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A systematic review of seismic-resistant precast concrete buildings

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ABSTRACT

Precast concrete buildings (PCB) offer several advantages, including swift construction, exceptional quality, enhanced durability, decreased formwork requirements, and reduced labour. However, it is crucial to effectively study the connections between the various prefabricated elements that make up the structure, particularly in the face of dynamic loads and seismic actions. Extensive research has been conducted to develop seismic-resistant PCB, underscoring the necessity of exploring research approaches, identifying trends, addressing gaps, and outlining future research directions. A thorough analysis was carried out on a literature set comprising 127 articles published between 2012 and May 2023, using a three-step research process that included bibliometric search, quantitative analysis, and qualitative analysis. The primary objective was to identify prevailing research trends and pinpoint current gaps that would contribute to the advancement of future research. The scientific mapping of authors' keywords revealed the correlation between PCB and topics such as dry connections, energy dissipation, optimal design, and progressive collapse, highlighting the diverse nature of current research in the field. Furthermore, the qualitative literature analysis demonstrated that frame and shear wall systems emerged as the predominant categories. This dominance can be attributed to the seismic performance reference being the traditional cast-in-place building approach. Nonetheless, this study brings attention to several notable research gaps. These gaps include the necessity to explore innovative, resilient structural systems in greater detail and the requirement for adopting state-of-the-art methodologies that facilitate decision-making processes in integrating PCB seismic safety and sustainability. This study provides a roadmap for future research projects and reports on the latest developments and trends in seismically safe PCB research.

1. Introduction

The construction industry is responsible for consuming 40% of material resources, 60% of minerals, 25% of water, 35% of energy, and 12% of soil; moreover, it contributes to over 25% of solid waste and 38% of greenhouse gas emissions worldwide [1]. As population growth continues, the demand for new structures and infrastructure is expected to rise significantly; by 2050, the need for new buildings is projected to surpass 415 billion m^2 [2]. Nevertheless, the transition of current building design, management, construction, and operation models towards sustainable development is often advocated as an alternative and an opportunity within the industry to mitigate the impacts above [3]. Prefabrication is widely recognized as a practical approach to fulfilling the requirements of sustainable development [4].

The precast concrete building (PCB) system involves components or complete modules that closely resemble those created in traditional cast-in-place construction. These elements are manufactured in a factory or on-site and assembled with minimal on-site construction [5]. Despite its long history, researchers have classified this technique as a modern method of construction (MMC) within the industrialized building systems (IBS) category, specifically as a subcategory of off-site and near-site prefabrication (OSPM) [6].

In late 1970 s New Zealand, using precast concrete elements for seismic resistance in portal frames and moment-resisting walls was not the norm but rather an exception. However, by the mid-1980 s, it witnessed a rapid expansion, driven by high-interest rates and the demand for additional space, even without complete technical support. The system's accelerated construction pace provided a distinct cost advantage over traditional methods [7]. Initially, design assumptions were based on extrapolations from tests conducted on cast-in-place

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specimens. Still, concerns emerged regarding the need for further investigation into design solutions. While contractors responded to the growing demand, starting in 1988, the University of Canterbury and other institutions embarked on in-depth studies of the design, research, fabrication, and construction aspects [8]. Research on precast concrete seismic systems has been extensive worldwide. In the 1990 s, the United States witnessed the progression of the PRESS (Precast Seismic Structural Systems) research program, which received sponsorship from the National Science Foundation (NSF), the Precast/Prestressed Concrete Institute (PCI), and the Precast/Prestressed Concrete Manufacturers Association of California (PCMAC). This program spanned a decade and involved testing a five-story precast concrete building at a 60% scale under simulated seismic loading. Despite being subjected to drift levels of up to 4.5%, the structure exhibited unusual behaviour [9]. The PRECAST EC8 project was successfully concluded in 2007 following four years of extensive research. The project was based on studies conducted by ASSOBETON (Italian Association of Precast Producers) and the ELSA laboratory of the joint research centre, along with the project "Seismic behaviour of industrial precast concrete buildings". These studies showcased the exceptional performance of precast structures during seismic events, highlighting their equivalence to traditional cast-in-place systems, even in the absence of monolithic joints [10]. The SAFECAST project, which concluded in 2012, focused on investigating the seismic behaviour of both traditional and innovative mechanical connections and the impact of shear walls in conjunction with portal frame structures—the project aimed to provide guidelines for designing such systems effectively [11]. In the subsequent SAFECLADDING project, which concluded in 2015, the seismic behaviour of precast concrete buildings (PCB) with cladding panels was extensively studied. The project evaluated design criteria, including isostatic, dissipative, and integrated approaches. It successfully validated the reliability of the dissipative system [12]. Over the years, numerous research endeavours worldwide have contributed significantly to seismic safety in PCB, expanding the existing knowledge base in this area.

