

Original Article

Influence of Uncertainty in Concrete Compressive Strength on Structural Ductility

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Abstract - The occurrence of recent earthquakes has put in evidence, yet again, that reinforced concrete buildings are not as safe as thought. This circumstance is true, even in areas where there are seismic standards that have the purpose of guaranteeing that buildings are safe during earthquakes. Besides, this situation reveals the need for a better understanding of how factors, like the variability of concrete strength, can affect the performance of structures. On one hand, the strength of concrete is very important to consider in the occurrence of an earthquake because it can have an important effect on how a building responds to these kinds of loads. This study observes the changes in the strength of concrete, and also analyzes how ductile mid-rise reinforced concrete buildings are, because these types of buildings are common in the Peruvian city landscape. With the aim of attaining the objectives of this research, a four-story model was first created and later analyzed. This model was thoroughly analyzed in four different concrete scenarios with different strengths: 21, 28, 35, and 42 MPa. In order to execute these analyses, it was necessary to do three things: to create the capacity curves, to identify the yield and ultimate displacements, and to calculate ductility as the ratio of the two. The outcomes evidenced that as the concrete strength increased, the building's base shear capacity also increased, but by about 4.4%. To be more specific, the pressure increased from 360 tons at 21 MPa to 376 tons at 42 MPa, but this strength rise also made the material 28% less flexible. This circumstance means that the material could not deform or absorb energy as easily during an earthquake. In short, stiffer concrete can make structures stronger, but it can also make them less ductile. This situation makes them more likely to fail during earthquakes. This study exhibits how material quality affects the performance of structures against earthquakes. This research also provides important information that can be used with the objective of improving building design, quality control, and planning structural reinforcements in areas where earthquakes are common. One important thing to mention is that the analysis looked at a regular, average-height model. Hence, in the future, irregular structures and the use of probabilistic methods ought to be studied with the objective of making these findings more relevant.

Keywords - Capacity Curve, Plastic Hinges, Seac Vision 2000, Nonlinear Static Analysis.

1. Introduction

The occurrence of recent earthquakes, like the one that happened in Kahramanmaraş in Turkey in 2023, has evidenced, once again, the risks that reinforced concrete buildings still have, even in areas with modern seismic design codes [1, 2]. These natural disasters reveal an important problem: when infrastructure is damaged or collapses, a lot of human and economic losses are often caused [3, 4]. Figure 1 depicts the damage that reinforced concrete buildings withstood during the earthquake. Besides, it is necessary to point out that reinforced concrete is still the most commonly utilized structural system in the world, which implies the importance of ensuring that this material can resist the forces caused by earthquakes. Also, researchers are studying why major earthquakes do not behave as expected. As a

consequence, they want to know what causes structures to respond the way they do, and one of the most important aspects they are studying is the quality of the materials, especially the ones that affect the concrete strength.



Fig. 1 Damage observed in reinforced concrete buildings during the Kahramanmaraş earthquake sequence, Turkey (2023).
(1a) Collapsed building in the city of Harim, Syria, near the border with Turkey—(1b) Debris from collapsed buildings in Kahramanmaraş, near the earthquake epicenter



The aim of the investigation is to analyze how the natural changes in strong concrete, which are common in real construction situations, directly affect the safety of a building. Besides, while building codes determine minimum standards, the reality is that they are usually neglected; one clear example of this is when the employed material may not comply with the required compressive strength or other properties [7]. This circumstance of choosing the wrong material can have a big impact on the stiffness, ductility, and the ability to absorb energy of a structure, weakening its resistance to earthquakes [8]. Additionally, it is very important to understand how strong these buildings are in different situations because this information can be used to make better building plans, improve quality control, and support effective repairing strategies, especially in cities that have a large population where there is a risk of earthquakes [2, 9–12].

