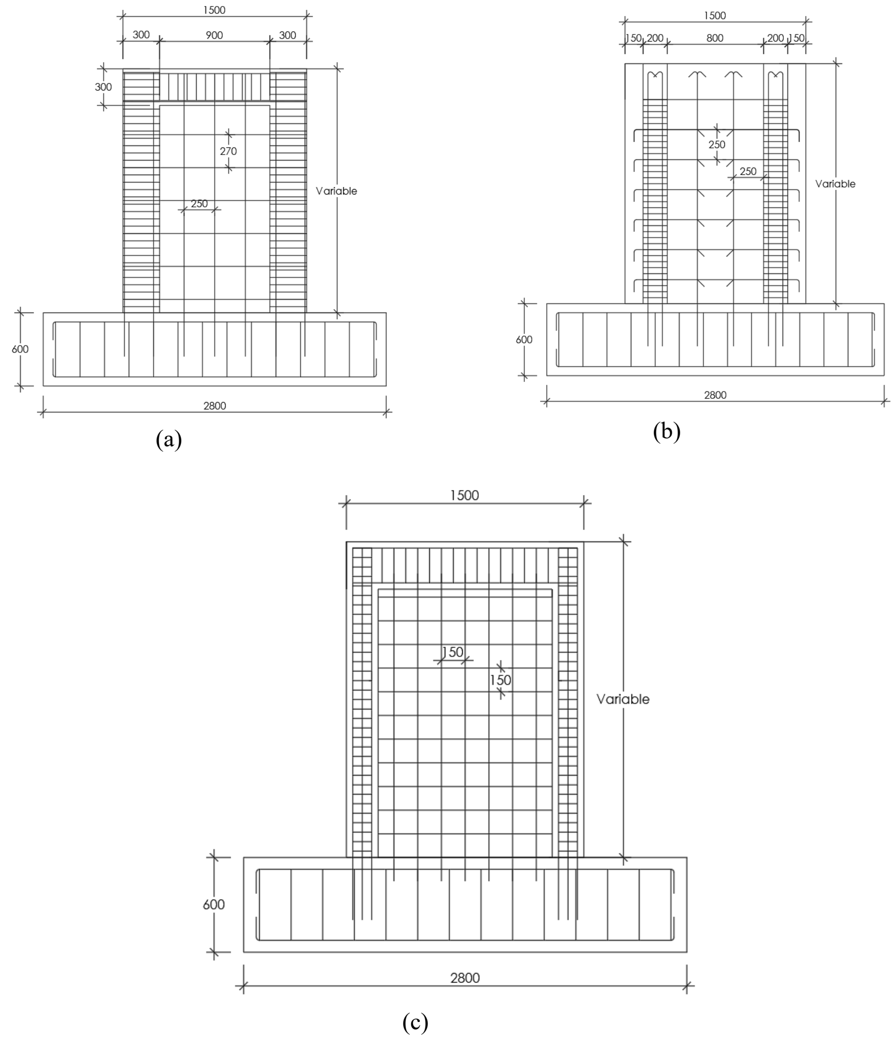


Fig. 2 Elevation view details: (a) SW1, (b) SW2, (c) SW3

3. Methodology

3.1 Experiment program

In this research work, numerous mathematical analyses were carried out using structural calculation software such as SeismoStruct and SAP2000 v 22.2.0, taking into consideration that the results from SAP2000 needed to be fine-tuned with the ones provided by SeismoStruct V2023.

Through tests and demonstrations performed in the SeismoStruct User Manual - examples, the software's great analytical capabilities are demonstrated by providing a response that closely approximates the real behaviour of a structure. The analysis involves both, linear and nonlinear methods, serving as a guide to achieving similar results using software such as SAP2000 by making a series of adjustments to parameters in its properties [11].

