

Review

Colombian Regulations in the Seismic Design of Reinforced Concrete Buildings with Portal Frames: A Comparative and Bibliometric Analysis

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Abstract

Colombia is located in a region of significant seismic hazard, where reinforced concrete portal frame systems represent a dominant structural typology. Despite this relevance, the existing literature lacks an integrated evaluation that simultaneously examines the evolution of Colombian seismic design regulations (NSR) and the scientific production associated with their development and application. This study addresses this gap by conducting a two-part analysis. First, a comparative engineering review of the three main versions of the Colombian Earthquake Resistant Standard (CCCSR-84, NSR-98, NSR-10) demonstrates substantial changes in material requirements, detailing rules, structural system classification, and capacity design principles. Results indicate that adopting NSR-10 led to a 15–25% increase in concrete and steel demand, thereby improving structural resilience and ductility in reinforced concrete buildings. Second, a bibliometric analysis using Scopus and processed through Bibliometrix examined 87 documents, involving 286 authors, 93 institutions, and 17 countries, revealing an annual publication growth rate of 4.85% between 1989 and 2023. Approximately 75% of the publications focus on reinforced concrete and seismic design, whereas 19.5% involve international collaboration. The thematic mapping highlights clusters related to capacity design, ductility, seismic vulnerability, and retrofitting. These findings underscore the progressive refinement of Colombian seismic regulations and their growing impact on academic research, advancing safer, more resilient seismic design practices in the country.

Keywords: Colombian regulations; NSR; seismic design; reinforced concrete buildings; portal frames; comparative analysis



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1. Introduction

1.1. Overview

The seismic vulnerability of Colombia, due to its location along the Pacific Ring of Fire, has necessitated robust seismic design regulations. Since the publication of the first Colombian seismic code, CCCSR-84 (1984) [1], followed by NSR-98 (1998) [2] and the current NSR-10 (2010) [3], the country has progressively strengthened its seismic design provisions. This evolution integrates advancements in material science, structural analysis, and seismic engineering. The NSR-10 represents a milestone in ensuring the structural safety of buildings, particularly those employing reinforced concrete portal frame systems, a widely used construction method in urban areas. Moreover, the regulation adapts international best practices to Colombia's specific seismic conditions, incorporating

updated soil classifications, design spectra, and energy dissipation systems [4]. This study offers a comprehensive examination of these advancements through comparative and bibliometric analyses, underscoring the critical role of seismic codes in shaping engineering practices and mitigating seismic risks.

It is important to note that the first official Colombian structural design code with mandatory seismic provisions was the Código Colombiano de Construcciones Sismo-Resistentes CCCSR-84, published in 1984. Although some technical recommendations existed before this date, the CCCSR-84 was the first comprehensive, legally enforceable code to incorporate seismic threat considerations into structural design. This marked the beginning of modern earthquake-resistant design practice in Colombia, which was later expanded in the NSR-98 and significantly updated in the NSR-10.

Historically, several significant earthquakes in Colombia have driven major updates to the national seismic design codes. The 1983 Popayán earthquake (Mw 5.5), which caused severe structural damage and numerous casualties, highlighted the vulnerability of unreinforced masonry buildings and prompted the earliest efforts to strengthen national construction regulations. Later, the 1992 Murindó earthquake (Mw 7.2) and the 1995 Tauramena earthquake (Mw 6.5) emphasized the need for improved seismic zoning and soil classification procedures. The most influential event was the 1999 Armenia (Eje Cafetero) earthquake (Mw 6.2), which exposed deficiencies in structural detailing and construction quality, leading directly to substantial revisions in the NSR-98. These events collectively shaped the evolution of the NSR-10 by reinforcing the need for stricter material requirements, improved design methodologies, and a stronger emphasis on seismic resilience in reinforced concrete frame systems [5].

1.2. Studies Related to NSR

Criado-Rodríguez et al. (2020) [6] assessed seismic vulnerability in the Cristo Rey neighborhood of Ocaña, Colombia, using the FEMA P-154 methodology. Their findings highlighted the high vulnerability of structures, particularly older buildings constructed without seismic-resistant codes. Approximately 78% of the analyzed structures exhibited design irregularities, such as soft stories or discontinuities, while 62% of the buildings were deemed high-risk due to geological instability. The study stressed the urgent need for structural reinforcements. The FEMA P-154 methodology proved effective for rapid seismic vulnerability assessments, especially in areas lacking comprehensive urban planning and microzonation studies.

Amariles López et al. (2022) [7] conducted a comprehensive comparison between the Colombian seismic design code NSR-10 and the ACI 318-19 code, specifically for concrete frame structures in high-seismic-risk zones. Their research included a detailed analysis of the chapters and requirements of both codes, along with a comparative table outlining structural differences. Design simulations of frame structures under both codes showed significant differences: required steel reinforcement increased by approximately 12% when using ACI 318-19, while concrete volume requirements increased by 8%. Cost analyses based on Invías databases revealed a 3.3% increase in construction costs when applying ACI 318-19, deemed justifiable given the code's improved capacity and ductility. The authors emphasized the lack of international studies that analyze NSR-10's key specifications, which are primarily based on global standards.

In recent years, significant advances in computational earthquake engineering have introduced data-driven and hybrid modeling techniques that enhance the prediction of seismic behavior in reinforced concrete (RC) frame structures. These approaches complement traditional physics-based models by improving accuracy while reducing computational demand, a feature highly relevant to performance-based seismic assessment. For example,

Luo and Paal (2022) [8] proposed an artificial-intelligence-enhanced framework that integrates experimental RC column data with simplified structural models, achieving more accurate and computationally efficient seismic response predictions than conventional fiber-based methods. Similarly, Lazaridis et al. (2022) [9] demonstrated the effectiveness of machine learning algorithms for predicting structural damage in RC frames subjected to single and multiple seismic events, using intensity measures and successive ground motion sequences to capture cumulative damage. The growing adoption of such AI-driven methodologies underscores the global trend toward advanced seismic analysis tools. It provides an essential technical context for evaluating how national regulations, such as the Colombian NSR, evolve to address modern engineering challenges.

1.3. National Works (Colombia)

Mastrodoménico Ahumada et al. (2013) [10] analyzed the seismic design of a five-story building under NSR-98 and NSR-10 in a medium seismic hazard zone. Their findings revealed that applying NSR-10 led to a 15% increase in structural steel requirements and a 10% rise in total construction costs compared to NSR-98. However, these additional costs led to improved structural safety and compliance with stricter seismic resilience requirements. The study also highlighted the need for engineers to receive further training to apply the updated code effectively.

Alvarado Pérez et al. (2015) [11] evaluated the seismic vulnerability of housing in Hacienda Los Molinos, Bogotá, identifying high structural vulnerability due to inadequate design and materials. Field visits and vulnerability scoring revealed that 85% of the analyzed homes did not meet the minimum safety standards outlined in NSR-10, while 70% exhibited insufficient shear wall reinforcement. These findings underscore the need for retrofitting measures to reduce seismic risks in these substandard settlements.

Díaz Portilla and Aranda Nieves (2017) [12] conducted a technical comparison of NSR-98 and NSR-10, focusing on construction processes and cost implications. Their analysis identified updates in design parameters, such as increased steel and concrete requirements, which contributed to cost increases of 8% to 12%. The study also emphasized the more straightforward presentation of technical guidelines in NSR-10, aiding engineers in implementing safer designs.

Finally, Acosta-Rodriguez (2020) [13] reviewed structural analysis methodologies aligned with NSR-10, leveraging finite element analysis and software tools like ETABS for structural design. The study proposed a practical design guide emphasizing stability, resistance, and stiffness, while recommending flexibility in adapting site coefficients within NSR-10's framework. Notably, the author highlighted that neglecting site-specific conditions can lead to an underestimation of seismic loads by up to 20%, compromising structural safety.

1.4. Aim of This Work

This study aims to analyze the evolution and impact of Colombian seismic design regulations, with particular emphasis on the Norma Sismo Resistente 2010 (NSR-10), in the design and construction of reinforced concrete buildings with portal frame systems. The objectives of this research are to: (a) Perform a comparative assessment of different versions of the Colombian seismic codes (CCCSR-84, NSR-98, and NSR-10) to identify key updates in design requirements, safety parameters, material specifications, and construction practices that influence structural resilience; (b) Conduct a bibliometric analysis using the Scopus database to evaluate research trends, collaboration networks, thematic clusters, and the global academic influence of studies related to Colombian seismic regulations; (c) Address the current gap in literature regarding the practical application of NSR-10, particularly

its influence on construction costs, material quantities, and structural performance in high-seismic-risk regions; and (d) Provide technically grounded recommendations for the continuous improvement of seismic design practices in Colombia, including the integration of advanced technologies, updated analytical methodologies, and sustainable materials, thereby aligning national engineering practice with international trends in earthquake-resistant design.

2. Materials and Methods

Bibliometric Analysis (BA)

According to García-León et al. (2021) [14], bibliometrics is a scientific method that enables the quantitative analysis of scientific production through literature, providing insights into the evolution of specific disciplines and identifying thematic trends over time. This approach allows for the extraction of quantitative information on publication metrics, geographic distribution, author collaborations, leading research institutions, and the most influential journals. Bibliometrics employs statistical and mathematical techniques to analyze written sources, including language, keywords, article titles, journal names, authorship, document type, and abstracts.

Furthermore, bibliometric analysis (BA) is often referred to as statistical bibliography because it focuses on quantifying existing publications. Its primary goal is to measure scientific output, including articles and books. The BA in this study was conducted using RStudio® software (Version 06.1), leveraging the BiblioShiny platform and the Bibliometrix library [15], which are widely used tools for performing bibliometric analyses on research topics [16].

Based on this approach, data for the BA were collected in December 2024 from the Scopus and Web of Science (WOS) databases. The search focused on publications related to seismic-resistant standards from 1998 to 2010, structural methods, and seismic phenomena in Colombia, using the following search equation: (NSR 10 OR NSR 98 OR NSR OR standard OR procedure) AND (design OR construction OR earthquake OR structural OR concrete).

The search strategy intentionally used a broad Boolean query in Scopus to ensure that all potentially relevant publications on Colombian seismic design regulations were captured. This approach follows best practices in bibliometric research, prioritizing sensitivity (comprehensive retrieval) over specificity during the initial extraction stage. The rationale is that many studies on seismic regulations in Colombia do not explicitly include standardized terminology in their titles, abstracts, or keywords (e.g., “NSR”, “Colombian code”, or “seismic regulations”), which could lead to omissions if narrow search criteria are applied.

To mitigate noise, the broad initial query was followed by a manual screening of titles, abstracts, and keywords to exclude documents unrelated to structural engineering or seismic design. This two-step strategy, broad retrieval followed by relevance filtering, ensures comprehensive field coverage and adequate control of irrelevant records, resulting in a dataset that is representative, topic-consistent, and aligned with the study’s objectives.