Contemporary investigations on the seismic resistance of reinforced concrete buildings are generally classified into these three categories: nonlinear performance-based analysis, data-driven prediction methods, and research on structural typologies and seismic protection systems. Additionally, earthquake engineering has thrived in recent years because it has evolved toward more advanced assessment techniques that permit overcoming the limitations of linear elastic analysis. Seismic design based on performance is a design that employs methods like static pushover and time history analysis, and it is now a common and practical way to evaluate how well structures can resist seismic forces [13–15]. At the same time, new technologies, like machine learning, have been utilized with the aim of improving the prediction of seismic demand, expected damage, and basic vibration periods of buildings [16–19]. Other investigations have explored the influence of specific building designs, nonstructural elements, and the means for earthquake protection on the behavior of buildings, and how these factors influence it. These investigations have exposed not only how well energy dissipation devices and seismic isolation work, but they have also revealed the impact of masonry infill walls and irregular configurations (such as soft stories or hillside construction) on load distribution and overall vulnerability. Furthermore, the results of the numerical simulations performed on mid- and high-rise buildings have provided valuable information on dynamic performance; these outcomes help in the atomization of both the design practices and the retrofit solutions [20–26].

Even though there have been big advances in the way research is done, there are no studies that look at how things like concrete compressive strength variability affect important nonlinear seismic performance parameters in a step-by-step way. Some recent studies have used probabilistic pushover analysis to evaluate the seismic capacity of particular structural designs under various loading conditions. Machine learning techniques have also facilitated more precise estimates of fundamental periods in reinforced concrete buildings. This has enabled better assessments of how material

variability influences dynamic response and vulnerability [27, 28]. However, many studies still focus on assessing damage after an earthquake or how things slowly get worse over time. These studies show the consequences of poor construction quality, but they do not explicitly model how this affects how things perform over time. There are not many studies that directly link changes in how strong concrete is under pressure (f_c) to how flexible it is, how the capacity curve changes over time, and when plastic hinges appear. These are all important factors in assessing how well a building can withstand earthquake events.

The main purpose of this current research is to employ the nonlinear static analysis with the objective of understanding how uncertainty in concrete compressive strength affects the ductility of reinforced concrete buildings. This investigation is dissimilar from previous research, given the fact that this paper focuses on compressive strength (which is the main variable that affects the behavior of the curve), on the flexibility of the duct, and on the formation of a plastic hinge. The most important contribution of this paper is that it clearly and physically demonstrates how the quality of the employed material affects the ease with which it fails during the occurrence of an earthquake. This study provides practical tools to support performance-based assessment, structural design, and seismic retrofitting of reinforced concrete buildings. Likewise, this research employs a special kind of computer program with the objective of studying how uncertainty in materials affects structures.

2. Materials and Methods

The structural ductility of a reinforced concrete building was evaluated in this research paper; this evaluation was conducted through the analysis of the influence of material uncertainty on the concrete's compressive strength. With the purpose of achieving the objectives of this investigation, different scenarios had to be created with the aim of exposing the changes in the quality of the material. Additionally, nonlinear static analyses were executed with the objective of getting capacity curves and key ductility-related parameters, such as the initial stiffness, the maximum base shear, and the ratio between ultimate and yield displacements. The process involved the creation of a structural model where different strengths of the concrete were assigned, and the results across different scenarios were systematically compared as well. This process was carried out with the aim of comprehending how changes in material properties affect ductility.

2.1. Structural Configuration

To analyze this, a typical reinforced concrete residential building model was used. This model is representative of common construction practices in highly seismic urban areas of Peru. This structural typology is chosen to create a realistic picture of how buildings usually behave in engineering. This lets the study focus specifically on how the variability in concrete properties affects the main variable of interest.

2.1.1. Inclusion Criteria

The structural model is like a reinforced concrete building with a regular layout in its plan and elevation. This condition was chosen to get rid of the effects of geometric irregularities and make sure that the analysis focuses only on material uncertainty. Figure 2 shows a bird's-eye view of the building that was used as the study model.