3.2 Materials

Table 1 Mechanical properties of materials

Specimens	Compressive Strength $f'c$ [MPa]	Elasticity Modulus E_c [MPa]	Yield point f_y [MPa]
SW1	21.5	18 123,3	420
SW2	21.5	18 123,3	420
SW3	21.5	18 123,3	600

The modulus of elasticity of concrete is a factor that determines how resilient concrete can be to loads and stresses generated. The factor described in the regulations is 15 $100\sqrt{(\boldsymbol{f'c})}$. However, this modulus of elasticity is achieved in the best possible conditions, meaning under optimal circumstances. Nevertheless, this matter was studied in Henry Alejandro's thesis (2014), which indicates that the modulus of elasticity factor ranges between 12 000 and 13 000. Therefore, it is decided to use 12 $100\sqrt{(\boldsymbol{f'c})}$.

3.3 Assignment of elements

In this case, a frame element is used, applying the wide column method. This method deduces that the lateral displacements of a structural wall can be accurately measured by considering deformations due to bending and shear. Additionally, the wide column method indicates that a wall can be idealized as a one-dimensional element with each of the wall properties acting along its centroidal line. This is why each of the presented walls is studied using this methodSoil characteristics [12].

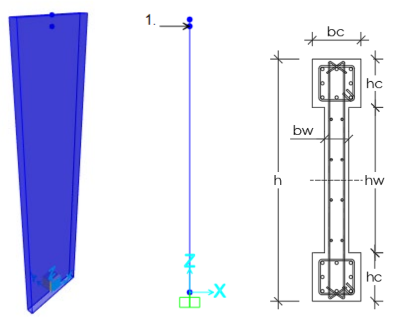


Fig. 3 Wall as column section- Frame Extrude.

As shown in Fig. 3, the wide column method has a peculiarity where it does not consider edge elements that are common in structural walls, their dimensions are only two, without considering their height: length and width. By calculating the moment of inertia of the wall in the force direction, it is possible to create a rectangular section with an equivalent thickness that preserves the same moment of inertia as the original wall. This is determined in equation 3.

$$I = \frac{b_c * {h_c}^3}{12} - \frac{(b_c - b_w) * {h_w}^3}{12} \quad (1)$$

$$I = \frac{b * h^3}{12} \quad (2)$$

$$b = \frac{I * 12}{h^3} \quad (3)$$

Where I, is the Inertia of the section in the sense of analysis, b_c, is the head width, h_c, head height, h_w, wall web height, b_w, web width, and b, the equivalent web width. The Table 2. Shows values obtained.

Table 2 Wall's characteristics

Specimen	h $[mm]$	b_c $[mm]$	h_c $[mm]$	h_w $[mm]$	b_w $[mm]$	b $[mm]$	I$[cm^4]$
SW1	1500	300	300	900	150	267,6	7.526 250
SW2	1500	150	150	1200	150	150	4.218 750
SW3	1500	200	200	1100	80	152,68	4.294 000

Regardless of the section of the wide column, the amount of original steel should not be altered, even in cases where the reinforcement ratio may be different due to the new equivalent dimensions of the wall. Therefore, calculate the total amount of steel corresponding to the wall in its original section, and establish a new number of bars to be assigned to the model, while ensuring that the original core is maintained by conserving the cover.

Such parameters are always maintained in each cross-sectional area of walls SW1, SW2, and SW3, with their sole variable being height, as they are evaluated at heights of 2 000, 3 000, 4 000, 5 000, and 6 000 mm to measure and compare the theoretical and experimental (Force vs. Displacement) relationship of each wall while their slenderness increases.

Table 3 Steel of the walls

Type	Wall	Wide Column		
	As_{long} $[cm^2]$	$\emptyset$ $[mm]$	n #	As_{long} $[cm^2]$
SW1	16,588	10	22	17,279
SW2	19,678	10	24	18,85
SW3	15,708	10	20	15,708

The parameters used in SAP2000 software for creating load cases are detailed in Table 4, where Gravitational Case No Lineal (CGNL) takes as an initial case the stresses and loads generated by its self-weight. On the other hand, the Static Analysis No Lineal (AENL) case starts from the analysis performed with its own weight and continues by applying a previously placed lateral load on a node of the mathematical model. This load is iteratively increased until the structure collapses.

