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Evaluation of the Seismic Performance of a High-rise Building in Lima, Peru, Using the FEMA 440 and SEOAC Methodologies

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Abstract. This article develops two three-dimensional models: one for designing an 18-story building, considering the E030 and E060 norms of Peru, and a second nonlinear model aimed at estimating the lateral capacity of the structure through nonlinear static analysis and verification of seismic performance. It highlights the prevalence of informal structures in Peru, which lack a performance-based design methodology. In this context, relying solely on elastic design may be insufficient, especially for tall buildings. A "seismic gap" is identified, referring to the discrepancy between current design practices and the actual seismic demands that structures may face, raising concerns about the vulnerability of existing and future structures to a potential earthquake. The nonlinear static analysis showed that the 18-story structure reached a maximum base shear of 1752 tons and a maximum displacement of approximately 53 cm in the X direction, and similarly, a maximum base shear of 1538 tons and a maximum displacement of 51 cm in the Y direction.

Introduction

Tall reinforced concrete buildings present a significant challenge in seismic design due to their structural complexity and dynamic response to seismic events. In recent decades, various approaches have been developed to improve the seismic performance of these structures, ranging from the implementation of new materials to the refinement of analysis and design methods. In [1], the seismic performance of medium and high-rise buildings constructed with Engineered Cementitious Composites (ECC) was compared with conventional reinforced concrete (RC) structures. The results showed that the use of ECC allowed for a significant reduction in steel reinforcement and improved overall seismic performance, with increased lateral capacity and better cyclic response. On the other hand, [2] focused on the seismic response evaluation of a building with structural concrete walls and coupling slabs in Chile. The study revealed that the fundamental period of the building was 0.613 seconds, with a stiffness index of 67 m/s, classifying it as having normal stiffness. The elastic base shear obtained from the spectral response analysis in the transverse direction was 46,920 kN, equivalent to 45.9% of the seismic weight of the structure. In [3], a new approach was proposed to assess the residual service life of tall reinforced concrete buildings before and after rehabilitation. The presented case study showed that the residual service life of existing beams was 65.6 years, while columns exceeded 94.1 years. Additionally, it was found that story drift increased with the design service life, with seismic action being more influential than wind load after 35 years. An extensive study conducted in [4] on 30 existing reinforced concrete buildings in Turkey revealed that the average displacement ductility factor was 3.78 for frames and 3.28 for dual systems, values lower than those expected by the code. The ultimate displacement-to-total height ratio ($\delta u/H$) was approximately 1% for all buildings, while the yield displacement-to-total height ratio ($\delta y/H$) ranged between 0.2% and 0.3%. Regarding analysis methods, Mehmood et al. [5] evaluated the accuracy of the Uncoupled Modal Response History Analysis (UMRHA) method compared to the Nonlinear Response History Analysis (NLRHA) method for predicting the seismic response of tall buildings. The results showed average discrepancies of 12% for floor shear, 15% for floor moment, 18% for

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story drift ratio, and 19% for floor acceleration. Finally, Ren et al. [6] investigated the seismic behavior of tall buildings using composite steel-concrete columns and shear walls. The analyses revealed that the scheme with shear walls reinforced with steel plates (SPRSW) was generally the most effective in reducing deformations, especially in the lower floors. In this context, the present study focuses on evaluating the seismic performance of a tall reinforced concrete building using the criteria established by FEMA 440 and SEAOC.

Methodology

The main objective of this study is to analyze the seismic design of an 18-story reinforced concrete building in Lima, Peru, to enhance its structural strength and seismic response capacity. To achieve this, the specific goals are: (a) Develop accurate structural models, considering key elements such as columns, beams, and walls. (b) Evaluate the building's seismic response through nonlinear analysis. (c) Assess the seismic performance concerning design, service, and maximum considered earthquakes using FEMA 440 and SEAOC methods. The case study focuses on an 18-story building designed for multifamily residential use, located in Lima, Peru. The reinforced concrete structure has a modern and elegant design that harmoniously integrates with the urban environment of the city. Each floor houses spacious apartments with an average area of 160 m², carefully planned to provide comfort and functionality to residents.
Figure 1 shows the procedure followed in this investigation.