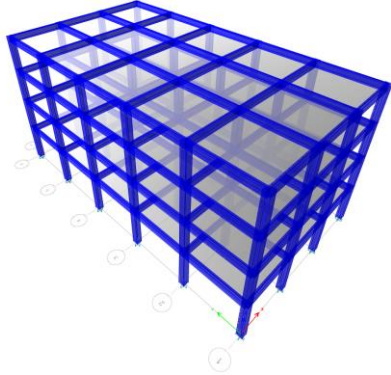


Fig. 2 Geometric configuration of the structural model used in the analysis

The design was developed following the rules of the Peruvian Technical Building Standard E.060 Reinforced Concrete [29] and the Standard E.030 Seismic Resistant Design [30]. This makes sure that the model is technically valid and follows the current Peruvian regulations.

2.1.2. Description of the Building Model

The model shows a four-story Reinforced Concrete building designed for people to live in. Each floor is 3.0 meters tall, but the first floor is 3.5 meters tall. The building has three 4.50-meter spans in the X direction and five 5.0-meter spans in the Y direction. This creates a regular pattern in the building's layout. The building's structure includes strong, reinforced concrete frames that resist the forces that make buildings collapse. The floor slabs are 20 centimeters thick. They are lightweight, and they are a common construction method in local residential buildings.

The definition of gravity loads was based on Standard E.020 Loads [31]. For the 20-centimeter-thick, lightweight slabs, a self-weight of 300 kilograms per square meter was considered, based on a unit weight of 2400 kilograms per square meter for concrete. An extra 100 kilograms per square meter was added for architectural finishes. A load of 150 kilograms per square meter on each partition was put with the purpose of representing the weight of the inside walls, following the advice of the experts [32]. Finally, a live load of 200 kgf/m² was included for residential use.

Figure 3 shows the overall structure of the model, including where the beams and columns are placed. The columns were designed with square cross-sections that are 55 centimeters by 55 centimeters. This is similar to the sizes used in mid-rise residential buildings. Table 1 shows the details of

the longitudinal and transverse column reinforcement. Table 2 shows the beam reinforcement specifications in summary.

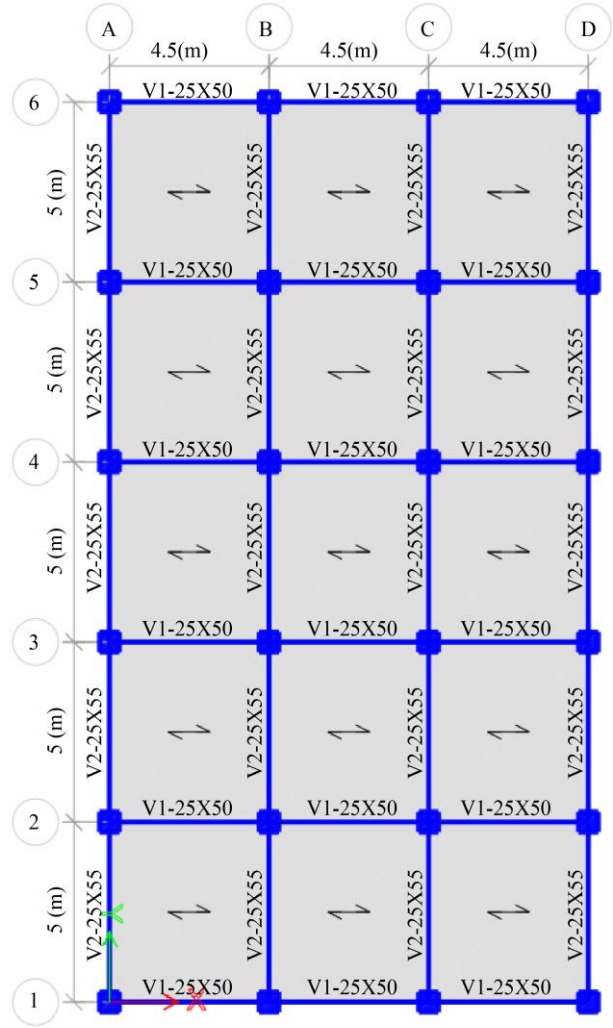


Fig. 3 Plan layout of the structural model and beam section labels

Table 1. Details of longitudinal and transverse reinforcement adopted in 55 x 55 cm column sections