Table 4 Nonlinear loads assignments

Load Case Name	CGNL	AENL
Load Case Type	Static	Static
Load Analysis Type	Nonlinear	Nonlinear
Initial Conditions	Zero initial Conditions – Start from Unestressed State	Continue from State at End of Nonlinear Case - CGNL
Modal Load Case	Modal	Modal
Load Applied	Load Pattern – DEAD – Factor (1.0)	Load Pattern – Lateral Force – Factor (1.0)

Load Application	Final Stage Only	Displacement Control – Use Monitored Displacement – [Value]`
Results Saved	Full Load – DOF U1 - # Joint Analysis	Multiple States – Min 10 – Max 100 – Save positive Displacement
Nonlinear Parameters	Default	Default
Geometric Nonlinearity Parameters	None	None
Mass Source	Previous	Previous

3.4 Plastic Hinge

Assign Frame Hinge is the tool that helps us place a plastic hinge within a structural element, which, based on the conducted research and iterations, is recommended to be positioned as close to the ground as possible [13].

To assign the plastic hinge point, it is necessary to determine where plasticization typically occurs in each structural element. This knowledge is gained through laboratory tests involving repetitive and incremental lateral loads, inducing fatigue and structural exhaustion, thereby revealing the areas that yield first. In the case of structural walls, this often occurs very close to the base, which is considered a relative or absolute measure of the wall's length. This is assigned in SAP2000, which operates with ASCE 41-13 standards, by the other hand in SeismoStruct this is automatically assigned.

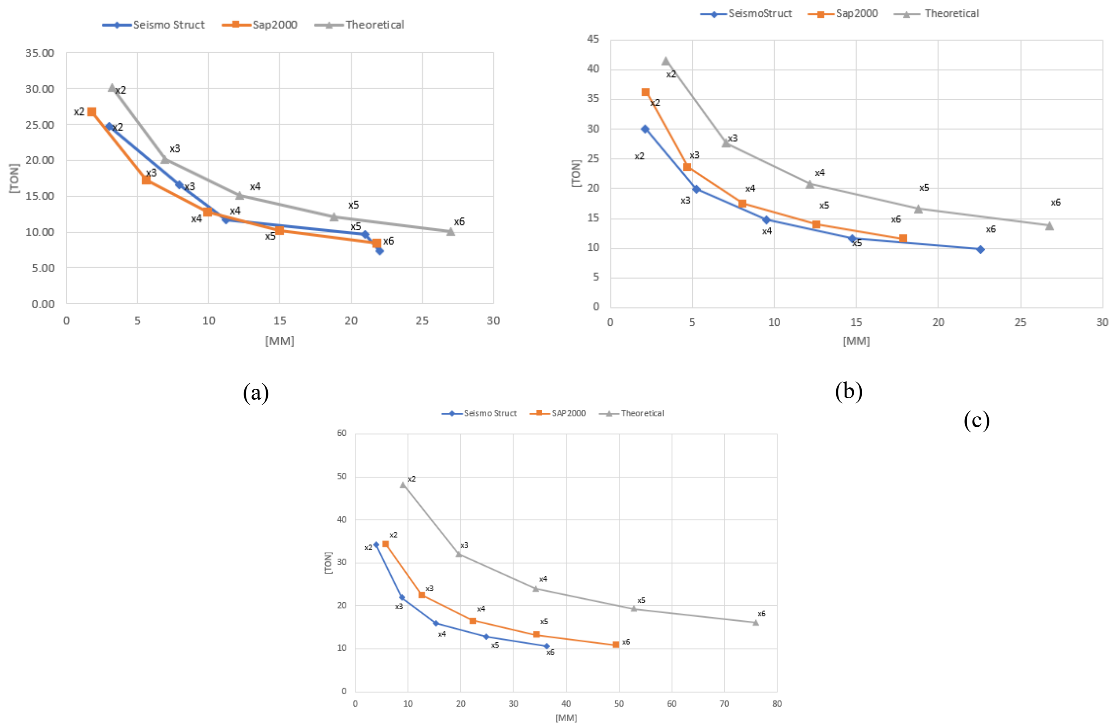
3.5 Elasticity Module and Cracking of Inertia