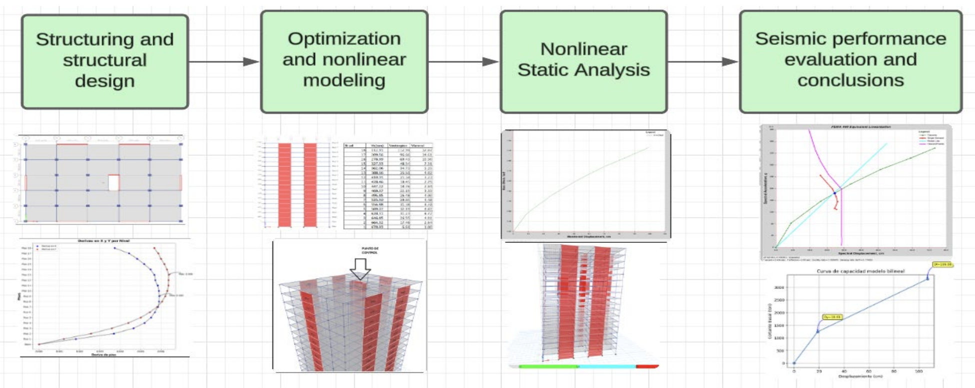

Fig. 1. Research flow chart.

Effective Reinforcement Provision. For Columns, the table 1 shows the column reinforcement used for the non-linear model.

Table 1. Reinforcing steel for reinforced concrete columns.

SECTION	MATERIAL	LOC.	STEEL	BAR DIAMETER (mm)	STEEL DISTRIBUTION
C(60x60) 1	Concrete 350 kgf/cm^2	A-5	A615 Grade 60	19 - 25.4	(0-14)/ 1/2“ @10cm
C(60x60) 2	Concrete 280 kgf/cm^2	A-5	A615 Grade 60	19 - 25.4	(0-14)/ 1/2“ @15cm
C(60x60) 3	Concrete 210 kgf/cm^2	A-5	A615 Grade 60	19 - 25.4	(10-4)/ 3/8“ @15cm
C(60x85) 1	Concrete 350 kgf/cm^2	C-5	A615 Grade 60	19 - 25.4	(0-14)/ 1/2“ @10cm
C(60x85) 2	Concrete 280 kgf/cm^2	C-5	A615 Grade 60	19 - 25.4	(0-14)/ 1/2“ @15cm
C(60x85) 3	Concrete 210 kgf/cm^2	C-5	A615 Grade 60	19 - 25.4	(10-4)/ 3/8“ @15cm
C(70x70) 1	Concrete 350 kgf/cm^2	B-5	A615 Grade 60	19 - 25.4	(0-14)/ 1/2“ @10cm
C(70x70) 2	Concrete 280 kgf/cm^2	B-5	A615 Grade 60	19 - 25.4	(0-14)/ 1/2“ @15cm
C(70x70) 3	Concrete 210 kgf/cm^2	B-5	A615 Grade 60	19 - 25.4	(10-4)/ 3/8“ @15cm

For Beams, the table 2 shows the beam reinforcement used for the non-linear model.

Table 2. Reinforcing steel for reinforced concrete beams.

SECTION	MATERIAL	LOC.	STEEL	BAR DIAMETER (mm)	STEEL DISTRIBUTION
V(30x45)	Concrete 210 kgf/cm^2	C-4	A615 Grade 60	19 - 25.4	Top(3-2) / Bottom(3-0)
V(30x50)	Concrete 210 kgf/cm^2	A-1	A615 Grade 60	19 - 25.4	Top(3-2) / Bottom(3-0)
V(30x60) A	Concrete 210 kgf/cm^2	A-5	A615 Grade 60	19 - 25.4	Top(3-2) / Bottom(3-0)
V(30x60) B	Concrete 280 kgf/cm^2	C-1	A615 Grade 60	19 - 25.4	Top(3-2) / Bottom(3-0)
V(30x60) C	Concrete 210 kgf/cm^2	A-2	A615 Grade 60	19 - 25.4	Top(3-2) / Bottom(3-0)
V(30x60) D	Concrete 210 kgf/cm^2	A-4	A615 Grade 60	19 - 25.4	Top(3-2) / Bottom(3-0)

For Walls, the table 3 shows the reinforcement steel for the walls located in Block 1 (first 3 levels) as only these levels enter the inelastic range.