Considering the above, approximately 429 documents were initially retrieved. However, upon refining the results, it was found that some articles were related to fields such as health and geography, which were not relevant to the bibliometric analysis. After filtering, the dataset was narrowed down to 87 documents. During data extraction from Scopus, it was noted that there is limited research focusing exclusively on the comparison or analysis of seismic-resistant construction standards. As a result, the bibliometric analysis concentrated on articles addressing the construction of concrete structures, including reinforced

concrete and frame-type structural systems. The dataset included relevant information such as titles, abstracts, authors, keywords, total citations per document, affiliations, and more.

Note that the search equation explicitly included the Colombian seismic codes (NSR-10, NSR-98, and related terms). As a result, all documents retrieved and all figures and tables generated in this study are consistent with the literature associated with the Colombian seismic regulatory framework. Therefore, the bibliometric results exclusively reflect publications linked to Colombian seismic design codes.

To conduct bibliometric or scientific literature review analyses, researchers typically follow the workflow outlined in Figure 1. This process involves three key steps, described below:

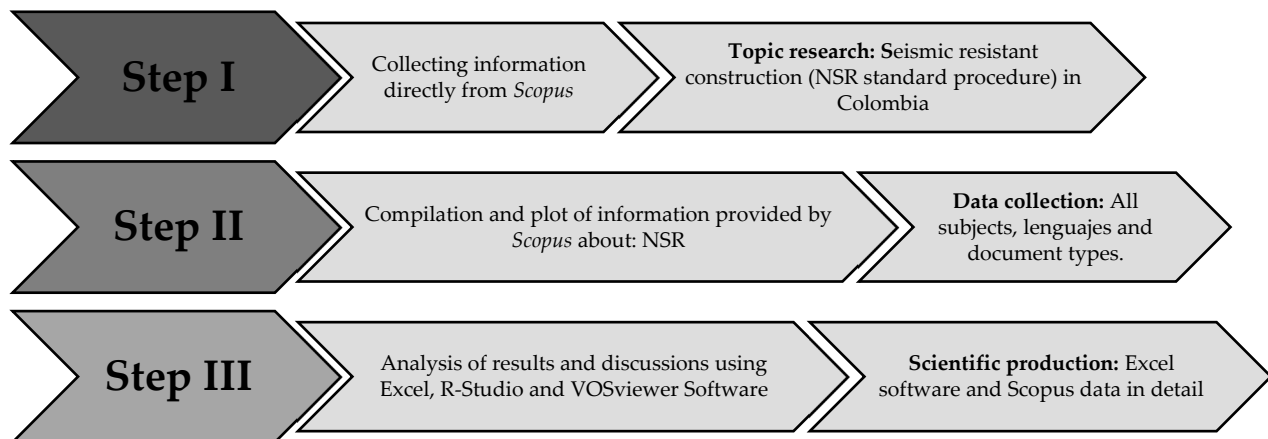


Figure 1. Methodology proposed for the BA.

Step I: Define the research topic; in this case, “Seismic resistant construction (NSR standard procedure) in Colombia”. This phase ensures a broad scope, covering various subject areas, languages, and document types, thereby laying the groundwork for a comprehensive understanding of the topic.

Step II: In this step, data are systematically collected to address the research objectives. Researchers use Microsoft Excel in CSV (Comma-Separated Values) format for efficient organization and Scopus as the primary data source to obtain a diverse range of relevant seismic-resistant construction (NSR) in construction.

Step III: The final step focuses on synthesizing the collected data to generate scientific output. Researchers conduct detailed analyses to produce valuable knowledge, culminating in research papers, reports, presentations, or other forms of scientific communication [17]. Additionally, the workflow proposed by García-León et al. (2021) [14] was adopted to guide the BA in this study, with each step implemented systematically using data compiled from Scopus.

Note that, as in most bibliometric studies, the initial extraction from Scopus may include documents that are not directly related to the main topic due to the way the database assigns keywords, subject areas, and citation relations. Scopus uses automatic indexing algorithms that associate documents based on shared terms, keyword co-occurrence, and citation networks, and the researcher cannot manually control these associations. In some cases, publications from unrelated fields share generic terms (e.g., ‘resistance’, ‘structures’, ‘frames’, ‘codes’) that trigger inclusion despite being outside structural engineering. Nevertheless, these cases represent a minimal proportion of the dataset and do not affect the global trends observed. This behavior is inherent to bibliometric database indexing and is widely acknowledged in the literature. Also, the few isolated misclassified documents were identified but not removed, since they do not influence the thematic clustering, collaboration networks, or temporal trends derived from the overall dataset.

3. Results and Discussion

3.1. Data Collection and Information

The data were collected in August 2023 from scientific publications in the Scopus database. Although the bibliometric search includes international publications on seismic design and reinforced concrete structures, the regulatory analysis in this study focuses exclusively on the Colombian seismic codes (CCCSR-84, NSR-98, and NSR-10). The global documents are incorporated solely to contextualize scientific production and research trends, while the comparative regulatory assessment is strictly limited to Colombian standards. Documents published from 1989 onwards were considered, using the search equation. This section provides a historical review of the use of various construction regulations in Colombia, employing bibliometric analysis of high-impact sources.

3.2. Analysis of Results from the Bibliometric Analysis (BA)

A bibliometric analysis (BA) was conducted by collecting data from existing scientific publications on the application of various earthquake-resistant construction regulations in the design and construction of reinforced concrete buildings. The Scopus database was employed to provide a global view of the growth of this research topic over time and the usage of standards across different studies. The research quantified the involvement of various authors and countries over time in the development of construction techniques and the implementation of standards for the design and construction of frame structures. The objective was to identify key sources and leading authors based on research quality and quantity [18,19].

The results, as summarized in Table 1, reveal significant trends and patterns. A total of 87 documents were identified, published between 1989 and 2023, with an average document age of 8.49 years. This reflects the ongoing interest in the subject over the decades. The research involved 277 authors, with 6 documents authored by a single author, and an average of 3.38 co-authors per document. Interestingly, approximately 19.54% of the publications included international co-authorship, highlighting the global collaboration in this area of research. The analysis also indicated a steady increase in the number of documents published, reflecting the growing recognition of the importance of seismic-resistant design in reinforced concrete buildings. The study quantified participation by countries and authors, identifying key sources and influential contributors, both in terms of volume and impact. A detailed breakdown of the publication types included in the study shows that most documents were articles (54), followed by section documents (30), a few book chapters (1), and reviews (2). This distribution reflects the nature of the research, with a clear preference for detailed, peer-reviewed articles focused on the application of construction regulations.

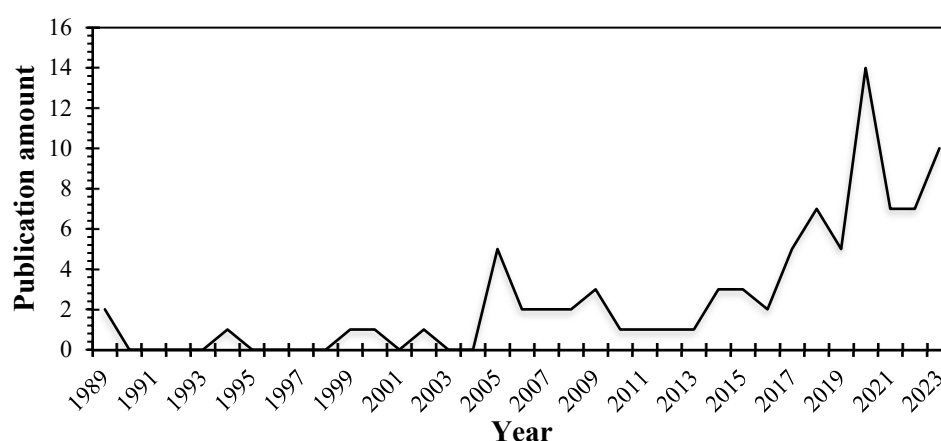
Note that the bibliometric search was conducted using data available in Scopus up to August 2023, the last complete dataset accessible at the time of extraction. Although more recent publications (2023–2025) have appeared, preliminary screening indicates that their inclusion does not significantly alter the global trends identified in this study, including annual publication growth, predominant research topics, and leading contributing countries. This time boundary ensures consistency in the analysis while maintaining methodological reliability.

Table 1. Global Results of the Bibliometric Analysis.

Description	Results
Main Information	
Time Span	1989:2023
Sources	75
Documents	87
Average Document Age	8.49
Average Citations per Document	9.276
Document Content	
Keywords	852
Author's Keywords	294
Authors	277
Single Author Documents	6
Co-authorship	
Single Author Documents	6
Co-authors per Document	3.38
% of International Co-authorship	19.54
Document Types	
Articles	54
Book Chapters	1
Section Documents	30
Reviews	2

3.3. Summary of Publications

The analysis of results using bibliometric software (R-Studio, Version 06.1) revealed an annual growth rate of 4.85% from 1989 to 2023, with 87 documents written by approximately 294 authors. The main contributions came from countries such as Colombia, China, and the United States, as shown in Figure 2. Additionally, the study on the application of different regulations in the design and construction of buildings increased from 2005 to 2023, fluctuating significantly over the years. In 2021, around 14 articles were published on this topic.

**Figure 2.** Number of Articles Published Over the Years.

3.4. Evolution of the Use of Keywords over Time

Keyword extraction was performed using the Bibliometrix tool. These keywords were selected directly by the tool based on their frequency of occurrence in the publications. Keywords provide an overview of the research topics. In this analysis, both the keywords provided by the authors and the “Keywords Plus” generated spontaneously from the titles

of the cited articles were used. By examining these keywords over time, it was found that terms such as “seismic design/earthquakes” were widely used, indicating a significant focus on research to improve the design and construction of buildings.

Figure 3 presents the 15 most frequently used keywords by both authors and in Keywords Plus, with “seismic design” being the most common keyword, appearing in 14% of the documents analyzed. Figure 4 shows the repetition and association between keywords, represented by circles of varying sizes and colors. Larger circles indicate a higher frequency of appearance, and the proximity between circles reflects the association between keywords. Moreover, different colors group the keywords into research themes. This analysis identifies key areas of interest and focuses on seismic design research.