C55x55	
Longitudinal Reinforcement	Transverse Reinforcement
<p>•12φ 3/4"</p>	<p>□φ 3/8 1@0.05, 5@10, R@25</p>

Table 2. Details of longitudinal reinforcement adopted in the beams of the structural model

V1-25X50	
Left	Right
<p>.50 .25 •6φ 5/8"</p>	<p>.50 .25 •6φ 5/8"</p>
V2-25X50	
Left	Right
<p>.50 .25 •8φ 5/8"</p>	<p>.50 .25 •8φ 5/8"</p>

2.2. Analytical Modeling

The analysis was performed using ETABS software, which is commonly used in structural engineering for the simulation of reinforced concrete buildings. This tool allowed the incorporation of nonlinear behavior through the definition of plastic hinges and the generation of capacity curves. This enabled a realistic evaluation of seismic behavior [33].

2.2.1. Modeling of Beams and Columns

The numerical model was developed following the code criteria and considering the concrete property variation scenarios defined in the study. This was done in accordance with the guidelines proposed in Nonlinear Structural Analysis for Seismic Design [34]. To show how rapid transitions in structural state can occur, plastic hinges were added to beams and columns. The idealized plans for this are shown in Figure 4. Model "a" was used for beams, and model "d" was used for columns.

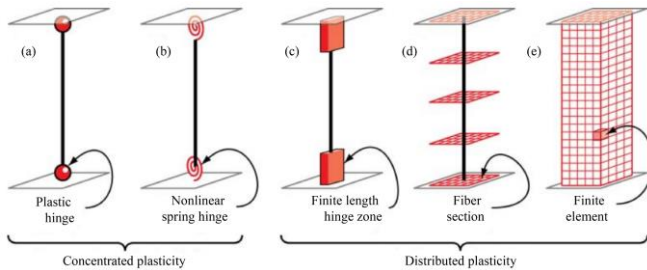


Fig. 4 Idealized models of beam-column elements

2.2.2. Modeling of Floor Slabs

The floor slabs were modeled as membrane-type elements, which allowed for the adequate representation of

their capacity to transmit gravitational loads without adding flexural stiffness [32]. At each level, a rigid diaphragm was used to simulate how the floors would behave as a whole and ensure that forces were correctly distributed to the frames. This simplification is appropriate for buildings with regular geometry. It allows the analysis to focus on material uncertainty, avoiding biases caused by geometric or modeling irregularities.

2.2.3. Modeling of Material Nonlinearity

The nonlinearity of reinforced concrete was incorporated by defining plastic hinges in beams and columns. This was done by following the guidelines of FEMA 356 [35] and ASCE 41 [36] for evaluating seismic performance. These hinges were placed at the ends of the structural elements. This allowed the representation of the initiation and propagation of plastic deformation. It also allowed the representation of the progressive degradation of stiffness and strength.

To show what could happen, the consideration of different concrete compressive strength scenarios was needed. These scenarios show the uncertainty that is part of construction. Table 3 shows the values used in each scenario, along with the mechanical properties that were derived, such as the modulus of elasticity and indirect tensile strength. These differences allowed us to see how the quality of the materials affected the structure as a whole.

Table 3. Mechanical properties of concrete in the different analysis scenarios

Scenario	f'c (MPa)	E c (MPa)
1	21	21,500
2	28	24,900
3	35	27,800
4	42	30,400

2.3. Case Studies and Analysis Variables

The analysis was performed using the concrete compressive strength scenarios summarized in Table 3. The building geometry, structural system, and loading conditions were kept constant. This approach was used to make sure that the results show only the effect of how different materials can vary, and not the effect of other possible variables.

The main purpose of this research is to study how much the structure can bend. The results were unraveled by looking at the capacity curves that are created through nonlinear static analyses. The ductility was determined by the relationship between the ultimate displacement (Δu) and the yield displacement (Δy), as shown in Equation 1.

$$\mu = \frac{\Delta u}{\Delta y} \tag{1}$$

Figure 5 shows the steps for identifying the parameters that define the overall ductility of the structure. Also, the process of how the plastic hinges formed in the beams and columns was recorded. This information can help us understand why the building might have collapsed.