Table 3. Reinforcing steel for reinforced concrete walls.

SECTION	MATERIAL	LOC.	STEEL	BAR DIAMETER (mm)	STEEL DISTRIBUTION
Wall T1	Concrete 280 kgf/cm^2	A-4	A615 Grade 60	9.5 - 25.4	(30-36) / 3/8“ @10cm
Wall T2	Concrete 280 kgf/cm^2	B-6	A615 Grade 60	9.5 - 19	(30-36) / 3/8“ @10cm
Wall TC	Concrete 280 kgf/cm^2	D-4	A615 Grade 60	9.5 - 19	(74-32) / 3/8“ @15cm

Analysis of Results

Figure 2 shows the capacity curves in the X and Y directions of a structure, revealing that the capacity in the X direction is greater than in the Y direction, as the blue curve reaches a higher base shear. The ultimate displacements are 53 cm in the X direction and 51 cm in the Y direction, indicating that the structure can displace more in the X direction before reaching its maximum capacity. Both curves exhibit an initially linear behavior followed by a nonlinear phase, typical of plastic deformations. In summary, the structure is more resistant and can displace more in the X direction, reflecting differences in structural stiffness and strength in each direction.

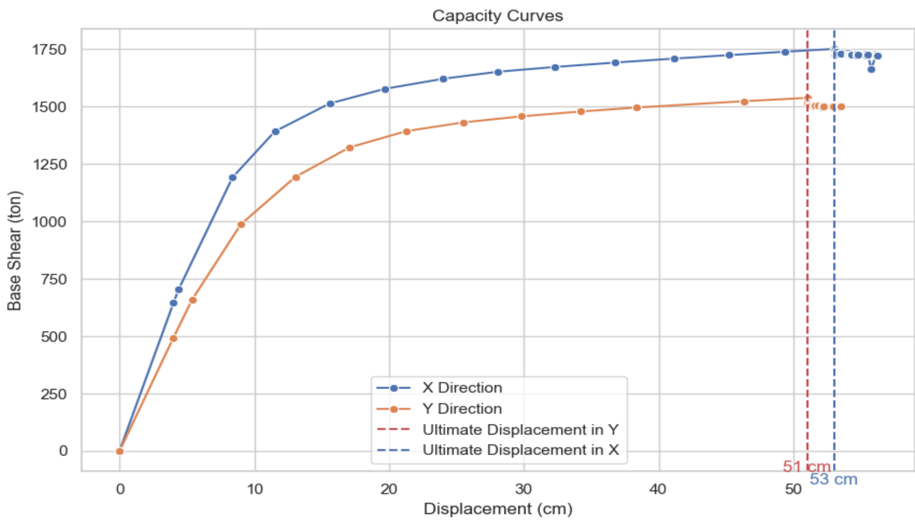

Fig. 2. Capacity curves in the X and Y direction.

To validate the obtained capacity curves, we compared our results with from [1], which present capacity curves for buildings with 3 to 8 stories in both directions. The general shapes, maximum base shear, and ultimate displacements are consistent. We verified characteristic parameters such as base shear capacity at yield and ultimate displacement, finding a good match. The base shear coefficients and ductility factors also reasonably match the values from the paper. The strength and stiffness in the X and Y directions of our analysis show similar trends and magnitudes to those in the paper. Finally, our nonlinear analysis methodology is consistent with that described in the paper, reinforcing the validity of our results.