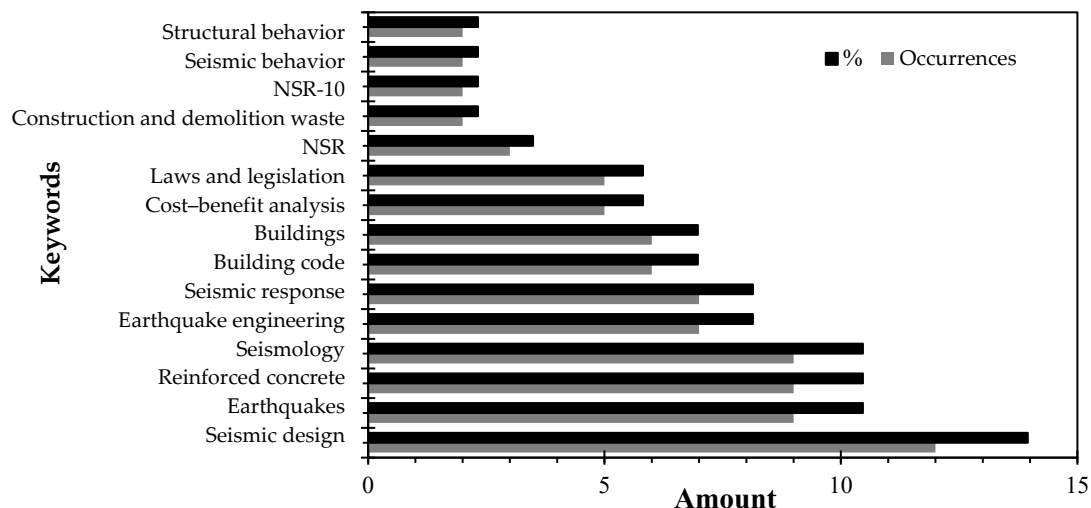


Figure 3. Fifteen Most Common Keywords Used in Publications.

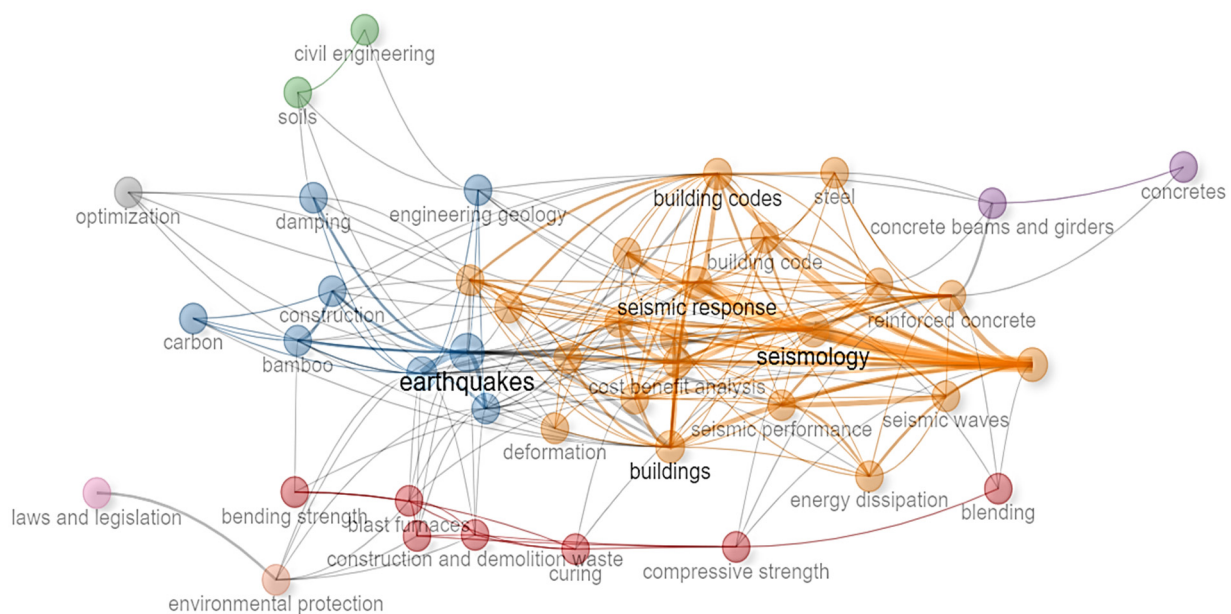


Figure 4. Interactions between keywords plus.

Figure 5 presents the keywords' dendrogram, revealing their hierarchical structure and grouping into related areas of the research topic. It highlights the term "reinforced concrete", a primary keyword, suggesting that the analysis of the articles focuses heavily on reinforced concrete design. This subject appears highly relevant to the research. Figure 6 shows the trend in keyword frequency of appearance in scientific publications.

This analysis offers further insight into the relevance and recurrence of specific topics over time, thereby contributing to a deeper understanding of the key research areas in the design and construction of structures. It demonstrates the strong interrelation among keywords associated with this topic.

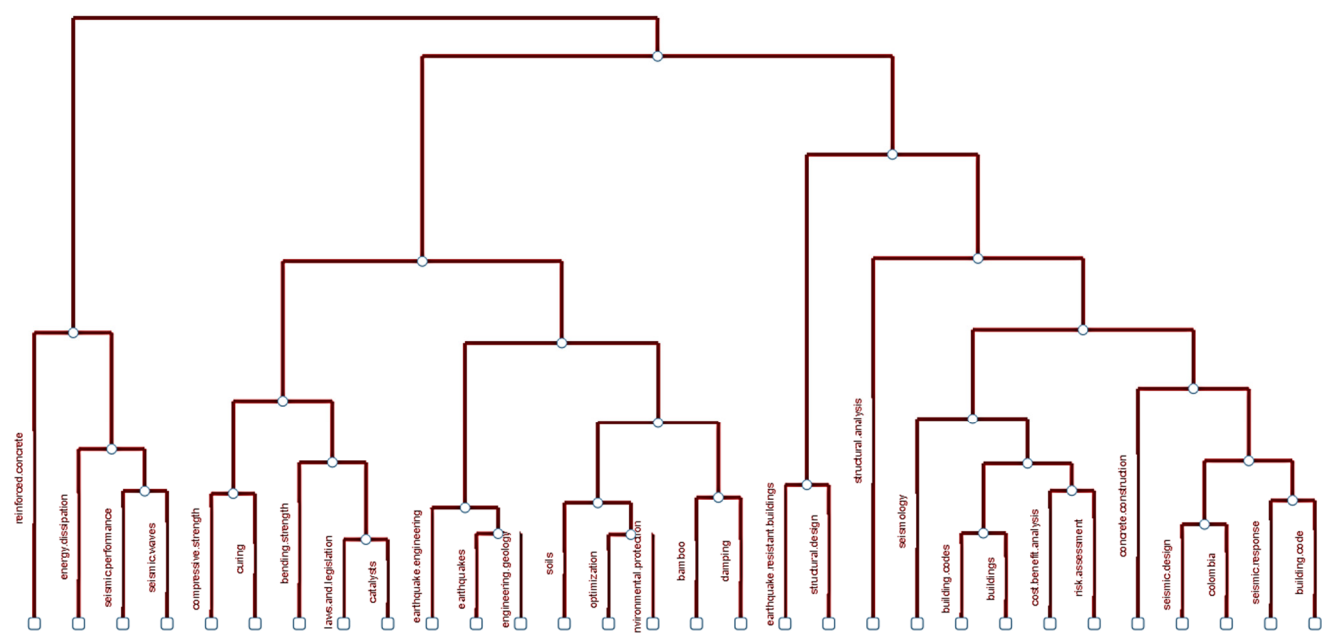


Figure 5. Keyword Dendrogram.

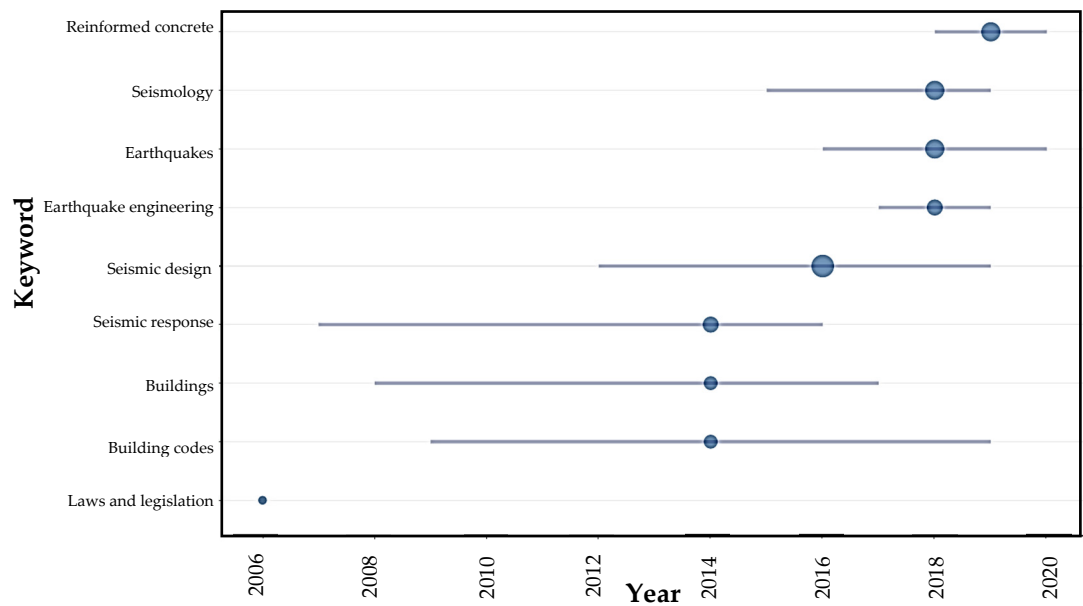


Figure 6. Keyword Trend.

3.5. Importance of Journals

According to Table 2, the journal Construction and Building Materials emerges as the most influential in the field of reinforced concrete structure design and construction. With an h-index of 2 and 53 citations, this journal plays a central role in disseminating key advancements and research in this area. Its high h-index reflects the significant impact and recognition of its articles within the academic community.

Table 2. The 20 Most Influential Journals Based on the Analysis.

No	Journal	h_Index	TC	NP	Publication Year
1	Construction And Building Materials	2	53	2	2018
2	Earthquake Spectra	2	19	2	2015
3	Materials And Structures/Materiaux Et Constructions	2	43	2	2005
4	Advances In Intelligent Systems and Computing	1	3	1	2021
5	American Concrete Institute, Aci Special Publication	1	1	1	2000
6	Applied Catalysis B: Environmental	1	41	1	2008
7	Applied Mathematical Modelling	1	22	1	2019
8	Applied Physics A: Materials Science and Processing	1	7	1	2020
9	ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE)	1	1	1	1999
10	Bulletin Of Earthquake Engineering	1	7	1	2020
11	Case Studies in Construction Materials	1	2	1	2018
12	Catalysis Today	1	30	1	2011
13	Classical And Quantum Gravity	1	2	1	1989
14	Compdyn 2017—Proceedings of the 6th International Conference On Computational Methods In Structural Dynamics And Earthquake Engineering	1	1	1	2017
15	Dalton Transactions	1	32	1	2005
16	Dyna (Colombia)	1	2	2	2018
17	Em: Air and Waste Management Association's Magazine for Environmental Managers	1	1	1	2002
18	Energy Procedia	1	1	1	2015
19	Energy Reports	1	1	1	2023
20	Engineering Structures	1	6	1	2007

Other journals, such as Earthquake Spectra (with an h-index of 2 and 19 citations) and Materials and Structures/Materiaux Et Constructions (also with an h-index of 2 and 43 citations), are also highly relevant, reflecting a consistent focus on seismic design and construction materials. Additionally, journals with more recent publication histories, such as Advances in Intelligent Systems and Computing (published in 2021) and Applied Mathematical Modelling (published in 2019), demonstrate the growing interest in interdisciplinary approaches to reinforced concrete design and earthquake engineering. The h-index values presented in the table indicate the citation impact and academic recognition of these journals. For example, journals such as the American Concrete Institute's ACI Special Publication (published in 2000) and Applied Catalysis B: Environmental (published in 2008) have published fewer articles but still demonstrate considerable impact in their respective areas. On the other hand, newer journals, such as Energy Reports (published in 2023), reflect the ongoing evolution of research in this field. In summary, the analysis reveals a clear trend: journals with a higher proportion of high-quality articles attract more citations. This highlights the importance of consistent publication and collaboration within established and emerging journals in reinforcing the global scientific community's understanding of seismic-resistant design and reinforced concrete construction.