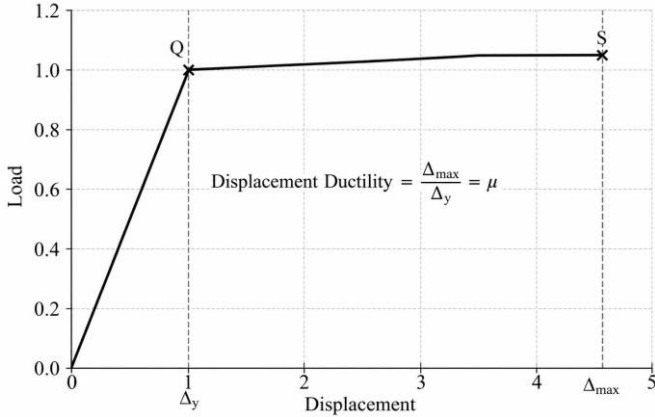


Fig. 5 Idealized Capacity Curve and Definition of Structural Ductility

2.4. Performance and Analysis Control Criteria

Nonlinear static analysis was controlled by monitoring the lateral displacement at the roof level, which was designated as the primary node. This parameter allowed us to track how the capacity curve progressed until it reached one of the limit states defined in ASCE 41 [36]. These include the formation of a global collapse mechanism, loss of numerical convergence, or a maximum displacement equal to 4% of the total building height.

The performance levels of the structure were divided into three categories. The Immediate Occupancy (IO) level is when there are small differences between floors, and the first plastic hinges start to form. The Life Safety (LS) level is associated with a moderate need for flexibility and the widespread development of hinges in beams and columns. The Collapse Prevention (CP) level is marked by a big decrease in stiffness and strength, as well as the possibility of losing overall stability.

To go along with the analysis control, the process of plastic hinge formation in beams and columns was closely watched. This made sure that the observed failure patterns matched the expectations from a ductile structure. It also confirmed that the structural ductility assessment was done under conditions that were both technically sound and representative.

3. Results

Nonlinear static analysis allowed us to create capacity curves for each concrete compressive strength scenario. These curves were employed with the purpose of determining important structural ductility parameters, like yield displacement, ultimate displacement, and their relationship. The results showed that the structure's initial stiffness, ultimate strength, and ability to withstand deformation without failing depend on the quality of the material used. To make the findings easy to understand, the capacity curves are shown in a comparative format, followed by the ductility values and related parameters for each scenario that was analyzed.

3.1. Capacity Curves

Figure 6 shows the capacity curves for the 21, 28, 35, and 42 MPa scenarios. In all cases, the behavior is roughly linear at first. It reaches a point where it cannot change anymore, and then it becomes inelastic. In this phase, the structure becomes very resistant and starts to break down a little.

The results show that the system gets stronger as the concrete quality improves. It can hold about 360 tons at 21 MPa, 368 tons at 28 MPa, 373 tons at 35 MPa, and 376 tons at 42 MPa. However, the total displacement was almost 0.28 m in all cases, while the yield displacement decreased from 0.034 m to 0.024 m between the 21 MPa and 42 MPa scenarios. This trend shows that, while lateral strength increases with f_c , overall ductility decreases because there is a reduced range of inelastic deformation available.