Seismic Performance according to FEMA 440. Figure 3 illustrates the seismic performance of an 18-story structure in both X and Y directions, marking performance points for Moderate Earthquake (ME), Design Earthquake (DE), and Maximum Considered Earthquake (MCE). The curve shows that while the structure behaves near-elastically under ME, it transitions to highly nonlinear behavior under MCE. The capacity is similar in both directions but slightly better in Y. All performance points are below the ultimate spectral displacement, indicating a safety margin even under severe seismic scenarios. Nonlinear static analysis revealed that at a moderate earthquake (Step 4), the X-displacement was 11.52 cm, slightly above the expected 11.17 cm, but with a drift of 0.00365, below the international limit of 0.005. For the design earthquake (Step 7), the horizontal displacement was 24.00 cm, exceeding 22.18 cm, and the drift of 0.0071 was marginally above the Peruvian limit of 0.007. Under the maximum considered earthquake (Step 10), the displacement reached 36.78 cm, higher than 35.12 cm, with a drift of 0.0100. Despite these displacements, the structure remains safe, with the X-direction walls on the first level showing a demand-capacity ratio of 0.216, well below the critical limit of 1, indicating robust performance even under severe conditions.

"In this section, the guidelines outlined in the FEMA 440 standard[7] were followed."

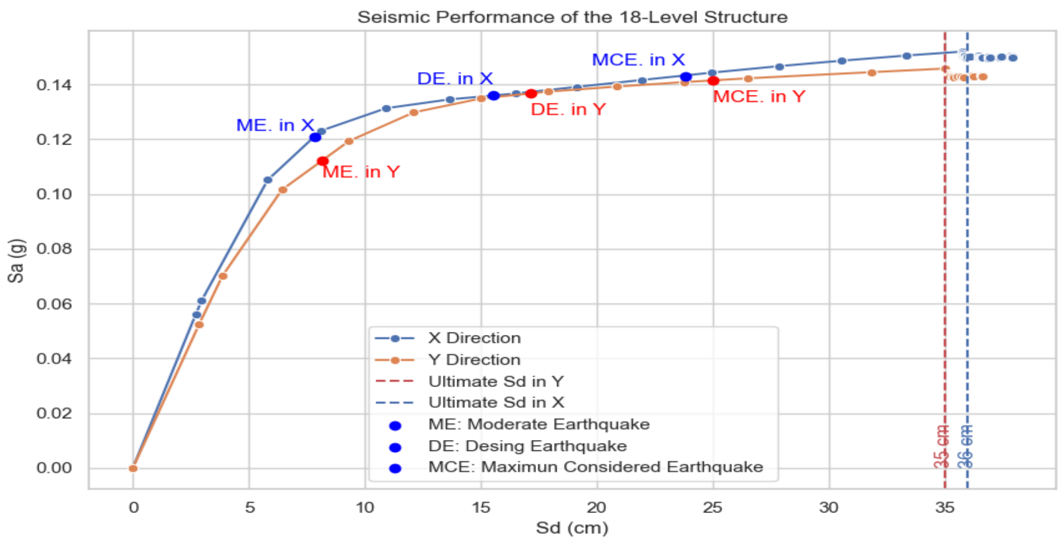

Fig. 3. Capacity Espectrum.

Seismic Performance according to SEAOC. The figure 4 shows a bilinear capacity curve for a structural model, illustrating the relationship between lateral displacement and base shear. The structural performance levels, from Immediate Occupancy (IO) to Collapse Prevention (CP), are color-coded. Three seismic performance points are highlighted: moderate earthquake (11.17 cm), design earthquake (22.18 cm), and maximum considered earthquake (35.12 cm). The curve features an initial elastic phase and a post-yield phase, with a maximum capacity of 52.80 cm and 1734 tons. The transition to nonlinear behavior occurs at 10.05 cm displacement, demonstrating the structure's ductility. This analysis is essential to understand structural behavior under different seismic intensities and evaluate its resistance capacity.

"In this section, the guidelines outlined in the SEAOC standard[8] were followed."