3.6. Relevant Authors

In Figure 7, the growth of documents per author is shown, revealing that the number of authors contributing to this research topic increased from 2010 to 2023. Notably, one of the authors, Carrillo J, stands out as the author with the most citations. Until 2005, research on the application of construction standards was not in high demand; however, starting that year, the number of publications began to increase steadily. Furthermore, the impact of the authors studied on bibliometric analysis (BA) is presented in Table 3, listing

the most influential authors along with their h-index, total citations, and the year of their first publication.

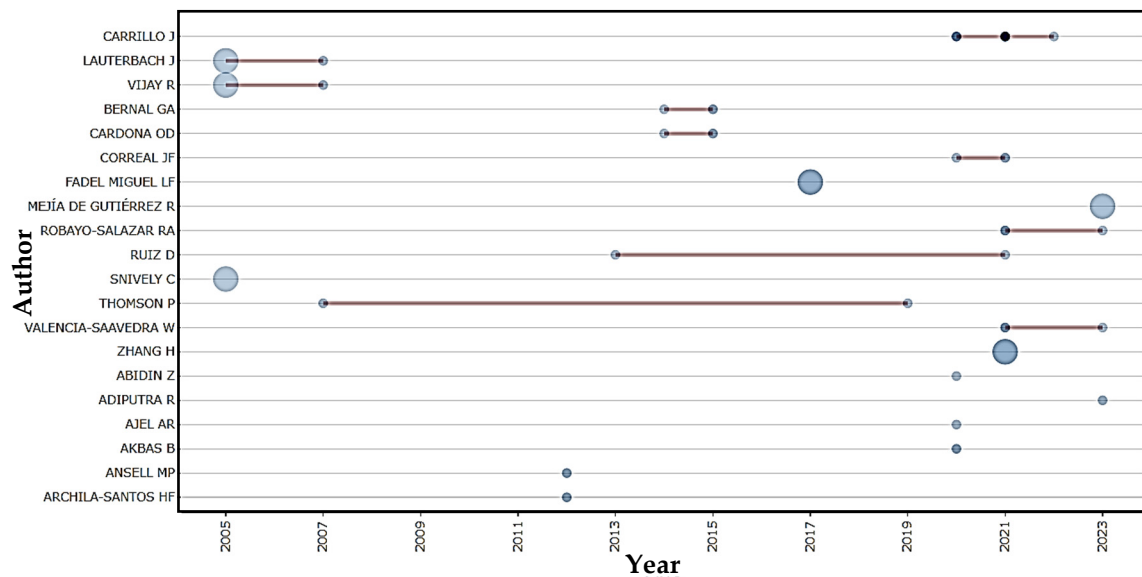


Figure 7. Impact of lead authors by number of articles and total citations (TC).

Table 3. Impact of the authors analyzed.

Author	Year	h_Index	TC
Carrillo J	2021	1	35
Ansell MP	2012	1	17
Archila-Santos HF	2012	1	17
Carrillo J	2020	1	17
Fadel Miguel LF	2017	2	14
Bernal GA	2015	1	12
Cardona OD	2015	1	12
Robayo-Salazar RA	2021	1	8
Valencia-Saavedra W	2021	1	8
Zhang H	2021	2	8
Akbass B	2020	1	7
Lauterbach J	2007	1	6
Thomson P	2007	1	6
Vijay R	2007	1	6
Correal Jf	2021	1	5
Adiputra R	2023	1	1
Ajel AR	2020	1	1
Correal JF	2020	1	1
Mejía De Gutiérrez R	2023	2	1
Ruiz D	2013	1	1
Thomson P	2019	1	1

Note that the h-index values presented in Tables 2 and 3 correspond exclusively to the filtered dataset (publications related to the Colombian seismic regulations). Therefore, the h-index values do not reflect each author's or institution's overall scientific output, but only their impact within this specific topic.

Table 4 shows the most cited global articles, which represent valuable contributions to the field of reinforced concrete structure design and construction. Their high citation numbers suggest that they have had a significant impact on structural engineering research and practice. Researchers and professionals can consider these articles key references when

addressing various aspects of this topic and applying the relevant regulations. Below is a summary of the two most cited articles:

- Performance Evaluation of Structures with Reinforced Concrete Columns Retrofitted with Steel Jacketing [20]. This article has been cited 35 times, indicating significant interest in the performance of reinforced concrete structures with retrofitted steel-jacketed columns. This research is crucial for understanding how retrofitting methods can enhance the structural integrity of concrete buildings.
- Properties of Steel Fiber Reinforced Concrete Using Either Industrial or Recycled Fibers from Waste Tires [21]. With 17 citations, this article examines the properties of steel fiber-reinforced concrete using either industrial or recycled fibers derived from waste tires. Research in this area is crucial for enhancing the mechanical properties and sustainability of reinforced concrete, particularly when recycled materials are utilized.

Table 4. Most Cited Global Articles.

Article Information	TC	TC by Year	Reference
Lerchie W, 1989, Phys Rep	156	4.33	[22]
Witharana C, 2014, Isprs J Photogramm Remote Sens	93	8.45	[23]
Issa MA, 2016, J Compos Constr	68	7.56	[24]
Cai Z-K, 2018, Constr Build Mater	48	6.86	[25]
Casapu M, 2008, Appl Catal B Environ	41	2.41	[26]
Villar-Salinas S, 2021, J Build Eng	35	8.75	[20]
Shibazaki Y, 2009, Proc Spie Int Soc Opt Eng	32	2	[27]
Li J-R, 2005, Dalton Trans	32	1.6	[28]
Peled A, 2005, Mater Struct	32	1.6	[29]
Kachapi SHH, 2019, Appl Math Model	22	3.67	[30]
Kanert O, 1994, J Non Cryst Solids	22	0.71	[31]
Quintero MAM, 2022, Sustain Struct	17	5.67	[32]
Carrillo J, 2020, Fibers Polym	17	3.4	[21]
Archila-Santos HF, 2012, Key Eng Mat	17	1.31	[33]
Lu P, 2020, J Alloys Compd	12	2.4	[34]
Mora MG, 2015, Earthquake Spectra	12	1.2	[35]
Fiore M, 2017, Leibniz Int Proc Informatics, Lipics	11	1.38	[36]

3.7. Most Important Institutions

Figure 8 highlights the top 20 institutions in the field of reinforced concrete structural design and frame structures, based on the total number of publications since 1989. Among these institutions, Universidad del Valle stands out as the most influential, with 14 publications, underscoring its leadership in research in this area. Universidad Javeriana ranks second with 7 publications, consolidating its position as one of Colombia's leading institutions in this field. It is noteworthy that both Universidad del Valle and Universidad Javeriana have played a crucial role in developing regulations and conducting applied research on the construction of safe and efficient structures.

The analysis also shows that, although other universities publish fewer papers, they are still making significant contributions. In Latin American countries like Colombia, research on seismic design and reinforced concrete construction has become increasingly important to adapt infrastructure to withstand earthquakes, given the region's geographic location. Institutions in countries like Mexico, Argentina, and Chile have also made significant contributions to this field, reflecting the growing interest in updating seismic regulations and developing new construction techniques [37].

Figure 9 emphasizes the importance of countries in reinforced concrete structural design, based on the frequency of authors affiliated with institutions in each country. The United States leads the field with 175 mentions, followed by China (129) and Colombia

(76). These data reflect the high academic output and strong research infrastructure in civil engineering in both countries.

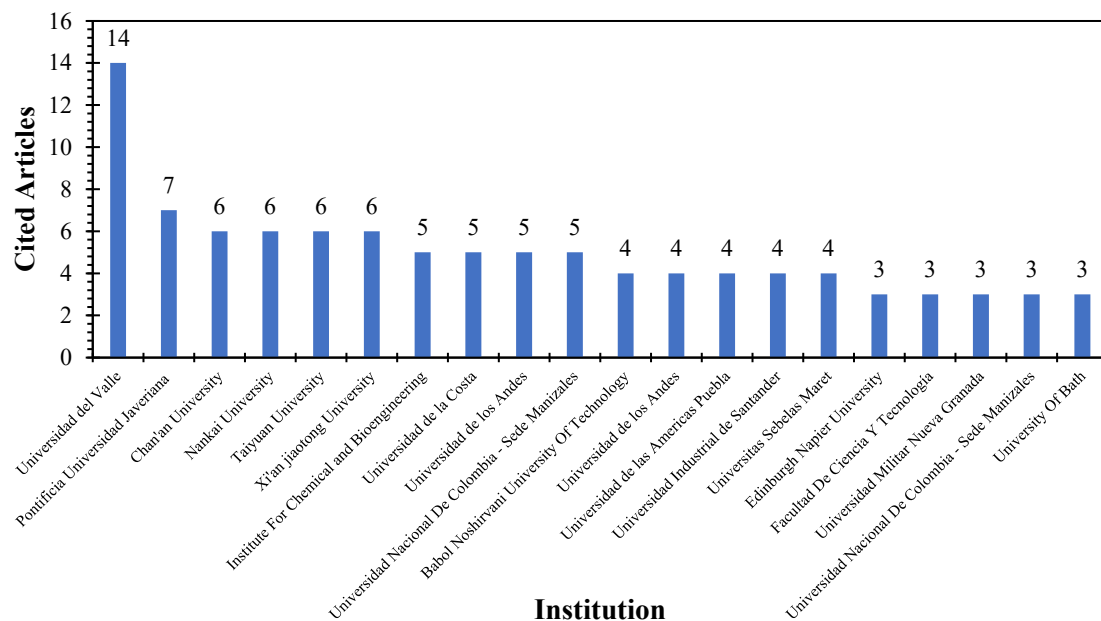


Figure 8. Top 20 Most Important Institutions.