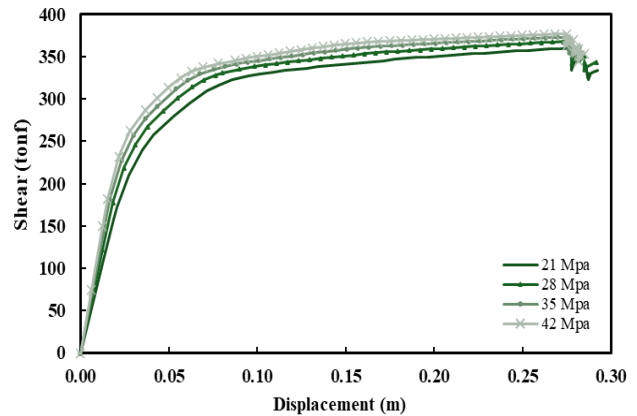


Fig. 6 Capacity curves for the different concrete strength scenarios

3.2. Structural Ductility

The ductility parameters for each concrete strength scenario are shown in Table 4. The values show that, while the Ultimate Displacement (Δ_u) stays almost the same at around 0.28 m, the Yield Displacement (Δ_y) goes down step by step from 0.0338 m in the 21 MPa scenario to 0.0243 m in the 42 MPa scenario. This change makes the material less ductile (μ), going from 0.122 to 0.088 between the extreme analyzed cases.

Table 4. The parameters associated with structural ductility

Concrete	Δ_y	Δ_u	μ
21 Mpa	0.033762	0.277671	0.12158994
28 Mpa	0.029246	0.277735	0.10530182
35 Mpa	0.026398	0.275696	0.09575039
42 Mpa	0.024279	0.274717	0.08837822

In summary, the results show that making the concrete stiffer makes the building stronger, but also makes it less flexible. While the total displacement remains almost the same at about 0.28 m, the displacement that results from yield strength decreases with higher material strength. This limits how much the material can deform without failing. This means that, on average, ductility decreases by about 30% between the

21 MPa and 42 MPa scenarios. This confirms that higher-strength concretes have a lower capacity for dissipating seismic energy.

4. Discussions

The results show that making the concrete stronger can help the building resist sideways forces, as seen in the higher maximum base shear stress values. However, this improvement is balanced by a big decrease in overall flexibility, meaning it cannot absorb as much energy when it is not in a solid state. This found pattern in the results matches the findings of other recent studies that reported that high-strength concretes behave more brittlely because they cannot change their shape that much after being pulled or pushed [20, 21]. Nevertheless, this present study provides a direct, nonlinear structural explanation of this effect on a global level.

In addition, the capacity curves manifest that the maximum displacement is almost the same across different concrete strengths. Nonetheless, the minimum displacement decreases steadily. Research using probabilistic thrust analysis has exhibited how changes in material properties can affect the inelastic response [27, 28]. Nevertheless, the findings presented in this paper clearly demonstrate how changes in f_c alone can lead to a decrease in the overall ductility and deformation capacity of the concrete. The data reveal that higher concrete strength does not necessarily lead to better seismic performance; this result exhibits the need to consider the quality of the material in terms of both strength and how

well it can be deformed because this is essential for assessing how well the concrete can resist the effects of earthquakes.

5. Conclusion

This investigation demonstrates that making concrete stronger can make buildings more able to resist sideways forces, as exhibited by the increase in maximum base shear. The 21 MPa and 42 MPa scenarios expose an approximate increase of 4.4%. This indicates that higher-strength concrete makes for stiffer and stronger structures.

However, we also saw a big decrease in how flexible the material was as the compressive strength increased. The results show a decrease of about 28%, from 0.122 at 21 MPa to 0.088 at 42 MPa. This shows that higher concrete strength makes structures stronger, but it also limits how much they can deform without failing, which reduces their ability to absorb and release energy during an earthquake. These findings show that we should think about how strong concrete is not only as something that holds up a building, but also as something that can make a building safer during an earthquake. The results are important for designing buildings that can withstand earthquakes and for retrofitting existing buildings to make them safer, especially in cities where earthquakes are common. Future research should expand the current framework by including irregular structural configurations and using probabilistic and dynamic analysis methods to more completely understand how material uncertainty affects structural response.