The inertia of the section is the property that mainly influences the resistance to lateral displacement of the structure. Therefore, when varying its geometric configuration, it can be affected. However, thanks to the method of the equivalent section, the inertia is guaranteed to be preserved. Additionally, the elasticity module was adjusted to $E = 12100\sqrt{f'c}\ [kg/cm^2]$ as the quality of the concrete cannot be ensured to meet the value given by ACI 318-19 of $E = 15100\sqrt{f'c}\ [kg/cm^2]$ [8].

3.6 Pushover

A pushover is a type of analysis used in structures to assess their performance under strong earthquakes. It is based on a nonlinear static analysis that involves pushing the structure to a certain height using an incrementally increasing load, resulting in corresponding increments in displacement. These increments continue until the structural element reaches failure, allowing for the determination of the maximum load capacity. The pushover analysis is widely used in earthquake-resistant engineering and is an important method for assessing structural behaviour under seismic conditions [14].

4. Results And Discussion



(a) (b) (c)

Fig. 5 Load vs. Displacement Curves: (a) SW1, (b) SW2, (c) SW3

In Fig. 5 a comparison can be observed between the results obtained using various types of analysis,

the following methods were employed: preserving the properties of each wall type, they were evaluated in both SAP2000 and SeismoStruct by performing a Pushover analysis and a cyclic loading simulation, respectively. From these analyses, maximum forces and displacements were obtained when the walls measured 2 000 mm, 3 000 mm, 4 000 mm, 5 000 mm, and 6 000 mm. This allows for cross-referencing with the results predicted by the theory.

For SW1, the results obtained from both SeismoStruct and Sap2000 software show great similarity, with a difference margin of 14% in force calculations and a difference of ±6mm (45%) in displacements, considering a reduction factor of 0.2 in inertia. When comparing the theoretical results, the structure is found to be much stiffer and capable of withstanding higher lateral loads.

For SW2, two types of steel were used, A36 steel with a yield strength of 2531 kg/cm2 and reinforcing steel with a yield strength of 4200 kg/cm2, with a relationship that the A36 steel has 60% of the yield strength of the reinforcing steel. This percentage was used to obtain an equivalent in steel bars. However, there is a 20% difference between the results obtained from SeismoStruct and Sap2000, which was reduced to 8% by considering a steel yield strength relationship of 50%. In terms of displacements, the difference is ±5mm (20%). Once again, it is observed that the theoretical calculations are higher than the iterative ones.

Finally, for SW3, which consists of central masonry and layers of reinforced concrete, a conservative approach was taken to consider only the contribution of concrete and welded mesh. The results from SeismoStruct and Sap 2000 show close agreement with a small error margin of 4.3% in load capacity, and a difference of ±4mm (45%) in displacements, considering a reduction factor of 0.3 in inertia. On the other hand, the theoretical calculations show significant differences, with forces and displacements containing unacceptable error margins exceeding 30%.

5. Summary And Conclusions

The modelling of the walls was successfully accomplished through the implementation of the wide column approach. This approach ensured the preservation of the mechanical properties while also observing a similarity in their seismic behaviour.

The calculated displacements approach each other when the wall's inertia is affected by a cracking coefficient ranging from 0.2 to 0.3, and a similar load capacity was obtained for each of the walls, with maximum error margins of 14%.

Reliable results were achieved concerning the load capacity and displacement of each wall by using the SAP2000 software. The analysis involved the application of factors and methods based on multiple iterations, considering the modeling and results from SeismoStruct as a basis.

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