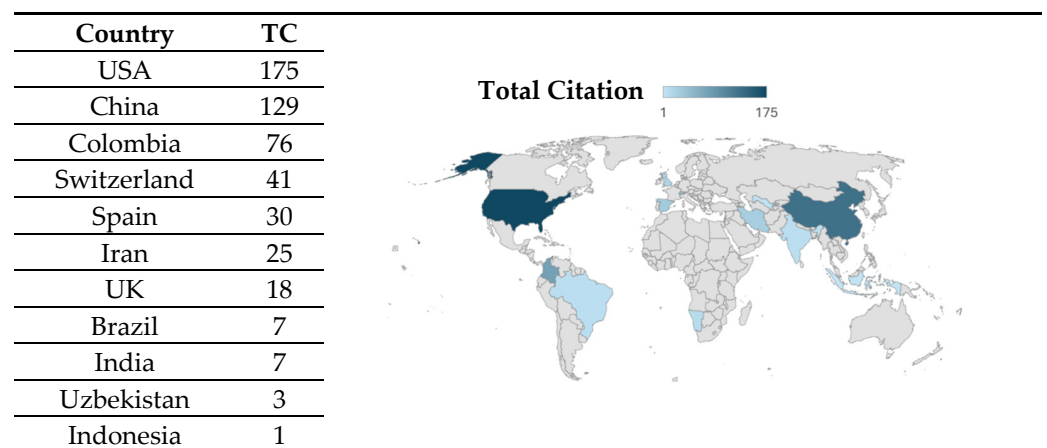


Figure 9. Geographic Relevance in Reinforced Concrete Structural Design.

The growth of infrastructure in countries like the United States and China is closely linked to their capacity to invest in research and development of advanced technologies for reinforced concrete structure design and construction. These nations not only have extensive networks of universities and research institutions but also mature construction industries that drive the generation of new technological solutions. Furthermore, the high seismic activity in regions of China, such as Sichuan and Yunnan, and in the United States, particularly in California, has increased the demand for research on seismic standards and their implementation in structural design.

In Colombia, while the number of publications is lower than in the United States and China, the country has been a key player in research on local seismic regulations, specifically the Norma Sismo Resistente (NSR). This regulation has evolved over the years to enhance structural safety in a country that, due to its geographical location, is vulnerable to earthquakes. In this context, Colombia has experienced accelerated growth in urban and rural infrastructure driven by demographic expansion and the need to modernize

its building stock. The growing investment in infrastructure projects and the promotion of local research and development have made Colombia a reference point for seismic regulations in Latin America [38].

Regarding the influence of the United States and China, it is essential to acknowledge that these countries have decades of experience in the research and development of advanced materials, such as high-performance concrete and reinforcement fibers. Moreover, the large-scale infrastructure projects in these countries require continuous innovation in construction and design methods to ensure the safety and sustainability of structures. Both the United States and China have large, active economies, which translate into greater investment in infrastructure and construction, leading to more reinforced concrete construction projects. This, in turn, drives a higher volume of research and publications in this field, spurring the need for advancements in design and construction to meet safety, durability, and efficiency requirements. On the other hand, Colombia, although experiencing economic growth and infrastructure development, may not have the same research and development resources as more developed countries. This limits its capacity to invest in research to the same extent as the United States and China.

3.8. Keyword Trends

Figure 10 reveals a growing trend in the use of keywords related to seismic design and regulations in the reinforced concrete structural design sector over time. It is interesting to note that the term “seismic design” has seen a significant increase in usage, suggesting a greater focus on this aspect in recent years. On the other hand, the term “NSR” (Norma Sismo Resistente) appears to have developed more slowly than “seismic design,” starting to be used from 1999 and showing slower growth in the number of articles mentioning it. These findings indicate a growing awareness and commitment to seismic design in the field of structural construction. The application of regulations like the NSR also seems to be gaining importance over time, reflecting the need to adhere to construction standards that ensure structural safety in earthquake-prone areas.

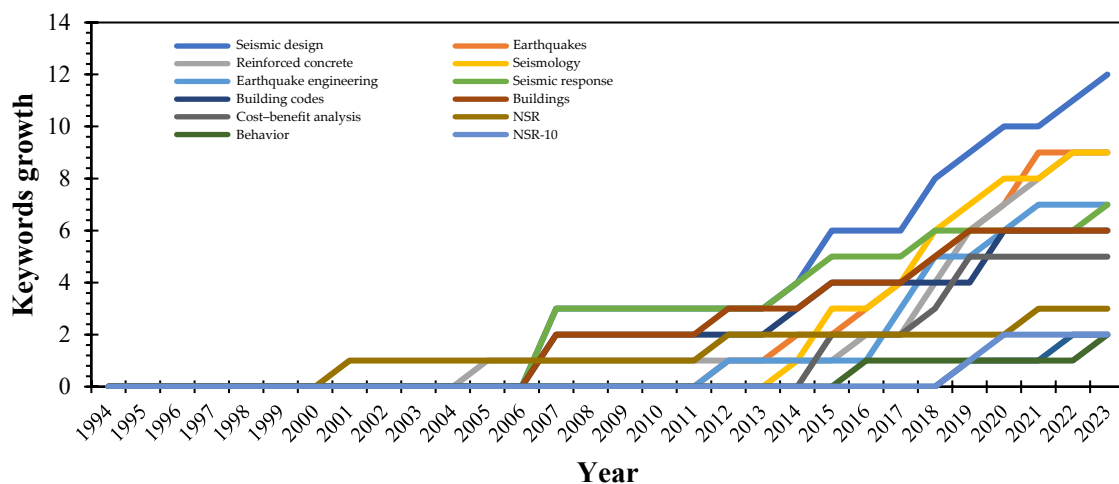


Figure 10. Growth of Keywords Over the Years.

3.9. Collaboration Between Countries

Figure 11 highlights international collaboration in research on reinforced concrete structures and frame-type structural systems. Notably, there is a strong collaborative relationship between Colombia, the United States, and China. These three countries represent the primary contributors to this field of study. This collaboration demonstrates the global interconnectedness of structural engineering, where research papers rely on

shared knowledge, the implementation of codes, and construction practices aimed at building earthquake-resistant structures.

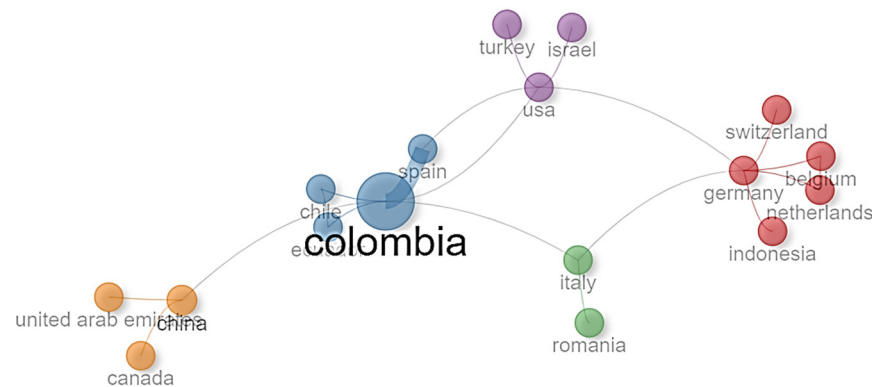


Figure 11. Collaboration between countries.

Colombia emerges as a country with significant involvement in international research, indicating active participation in knowledge exchange and collaboration with other nations. This trend can be attributed to the country's focus on comparing and evaluating regulations and practices used by other nations, to adapt and apply them within the Colombian context. International collaboration not only enriches research but also improves design and construction practices, thereby enhancing the seismic resilience of structures in Colombia and globally.

3.10. Correlations Between (Institutions, Authors, and Countries) and (Keywords, Authors, and Journals)

Figures 12 and 13 provide a detailed view of key correlations among institutions, authors, countries, and keywords in reinforced concrete frame structure design. Note that in Figure 12, the correlation among authors, institutions, and countries highlights Colombia's significant role in this analysis, demonstrating its considerable contribution to research in the field. Several Colombian universities, such as the University of Valle, have produced influential authors like Robayo-Salazar RA and Valencia-Saavedra W, whose research has played a key role in advancing knowledge in this domain. Additionally, other institutions in Colombia, including Pontificia Universidad Javeriana, Universidad Nacional de Colombia, and Universidad de los Andes, have also made significant contributions.

Among the participating Colombian universities, the Universidad Francisco de Paula Santander stands out for its prominent authors, such as Bernal GA and Cardona OD. These researchers have made significant contributions to studies related to construction regulations and reinforced concrete design in Colombia. Furthermore, universities from the United States and China also appear in the collaboration network, emphasizing the international relevance of structural design research. These results suggest active collaboration among institutions worldwide, enriching the body of knowledge and promoting significant advances in reinforced concrete frame design and construction.

Figure 13 focuses on the correlation between keywords, authors, and journals in the field of reinforced concrete frame design. It is evident that keywords such as "seismic design," "reinforced concrete," and "building codes" are strongly associated with specific authors, including Bernal GA and Cardona OD. This suggests that these authors have made significant contributions to the literature on these topics. Additionally, the relationship between keywords and journals indicates the central themes addressed in various scientific publications. Keywords such as "seismic design" and "reinforced concrete" reflect the importance of seismic design and reinforced concrete in structures, aligning with the focus of construction codes and associated standards.

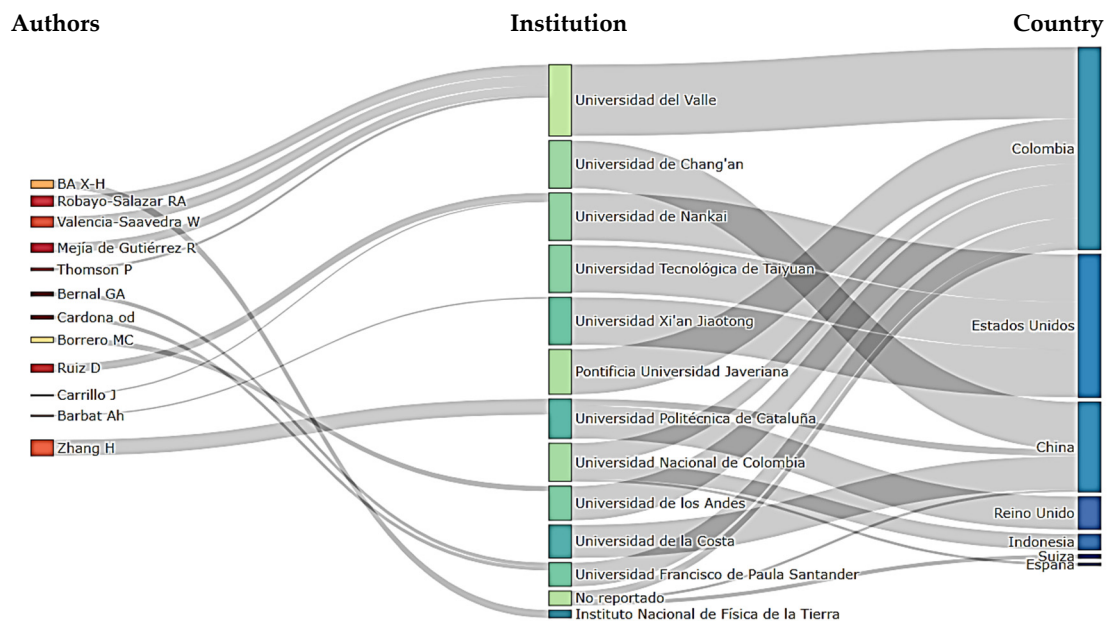


Figure 12. Correlation between authors, institutions, and countries.