References

- [1] T. Oliver, Summary Of News Of The Earthquake In Turkey And Syria On February 8, CNN, <https://cnnespanol.cnn.com/2023/02/08/ultimas-noticia-terremoto-turquia-siria-orix/>
- [2] Martin Lyubomirov Ivanov, and Wan-Ki Chow, "Structural Damage Observed in Reinforced Concrete Buildings in Adiyaman During the 2023 Turkiye Kahramanmaraş Earthquakes," *Structures*, vol. 58, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [3] Juan Gutiérrez Trejo, and Gustavo Ayala Milián, "Analysis of the Seismic Resilience of Buildings," *Seismic Engineering*, no. 107, pp. 47-73, 2022. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [4] Grzegorz Ludwik Golewski, "The Phenomenon of Cracking in Cement Concretes and Reinforced Concrete Structures: The Mechanism of Cracks Formation, Causes of Their Initiation, Types And Places of Occurrence, And Methods of Detection—A Review," *Buildings*, vol. 13, no. 3, pp. 1-34, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [5] Moustafa Moufid Kassem et al., "Development of a Uniform Seismic Vulnerability Index Framework for Reinforced Concrete Building Typology," *Journal of Building Engineering*, vol. 47, 2022. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [6] René Lagos et al., "The Quest for Resilience: The Chilean Practice of Seismic Design for Reinforced Concrete Buildings," *Earthquake Spectra*, vol. 37, no. 1, pp. 26-45, 2021. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [7] Ismail Ozan Demirel, Ahmet Yakut, and Baris Binici, "Seismic Performance of Mid-Rise Reinforced Concrete Buildings in Izmir Bayrakli After the 2020 Samos Earthquake," *Engineering Failure Analysis*, vol. 137, 2022. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [8] Cem Yalçın, "Seismic Design of RC Frame Structures Based on Energy-Balance Method," *Engineering Structures*, vol. 237, 2021. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [9] Structural Assessment and Rehabilitation of Existing Buildings in Mexico City, Helios, 2025 [[Publisher Link](#)]
- [10] Muhammet Kamal, and Mehmet Inel, "Simplified Approaches for Estimation of Required Seismic Separation Distance Between Adjacent Reinforced Concrete Buildings," *Engineering Structures*, vol. 252, 2022. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [11] Jhamir Estiven Martinez Najarro, "Influence of the Use of SLB Dampers on the Seismic Response of the Structural System of San Basilio Private School in the Ate District, Lima, 2024," Technological University of Peru, 2025. [[Publisher Link](#)]
- [12] P.D. Gkournelos, T.C. Triantafyllou, and D.A. Bournas, "Seismic Upgrading of Existing Reinforced Concrete Buildings: A State-of-the-Art Review," *Engineering Structures*, vol. 240, pp. 1-20, 2021. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]