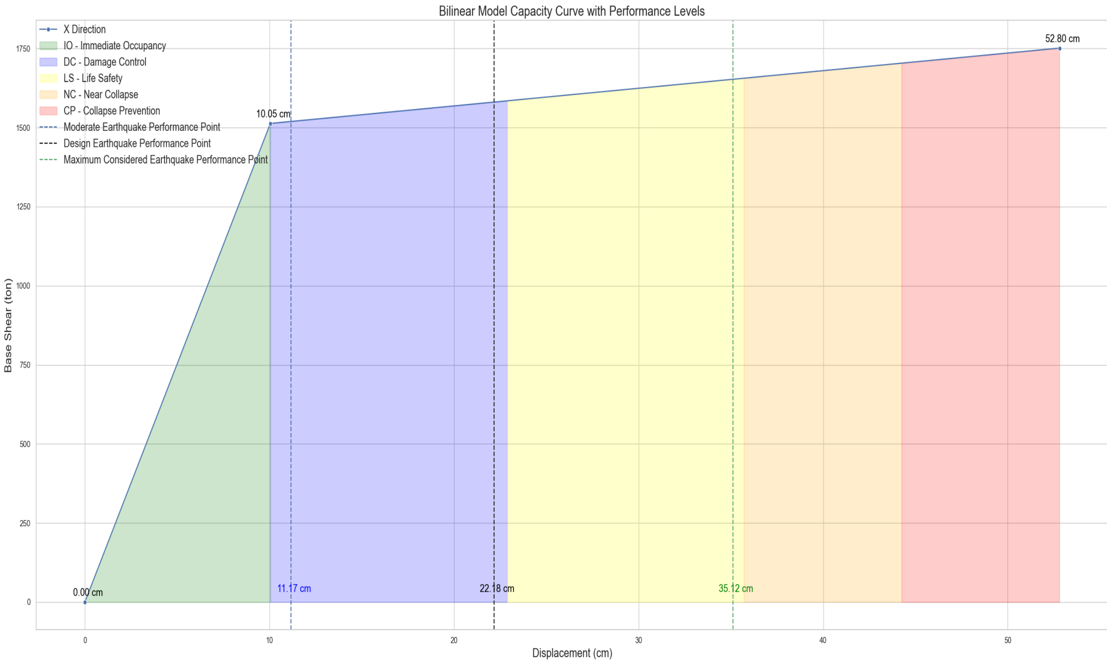

Fig. 4. Bilineal Model for SEAOC Methodology.

"The nonlinear analysis and the results presented, such as capacity curves, forces, displacements, and others, were obtained and calculated using the ETABS software[9]."

Conclusions

The 18-story building showed good structural behavior under moderate (ME) and design (DE) earthquakes, with horizontal displacements slightly exceeding expected values but within acceptable limits. For the maximum considered earthquake (MCE), although displacements were greater, the structure proved to be safe, with a demand-capacity ratio well below the critical limit, indicating robust performance even under severe conditions.

The analysis revealed a bilinear capacity curve illustrating the relationship between lateral displacement and base shear. The structure showed an initial elastic phase followed by a post-buckling phase, with a maximum capacity of 52.80 cm and 1734 tons. The transition to nonlinear behavior occurred at a displacement of 10.05 cm, demonstrating the structure's ductility.

Both methodologies were used to evaluate the building's seismic performance. The seismic performance points under different seismic intensities confirmed that the structure has adequate safety margins, even under severe seismic scenarios, supporting the validity of the nonlinear analysis methods employed.

Based on the results, the implementation of performance-based design methodologies is recommended to improve the seismic resilience of tall buildings in Peru. Incorporating nonlinear analyses in the design process can provide a better understanding of structural behavior under different seismic scenarios and help identify and mitigate potential vulnerabilities.
Furthermore, the analysis demonstrated that the baseline shear capacity and the structural displacements are consistent with values observed in previous studies, which supports the reliability of the models and methods used. The comparison with capacity curves from other studies showed a good match in terms of overall shape, maximum baseline shear capacity, and ultimate displacements.

Finally, the study highlights the importance of considering both local regulations and advancements in seismic design methodology to ensure the safety and durability of tall structures in high seismic activity areas. The adoption of innovative materials and advanced analysis techniques can significantly contribute to improving the seismic performance of buildings, thereby reducing the risk of damage and losses during seismic events.

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