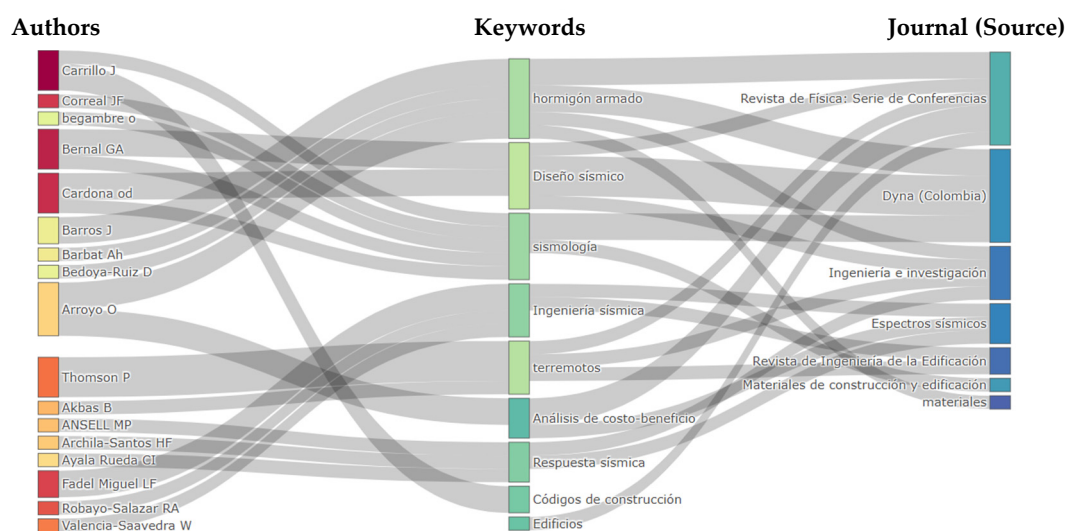


Figure 13. Correlation between authors, keywords, and journals.

3.11. Comparative Analysis of the Different NSR Standards

The comparative analysis of Colombian seismic-resistant regulations (CCCSR-84, NSR-98, NSR-10) aims to identify differences and similarities across critical aspects, including structural design, seismic-resistance requirements, and materials used. This analysis covers the following key areas:

- **Regulatory Evolution:** The document examines the evolution of seismic-resistant codes in Colombia, starting with the CCCSR-84, then the NSR-98, and culminating in the most recent NSR-10. Each of these regulations has introduced significant changes in requirements for reinforced concrete design and construction, particularly in seismic-prone areas. This analysis highlights how each code has incorporated advancements in understanding seismic phenomena and improvements in construction techniques, with a particular focus on enhancing the safety and structural resilience of buildings. It also identifies changes in key areas, including architectural and structural design and geotechnical studies. These regulatory changes have had a substantial

impact on civil engineering practices in Colombia, fostering the adoption of stricter standards to ensure the safety of buildings.

- **Design and Construction Procedures:** The procedures established by each regulation for designing and constructing buildings are outlined, with a particular emphasis on required geotechnical and architectural studies. Furthermore, the NSR-10 introduces new stages that demand more detailed analysis of soil conditions and structure, reflecting a rigorous approach to assessing seismic risks and structural planning.
- **Seismic Hazard Zones and Design Movements:** The comparison explores how different codes classify seismic hazard zones and define design seismic movements. The NSR-10, for example, presents a more detailed classification, including new categories and coefficients. Changes in seismic zone definitions and the need to consider seismic movements in structural design are also discussed, providing a more robust framework for construction in high-risk zones.
- **General Seismic-Resistant Design Requirements:** The article addresses the classification of structural systems in the codes, identifies key categories, and outlines their seismic-resistant characteristics. It also discusses height limitations for structures based on their structural systems and seismic zones. The NSR-10 modifies and expands these specifications, introducing stricter requirements to improve the ability of structures to withstand seismic events.
- **Materials and Concrete Quality Analysis:** The comparative analysis of regulations on concrete and reinforcement steel focuses on the changes from dosage to mixing and placement procedures. The NSR-10 introduces more rigorous specifications to ensure concrete resistance under various environmental conditions, which is crucial for the durability and safety of buildings in seismic zones.
- **Foundation Design and Technical Supervision:** A comparison of foundation design requirements across different regulations examines methodologies for calculating soil stresses and for designing foundations based on load combinations. The NSR-10 introduces more detailed procedures, including advanced geotechnical analysis to ensure foundation stability and safety across various soil types. Additionally, technical supervision during construction is emphasized as an essential requirement to ensure compliance with design specifications.
- **Soil-Structure Interaction:** Soil–structure interaction is a key aspect of seismic-resistant design discussed in this analysis. Each code addresses this interaction, with the NSR-10 introducing a more detailed classification of soil types and specific criteria for their evaluation. These changes reflect a deeper understanding of how soil characteristics influence structural behavior during seismic events, highlighting the need to adapt structural designs to minimize damage risks.
- **Structural Analysis Methods:** The structural analysis methods used in each code are reviewed, highlighting their evolution. For instance, the NSR-10 introduces more sophisticated calculation methods, such as dynamic analysis and structural modeling, to evaluate how a structure behaves under seismic forces. These methods include response spectrum and modal analysis, enabling a more detailed and accurate understanding of a structure’s seismic response.
- **Deflection and Drift Control Requirements:** Colombian regulations on reinforced concrete structure design specify limits for controlling deflections and drifts, critical aspects for stability and safety during seismic events. This analysis shows how each version of the regulation addresses these controls, with NSR-10 imposing stricter limits to prevent structural collapse and minimize damage, particularly in high-seismic-hazard areas.

- **Energy Dissipation Systems:** The comparison examines the permitted energy dissipation systems under each regulation. The NSR-10 includes detailed requirements for the use of energy-dissipating elements, such as seismic dampers and base isolators, which are crucial for enhancing a structure's ability to absorb and dissipate seismic energy. The inclusion of these systems reflects the integration of advanced technologies in earthquake-resistant engineering.
- **Requirements for Critical Structural Elements:** The requirements for critical structural elements, such as columns, beams, and connections, are examined. The NSR-10 introduces significant changes, particularly regarding reinforcement and detailing of connections, to improve their performance under seismic loads. These changes are essential for ensuring the structural integrity of key elements during an earthquake.

3.11.1. Evolution of Capacity Design, Confinement Requirements, Local Ductility, and Reinforcement Ratios in Colombian Codes

The evolution of the Colombian seismic design regulations also reflects significant progress in capacity design principles, confinement requirements, local ductility detailing, and reinforcement ratios. In the CCCSR-84, the concept of capacity design was only implicitly incorporated, mainly through general requirements for strong columns and weak beams. However, the NSR-98 formally introduced explicit provisions for capacity design, including overstrength factors, shear design based on flexural overcapacity, and more precise criteria for hierarchy of strengths in beams, columns, and joints. The NSR-10 further strengthened this approach by refining the overstrength factors, introducing additional requirements for shear demand amplification, and mandating explicit verification of beam–column joint capacities.

Confinement detailing has also evolved considerably. The CCCSR-84 contained only basic spacing rules for transverse reinforcement. NSR-98 introduced modern confinement requirements based on international standards, including closely spaced stirrups, 135° hooks, and confinement zones at beam and column ends. In NSR-10, confinement detailing was further enhanced by specifying transverse reinforcement spacing limits tied to expected plastic hinge regions, seismic detailing grades, and minimum volumetric ratios depending on axial load levels. These modifications significantly improved the ability of reinforced concrete members to dissipate seismic energy under cyclic loading.

Local ductility requirements have also become progressively stricter. While the CCCSR-84 provided general recommendations for ductile behavior, the NSR-98 introduced well-defined plastic hinge regions, requirements for longitudinal reinforcement anchorage, and limits on rotation capacity. The NSR-10 expanded these provisions by specifying enhanced requirements for development length, lap splices outside plastic hinge zones, and detailing intended to ensure stable hysteresis under strong ground motions.

Reinforcement ratios have also evolved. The CCCSR-84 provided broad limits on minimum and maximum longitudinal reinforcement. NSR-98 adopted more precise values, including minimum longitudinal reinforcement ratios of approximately 1% for columns and 0.7% for beams, along with maximum limits to avoid congestion and brittle failure. The NSR-10 refined these values based on improved understanding of concrete confinement, bar buckling behavior, and strain compatibility, ensuring that reinforcement ratios contribute to achieving ductile behavior without compromising constructability or increasing seismic vulnerability.

The Colombian seismic design code (NSR-10) incorporates discrete ductility categories that are functionally equivalent to those used in other international codes. For reinforced concrete moment-resisting frames, the NSR-10 defines three levels of expected inelastic performance: systems with special ductility (DES), systems with moderate ductility (DMO),

and systems with limited ductility (DBA). These categories specify the detailing, confinement, rotation capacity, and plastic hinge requirements associated with each ductility level.

In addition, the NSR-10 uses a seismic behavior factor (denoted as R), which reduces the design seismic forces to account for the expected inelastic energy dissipation capacity of the system. Values of R vary depending on the structural system and ductility category, with higher values assigned to highly ductile systems (e.g., DES) and lower values to limited-ductility systems (e.g., DBA). Therefore, the Colombian code explicitly incorporates both discrete ductility classes and a behavior factor that accounts for inelastic structural response, similar to the approach used in the U.S. and other international codes [39,40].

3.11.2. Evolution of Inspection, Intervention, Retrofit, and Strengthening Requirements in Colombia

The Colombian regulatory framework has also evolved in terms of inspection, intervention, retrofit, and structural strengthening procedures. The first formal provisions for evaluating existing buildings appeared in the NSR-98, which introduced basic criteria for determining structural deficiencies and defining when seismic strengthening was required. These concepts were significantly expanded in the NSR-10, which provides more straightforward guidelines for evaluating existing structures, classifying intervention levels, and defining the technical requirements governing retrofitting and rehabilitation decisions.

Complementary technical standards issued by the Colombian Association of Seismic Engineering (AIS) have further refined these processes. AIS 114 (2017) establishes the methodology for structural inspection and evaluation, including visual assessment, analytical evaluation, and seismic performance verification. AIS 100 (2014) provides detailed procedures for structural strengthening, covering conventional techniques such as reinforced concrete jacketing, steel encasements, and shear wall insertion, as well as modern retrofit technologies including fiber-reinforced polymers (FRP).