- [13] Luisa Paulina Viera, “Performance-Based Seismic Design of Reinforced Concrete Buildings,” Master’s Thesis, Technical University of Ambato, 2004. [[CrossRef](#)] [[Google Scholar](#)]
- [14] Diego Gino et al., “Seismic Upgrading of Existing Reinforced Concrete Buildings Using Friction Pendulum Devices: A Probabilistic Evaluation,” *Applied Sciences*, vol. 10, no. 24, pp. 1-17, 2020. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [15] Herian Leyva et al., “Multi-Objective Seismic Design of BRBs-Reinforced Concrete Buildings Using Genetic Algorithms,” *Structural and Multidisciplinary Optimization*, vol. 64, pp. 2097-2112, 2021. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [16] Jong-Wha Bai, Mary Beth D. Hueste, and Paolo Gardoni, “Seismic Vulnerability Assessment of Tilt-Up Concrete Structures,” *Structure and Infrastructure Engineering*, vol. 11, no. 9, pp. 1131-1146, 2015. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [17] Seong-Hoon Hwang et al., “Machine Learning-Based Approaches for Seismic Demand and Collapse of Ductile Reinforced Concrete Building Frames,” *Journal of Building Engineering*, vol. 34, 2021. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [18] Petros C. Lazaridis et al., “Structural Damage Prediction of a Reinforced Concrete Frame Under Single and Multiple Seismic Events Using Machine Learning Algorithms,” *Applied Sciences*, vol. 12, no. 8, pp. 1-22, 2022. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [19] Niraj Shrestha et al., “Enhancing Seismic Vulnerability Assessment: A Neural Network Effort for Efficient Prediction of Multi-Storey Reinforced Concrete Building Displacement,” *Asian Journal of Civil Engineering*, vol. 25, pp. 2843-2865, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [20] Ingrid Angela Villafuerte Lujano, and Victor Ivan Fernández-Dávila González, “Seismic Response of 8-Story Reinforced Concrete Buildings with Irregular Plan,” *Engineering*, vol. 34, no. 2, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [21] Yati Aggarwal, and Sandip Kumar Saha, “Seismic Performance Assessment of Reinforced Concrete Hilly Buildings with Open Story,” *Structures*, vol. 34, pp. 224-238, 2021. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [22] Rayudu Jarapala, and Arun Menon, “Seismic Performance of Reinforced Concrete Buildings on Hill Slopes: A Review,” *Journal of The Institution of Engineers (India): Series A*, vol. 104, pp. 721-745, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [23] Mangeshkumar R. Shendkar et al., “Influence of Masonry Infill on Seismic Design Factors of Reinforced-Concrete Buildings,” *Shock and Vibration*, vol. 2022, no. 1, pp. 1-15, 2022. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [24] Xinyu Wang et al., “Seismic Retrofitting of Reinforced Concrete Frame-Shear Wall Buildings Using Seismic Isolation for Resilient Performance,” *Structures*, vol. 34, pp. 4745-4757, 2021. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [25] Sima S. Ijmulwar, and Sanjaya Kumar Patro, “Seismic Design of Reinforced Concrete Buildings Equipped with Viscous Dampers Using Simplified Performance-Based Approach,” *Structures*, vol. 61, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [26] Panagiota S. Katsimpini, and George A. Papagiannopoulos, “Effectiveness of the Seesaw System as a Means of Seismic Upgrading in Older, Non-Ductile Reinforced Concrete Buildings,” *Vibration*, vol. 6, no. 1, pp. 102-112, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [27] Pramod Kumar et al., “A Comparative Analysis of Machine Learning Algorithms for Predicting Fundamental Periods in Reinforced Concrete Frame Buildings,” *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, vol. 49, pp. 2257-2276, 2025. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [28] Xu-Yang Cao, De-Cheng Feng, and Gang Wu, “Pushover-Based Probabilistic Seismic Capacity Assessment of RCFs Retrofitted With PBSPC BRBF Sub-Structures,” *Engineering Structures*, vol. 234, 2021. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [29] Standard E.060 Reinforced Concrete, National Building Regulations. [Online]. Available: https://drive.google.com/file/u/1/d/19EYUVMgwvm6rDs47GV374avco2yIU5Kz/view?usp=sharing&usp=embed_facebook
- [30] Norma E.030 Seismic-Resistant Design, National Building Regulations, 2020. [Online]. Available: <https://drive.google.com/file/d/1W14N6JldWPN8wUZSqWZnUphg6C559bi-/view>
- [31] Standard E.020 Loads, National Building Regulations. [Online]. Available: https://drive.google.com/file/u/1/d/15atg-9w0OEXjR5C1m6IXUFihwYeUh1aN/view?usp=sharing&usp=embed_facebook
- [32] Ángel Francisco San Bartolomé Ramos, “*Analysis of Buildings*,” Pontifical Catholic University of Peru, 1998. [[Google Scholar](#)] [[Publisher Link](#)]
- [33] ETABS, Csiespana. [Online]. Available: <http://www.csiespana.com/software/5/etabs>
- [34] Gregory G. Deierlein, Andrei M. Reinhorn, and Michael R. Willford, “Nonlinear Structural Analysis for Seismic Design,” *NEHRP Seismic Design Technical Brief*, no. 4, pp. 1-36, 2010. [[Google Scholar](#)] [[Publisher Link](#)]
- [35] Federal Emergency Management Agency (FEMA), Federal Agencies. [Online]. Available: <https://www.usa.gov/es/agencias/agencia-federal-para-el-manejo-de-emergencias>
- [36] Infrastructure Leaders Building Communities, American Society of Civil Engineers, [Online]. Available: <https://www.asce.org/>