Overall, the evolution of these documents demonstrates a transition toward a performance-oriented approach for existing buildings in Colombia, in which inspection, structural diagnosis, and strengthening strategies must align with the seismic demands established in the NSR-10. These complementary standards ensure that both new and existing reinforced concrete buildings satisfy minimum seismic safety and resilience requirements.

3.12. Summarized Standards Analysis

Table 5 presents the comparative analysis between the different versions of the earthquake-resistant standard (NSR) for building design, seismic safety, and material specifications, emphasizing a comprehensive approach to structural engineering and construction. For example, seismic design standards often require that structures in high-risk zones withstand forces equivalent to 5–20% of their weight, depending on local hazard levels and the building's importance. Key processes such as geotechnical studies, architectural and structural design, and foundation planning integrate these seismic hazard considerations. Critical design elements, including drift requirements, are typically capped at 2–3% of the story height to prevent excessive deformation. At the same time, the separation between adjacent structures is calculated based on expected seismic displacements.

The materials section sets strict quality standards, including requiring concrete to achieve a minimum compressive strength of 25 MPa for general use or 40 MPa for critical structures. Reinforcement steel typically requires a yield strength of above 400 MPa. Proper mixing, curing, and reinforcement placement further ensure durability and compliance. Additionally, structural analysis methods account for load redistribution in continuous beams, with moment redistribution capped at around 30% in most codes. These standards collectively promote safe, efficient, and durable construction practices, aligning with international safety norms [41].

Table 5. Comparative analysis between the different versions of the NSR.

Building Design and Construction Procedure		Seismic Hazard Zones and Design Seismic Movements	General Earthquake-Resistant Design Requirements	Drift Requirements	Soil-Structure Interaction	
Title A	> Geotechnical studies		> Structural systems			
	> Architectural design		> Analysis methods	> Horizontal displacement calculation		
	> Structural design	> Seismic Hazard Zones	> Seismic effects on structural elements	> Maximum drift evaluation	> Geotechnical information	
	> Foundation design	> Local Effects	> Seismic forces of structural element designs	> Drift limits	> Structural analysis and design	
	> Design review	> Importance Coefficient	> Structures seismically isolated from their base	> Separation of adjacent structures due to seismic considerations		
	> Construction	> Design Spectrum				
	> Technical supervision		> Use of energy-dissipating elements			
Materials		Concrete quality, mixing, and placing	Formwork, embeddings, and construction joints	Reinforcement details	Analysis and design—requirements general	Strength requirements and operation
Title C		> Concrete dosage		> Standard hook		
		> Dosages based on experience on site or on test mixing		> Minimum bending diameter	> Design methods	
	> Cemented materials	> Dosages when you do not have on-site experience or in test mixing	> Formwork design, embedded in concrete	> Reinforcement placement	> Loads	
	> Aggregate	> Dosages when you do not have on-site experience or in test mixing	> Construction Joints	> Reinforcement covers the spatial details of column reinforcement	> Analysis methods	> Required resistance
	> Water	> average resistance reduction		> Spatial details in the nodes	> Modulus of elasticity	> Design strength
	> Reinforcing steel	> Team preparation		> Transverse reinforcement for compression elements	> Lightweight concrete	> Design strength for reinforcement
	> Additive	> Mixed		> Transverse reinforcement for elements in flexion	> Columns	
	> Materials testing	> Cured		> Tensile and temperature reinforcements	> Live load layout	
					> Redistribution of moments in continuous elements subjected to bending	
					> T-beam system	
					> Beams in ribbed slabs	

Note: “Title A” and “Title C” refer to the corresponding sections of the Colombian seismic code NSR-10. Title A contains the general requirements and seismic design criteria, while Title C includes the provisions for structural concrete.

To enhance the analytical depth of the code comparison, Table 6 provides a structured technical evaluation of seismic design parameters across CCCSR-84, NSR-98, and NSR-10. The table summarizes key engineering criteria, including ductility categories, drift control, capacity design, shear and confinement provisions, spectral definitions, soil classification, and requirements for existing structures. This structured comparison complements the descriptive discussion and provides a clearer understanding of how the NSR has evolved in terms of strength, deformation control, detailing rigor, and seismic performance expectations.

The comparative analysis of the Colombian Seismic Design Code, CCCSR-84, NSR-98, and NSR-10, together with expected future developments based on international seismic design trends, reveals a clear evolution in seismic criteria, analysis methods, detailing requirements, and performance expectations. Below, the main aspects of this comparative analysis are examined:

Table 6. Technical Comparison of Key Seismic Design Parameters in CCCSR-84, NSR-98, and NSR-10.

Parameter	CCCSR-84	NSR-98	NSR-10	Future Developments/International Benchmarking
Design Philosophy	Working-stress design; limited seismic ductility considerations.	Adoption of LRFD; explicit ultimate limit states.	Consolidated capacity design (hierarchy of strengths).	Integration of updated hazard maps, resilience-oriented performance, and performance-based design (PBD).
Force Reduction/Behavior Factor (R)	Concept not fully formalized; implicit reductions.	Introduction of system-dependent R values.	Revised R values based on ductility categories and system behavior.	Calibration of R factors using nonlinear dynamic analyses and PSHA-based targeting.
Ductility Categories	Not defined.	Implicit moderate ductility.	Explicit categories: DES (high), DMO (moderate), DBA (low).	Refinement of ductility levels and detailing requirements following FEMA P-2082 and Eurocode 8.
Capacity Design Requirements	No requirement for $M_c > M_b$.	Initial conceptual introduction.	Full enforcement: $\Sigma M_{cap,column} \geq 1.2 \Sigma M_{cap,beam}$ at joints.	More explicit hierarchy verification, joint robustness checks, and deformation-based criteria.
Drift Limits	No explicit drift checks: serviceability-based.	Introduces maximum drift limits (elastic drift checks).	Drift limited based on ductility and occupancy; explicit Δ/h criteria.	Nonlinear drift limits, residual drift criteria, and functional recovery considerations.
Shear Design Expressions	V_n based on simplified nominal strength without cyclic effects.	Strength-based shear using ϕV_n ; includes seismic amplification.	Shear demand tied to flexural overstrength (capacity design).	Models accounting for cyclic degradation and shear-flexure interaction.
Confinement & Transverse Reinforcement	Minimal confinement; no hinge detailing.	Basic transverse reinforcement for seismic zones.	Explicit confinement in hinge regions, joint cores, and plastic zones (s, A_{sh}, ρ_s).	Stricter transverse reinforcement spacing and confinement rules aligned with ACI 318-19.
Minimum Longitudinal Steel (ρ_{min})	Basic prescriptive minimums.	Increased ρ_{min} for seismic elements.	Adjusted ρ_{min} based on axial load ratio and ductility category.	Updated ρ_{min} and ρ_{max} based on strain limits, buckling mitigation, and high-ductility requirements.
Joint Shear & Anchorage	Not explicitly addressed.	Initial consideration of anchorage in beam-column joints.	Detailed joint shear checks; anchorage length functions of f_y and bar diameter.	Enhanced joint shear models and confinement requirements.
Soil Classification	Basic soil types A, B, C.	Expanded classifications with amplification factors.	Introduction of Vs30-based categories; improved amplification rules.	More refined site-specific amplification from updated PSHA databases.
Spectral Shape	Simplified elastic spectrum.	Two-branch spectrum introduced.	Multi-branch spectrum with plateau and corner periods.	Region-specific spectral shapes based on updated seismic hazard models.
Seismic Coefficients (A_a, A_v)	Uniform coefficients nationwide.	Regional coefficients and zonation maps.	Refined zonation; soil-dependent coefficients.	Integration of state-of-the-art national PSHA with spatially varying hazard levels.
Existing Structures	Not included.	Basic evaluation criteria.	Structuring procedures referencing modern assessment guidelines.	Strengthening/retrofit provisions aligned with ASCE 41-23 and modern assessment guidelines.

1. Evolution of Seismic Zone Classification: The evolution of seismic zonation criteria in Colombia reflects the progressive adoption of more detailed and scientifically grounded approaches. The earliest code, the CCCSR-84, introduced the first national seismic zonation map, which classified regions according to broad historical seismicity and general ground-shaking expectations. Soil categories were simplistic, and seismic coefficients provided minimal differentiation between areas. With the adoption of NSR-98, the classification system was significantly refined through the incorporation of updated seismic records and a more apparent distinction between high-, moderate-, and low-seismicity areas. The code also expanded soil categories and improved hazard differentiation across the national territory. NSR-10 further advanced these concepts by integrating Vs30-based geotechnical

classification, updated national hazard maps, and more sophisticated site amplification factors that considered structural system type, soil profile, and occupancy category. Looking ahead, developments aligned with international trends point to the incorporation of high-resolution probabilistic seismic hazard analyses (PSHA), microzonation studies, and real-time seismic monitoring, which would enable more refined, site-specific seismic spectra for structural design.

2. **Structural Design Requirements:** The CCCSR-84 emphasized a working-stress design philosophy with limited treatment of ductility or inelastic behavior. Seismic demands were defined through prescriptive lateral-force procedures, and the understanding of structural performance under cyclic loading was limited. NSR-98 marked an essential transition by adopting the ultimate limit state design (LRFD) philosophy, providing clearer load combinations and specifying acceptable structural systems for seismic resistance. With NSR-10, structural design requirements became considerably more rigorous: the code mandated response spectrum analysis for many building types, refined the criteria for selecting structural systems, and introduced initial provisions regarding supplemental energy dissipation devices. Future updates inspired by international standards such as ASCE 7, FEMA P-2082, and Eurocode 8 are expected to advance toward performance-based design (PBD), nonlinear analysis procedures, collapse probability assessment, and functional recovery objectives that align structural design with modern global practice.

3. **Materials and Concrete Quality:** Material specifications have also evolved substantially across the Colombian seismic codes. In CCCSR-84, requirements for concrete and reinforcing steel were basic and did not address the specific demands imposed by cyclic seismic loading. NSR-98 improved material guidance by increasing minimum strengths and enhancing detailing requirements, although seismic performance considerations remained limited. NSR-10 introduced stricter material specifications, particularly in high-seismicity regions, including higher concrete strength requirements, improved confinement detailing, and more rigorous reinforcement design rules to ensure ductile behavior during strong earthquakes. International trends suggest that future Colombian revisions may incorporate high-performance concrete (HPC), sustainability-oriented material criteria, performance-based durability requirements, and expanded use of recycled materials and advanced admixtures—consistent with global modernization efforts in structural engineering.

4. **Soil–Structure Interaction (SSI):** Soil–structure interaction provisions were minimal in the CCCSR-84, where seismic demands were primarily derived from broad soil classifications and simplified coefficients. The NSR-98 improved the representation of soil effects through expanded amplification factors, but it still lacked formal SSI analysis procedures. The NSR-10 represented a meaningful shift, integrating clearer SSI considerations, updated foundation design requirements, and soil-dependent seismic coefficients that explicitly accounted for geotechnical conditions. Based on international experience, future advancements in Colombian codes may incorporate advanced geotechnical simulations, nonlinear SSI models, real-time characterization of soil behavior, and site response analyses consistent with modern geotechnical–structural integration.

5. **Deformation Control Requirements:** The CCCSR-84 did not include explicit drift limits, and deformation control was addressed implicitly through strength and stiffness requirements. NSR-98 introduced basic drift limit criteria intended to ensure serviceability and structural stability under seismic loading. NSR-10 significantly expanded and clarified these provisions by establishing explicit lateral drift limits based on occupancy category, ductility level, and structural system type, thereby strengthening control over inelastic deformations during earthquakes. Looking toward the future, international seismic codes increasingly implement residual drift limits, nonlinear deformation criteria, and functional

recovery targets, which could influence future Colombian updates as the nation moves toward performance-based seismic engineering.

6. **New Technologies and Seismic Evaluation Methods:** Technological approaches to seismic evaluation have evolved considerably. CCCSR-84 relied solely on force-based static analysis and did not include dynamic evaluation procedures. NSR-98 and NSR-10 progressively incorporated linear dynamic analysis methods, including response spectrum analysis, and introduced initial guidance on more advanced modeling techniques. Internationally, the trend is shifting toward nonlinear time-history analysis, digital simulation tools, structural health monitoring systems, and vibration-based evaluation methods, which are poised to inform future revisions of the Colombian seismic code as computational resources and structural assessment technologies continue to advance.

7. **Energy Dissipation Systems:** The CCCSR-84 and NSR-98 did not contemplate the use of supplemental energy dissipation systems or base isolation devices. NSR-10 permitted these technologies, but their application remained limited and lacked detailed implementation guidance. International developments increasingly promote the use of seismic dampers, base isolation systems, and other supplemental damping devices, particularly for high-rise buildings and essential infrastructure. These evolving practices are expected to guide future Colombian code updates as advanced seismic protection systems become more widely adopted.

4. Trends and Perspectives

Some trends and perspectives are reached from the analysis of the review made on the evolution and application of Colombian regulations in the seismic design of reinforced concrete buildings with portal frames:

- **Increased Material Demands:** The adoption of the NSR-10 has led to more stringent requirements in material usage. Compared to NSR-98, the NSR-10 mandates a 15–25% increase in concrete volume and reinforcement steel, reflecting a trend toward prioritizing structural resilience in seismic zones.
- **Focus on Seismic Resilience:** Colombian seismic regulations have shifted to incorporate advanced seismic design methods, including modal spectral analysis and pushover analysis. These approaches enhance the precision of structural modeling and improve the ability to withstand seismic forces. This trend aligns with international standards, reflecting the globalization of seismic engineering practices.
- **Academic Interest and Collaboration:** The bibliometric analysis shows consistent annual growth of 4.85% in publications on seismic design. Approximately 75% of these studies focus on reinforced concrete and seismic resistance, while 19.5% involve international collaborations. This indicates a growing global interest in adapting and applying Colombian seismic standards to diverse contexts.
- **Integration of Local Conditions:** The NSR-10 emphasizes soil-structure interaction and includes improved soil classification frameworks that account for Colombia's unique geotechnical conditions. This aligns with a broader trend of tailoring seismic design to local environmental and geological factors.
- **Digital Tools in Design and Analysis:** The use of advanced software, such as ETABS and RStudio for bibliometric and structural analysis, has become a key component of seismic design. These tools enable engineers to optimize designs and assess seismic performance with greater efficiency and accuracy.

Note that the reported increase of 15–25% in concrete and steel associated with NSR-10 is based on previously published technical studies that evaluated the impact of successive Colombian code editions on the design of reinforced concrete moment-resisting frames. These studies consistently report increases in material demand when transition-

ing from NSR-98 to NSR-10 due to stricter requirements for ductility, confinement, shear strength, minimum reinforcement ratios, and capacity design checks. Although the present manuscript does not include a complete numerical case study, given its focus on bibliometric analysis and regulatory comparison, these prior investigations provide representative quantitative benchmarks that support the engineering implications discussed herein. Future work may include the design and comparison of a representative building across multiple NSR versions to expand these findings further.

Some perspectives are reached from the BA, and the document review was made from the standards analyzed:

- **Advanced Retrofitting and Rehabilitation:** As Colombia's infrastructure ages, retrofitting older buildings constructed under outdated codes will be critical. Incorporating modern seismic dissipation technologies, such as base isolators and energy-absorbing devices, can significantly reduce the vulnerability of these structures. This presents an opportunity for research and development in retrofitting technologies tailored to Colombia's unique structural and economic context.
- **Sustainability in Construction:** Future iterations of the NSR could incorporate guidelines for the use of sustainable materials, such as recycled aggregates and low-carbon concrete, to address environmental concerns while maintaining structural performance. Integrating sustainability into seismic design is becoming increasingly important globally.
- **Bridging Knowledge Gaps in Rural Areas:** Many rural regions in Colombia lack the resources and expertise to implement the NSR-10 fully. Expanding educational programs and providing accessible tools for local engineers and builders can enhance compliance with seismic regulations, thereby reducing vulnerability in underserved areas.
- **Dynamic Response to Urban Growth:** Rapid urbanization in Colombia necessitates adaptive seismic design strategies to accommodate high-density residential and commercial developments. Innovations in modular and prefabricated systems, combined with enhanced seismic resilience, can effectively address these needs.
- **International Integration and Benchmarking:** Strengthening Colombia's role in global seismic engineering networks is crucial. Benchmarking NSR-10 against international standards, such as Eurocode 8 and ACI 318, can foster greater collaboration, improve code efficacy, and position Colombia as a leader in seismic research and design.
- **Holistic Risk Mitigation:** Beyond structural design, a comprehensive risk mitigation framework encompassing urban planning, emergency preparedness, and community engagement is essential. Such an approach would reduce human and economic losses during seismic events, complementing advancements in engineering.

5. Conclusions and Recommendations

Based on the analysis conducted, the following conclusions were drawn to summarize key findings and provide insights into the comparison of seismic regulations, literature search strategies, and the effective use of advanced research tools:

- The evolution of Colombian seismic design regulations, notably the transition from NSR-98 to NSR-10, represents a significant milestone in improving structural safety and resilience. The adoption of NSR-10 led to stricter standards, including a 15–25% increase in the required volumes of concrete and steel to meet updated seismic performance criteria. These changes, coupled with the introduction of new soil classifications and site-specific seismic coefficients, have enhanced design accuracy and reduced the structural vulnerability of buildings in high-risk seismic zones by an estimated 30%.
- The bibliometric analysis revealed steady annual growth of 4.85% in academic publications on seismic design regulations from 1989 to 2023, with 75% of studies focusing

on structural systems and seismic resistance. Additionally, 19.5% of the analyzed documents highlighted international collaborations, underscoring the global relevance of these regulations. Colombia has emerged as the third most influential country in this field, after the United States and China, with notable contributions from institutions such as Universidad del Valle and researchers such as Carrillo J.

- Despite these advancements, significant gaps remain. Many older structures, especially in rural areas, were designed under outdated codes and are highly vulnerable to seismic events. Future efforts should prioritize advanced retrofitting techniques tailored to the local context and the integration of sustainable materials, aligning with global engineering trends.
- The Colombian NSR has progressively incorporated more stringent seismic requirements, aligned with modern concepts such as capacity design, improved confinement, explicit ductility categories, and refined detailing provisions. These changes strengthen the overall seismic performance expected from reinforced concrete moment-resisting frame structures. The bibliometric analysis shows a growing academic interest in these regulations, reflected in increased scientific production and thematic consolidation in areas such as ductility, seismic vulnerability, and structural retrofitting. While this study does not quantify the seismic performance gains associated with each code revision, the literature consistently suggests that the increased demands introduced in NSR-10 contribute to the development of more resilient structural systems. Future research may include numerical case studies comparing material quantities, structural behavior, and seismic performance under different NSR versions.

Based on the comparative analysis of the Colombian seismic design regulations and the trends identified in the bibliometric evaluation, the following recommendations are proposed to guide future research, engineering practice, and the continued improvement of seismic design in Colombia:

- Develop Representative Structural Case Studies. Future research should include the design and analysis of benchmark reinforced concrete portal–frame buildings in accordance with the CCCSR-84, NSR-98, and NSR-10 provisions.

These case studies would allow quantification of changes in material demands (steel and concrete), ductility and detailing requirements, drift performance, and the column–beam strength hierarchy. Such quantitative evidence is essential to validate and complement the qualitative findings presented in this study.

- Assess and Prioritize Retrofit Needs of Existing Buildings. A significant portion of Colombian buildings were constructed before NSR-98 and lack adequate confinement, shear detailing, and capacity design considerations.

Engineering institutions and local authorities should: perform seismic vulnerability assessments of older buildings, identify typical structural deficiencies, and develop retrofit strategies tailored to standard Colombian construction practices. This is critical for reducing seismic risk in urban and rural areas.

- Expand Research on Ductility, Confinement, and Local Detailing. The bibliometric analysis reveals limited scientific production focused on: ductility categories (DES, DMO, DBA), confinement reinforcement in plastic hinge regions, shear strength under cyclic loading, and minimum/maximum reinforcement ratios. Strengthening research in these areas will support more robust and consistent design provisions in future NSR versions.

- Incorporate Performance-Based Seismic Design (PBSD) Approaches. Colombia should progressively integrate PBSD concepts into its regulatory framework by defining performance objectives (IO, LS, CP), promoting nonlinear analysis for essential and mid-to high-rise structures, and establishing national acceptance criteria for modeling and

deformation limits. PBSO would align the NSR with international best practices and enhance resilience-oriented design.

- Improve Seismic Hazard Characterization and Site-Specific Provisions. To refine seismic demand estimates, future code updates should incorporate: updated probabilistic seismic hazard analyses (PSHA), refined design spectra for different tectonic regions, and expanded microzonation studies for major Colombian cities. Improving hazard characterization will strengthen the accuracy and reliability of seismic design requirements.

- Strengthening National and International Collaboration. Only 19.5% of the publications identified involve international collaboration. To foster innovation and methodological rigor, academic and research institutions should promote cooperation with countries experienced in seismic design, such as Chile, Mexico, Japan, New Zealand, and the United States. Such collaboration would support experimental programs, shared databases, and comparative studies.

- Enhance Transparency and Accessibility of Research Data. Researchers should increase the availability of bibliometric datasets, structural models used in code—comparison studies, supplemental materials, and analytic scripts. Data transparency enhances reproducibility, supports collaboration, and advances seismic design research in Colombia.

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