Researchers widely acknowledge the numerous advantages associated with implementing precast concrete construction. These advantages include accelerated construction speed, the superior quality of precast concrete units, enhanced durability, and reduced labour and formwork requirements [13]. Additionally, numerous studies have shown that precast structures can reduce carbon emissions by 10% and waste generation by 52% compared to traditional concrete structures [14]. However, there are also certain disadvantages to consider. Effective methods for joining precast elements, particularly to withstand seismic actions, need to be developed. Rigorous quality control measures are necessary to maintain relatively small tolerances, and specialized equipment with excellent erection capabilities is required [15]. These considerations are essential when comparing precast construction to traditional cast-in-place buildings. The connection system plays a crucial role in the overall structural performance. It has significant methodological implications for the installation and erection processes of prefabricated structural components.

The traditional primary objective of structural engineering has been to prioritize maximum safety while minimizing investment. However, in today's context, structural engineering has seen a growing emphasis on sustainability, leading to the recognition of other significant aspects. These aspects are categorized into three sustainability objectives: economic, environmental, and social [16]. Researchers believe that prefabricated construction is emerging as an efficient and sustainable alternative for designing, producing, and constructing structures [17]. Consequently, the traditional problem structural engineers face becomes more complex and necessitates a decision-making process for resolution [18]. Thus, a decision-making process must be employed to achieve a consensus among the three pillars of sustainability. This process facilitates the rational choice of a solution based on specific information and judgment regarding the chosen criteria [18]. For instance, in one study, researchers determined the optimal sustainable structural scheme for various housing alternatives using modern construction methods. They evaluated sustainability by considering 38 economic, environmental, and social indicators [19]. Other researchers have proposed a methodology for assessing the sustainable performance of building foundations through ground improvement interventions. They suggest employing the ELECTRE IS methodology to introduce a comprehensive set of 37 indicators [20].

A systematic review is needed to encompass the extensive literature on the seismic safety of precast concrete buildings (PCB). While this system is part of the broader industrialized building systems (IBS), previous reviews have generally examined it alongside other construction methods [21]. However, these reviews still need to delve into the specific issues and research trends directly related to the seismic safety of PCB. A comprehensive review of the seismic safety literature has been conducted to evaluate the progress, code development, and applications of various systems such as frames, walls, diaphragms, and bridges [22]. In addition, a comprehensive review of general concepts, code provisions, wall connections, results, and the impact of post-tensioning in walls was conducted [23]. In addition, a detailed review focused explicitly on hybrid post-tensioned relationships, emphasizing the column-beam connection and its influence on the behaviour and performance of frames under seismic loads [24]. However, current trends within the knowledge domains have yet to be evaluated to determine which seismic structural systems have garnered the most attention from researchers in recent years and how they take advantage of industrialized construction. In addition, an analysis of current research trends can provide valuable information to improve solutions that fit the changing needs of society, which defines the research questions addressed in this study. Therefore, the specific objectives of this study are: 1) To evaluate the quantitative analysis and its bibliometric parameters and develop scientific maps. 2) To identify categories and subcategories as current trends in knowledge. 3) To qualitatively analyze the literature. 4) To determine gaps in the research. 5) To facilitate future lines of research based on the analysis carried out.

2. Methodology

A literature review is an essential tool for exploring and understanding a specific area of knowledge. It facilitates the identification of knowledge gaps and plays a crucial role in establishing future research recommendations and encouraging interdisciplinary collaboration with related research areas [25]. This research aims to synthesize domain knowledge, identify research gaps, and outline future research directions in the field of PCB seismic safety. A combined review method, incorporating both quantitative and qualitative approaches, was employed to achieve these objectives. This study delves deeply into compressing the domain knowledge by utilizing this method, which encompasses both a quantitative review and a qualitative review. By integrating these approaches within a single research endeavour, the strengths of each method are maximized while mitigating their respective disadvantages [26]. In this study, the scientometric analysis served as the quantitative criterion, while the systematic review was employed as the qualitative criterion.

The scientometric analysis is a statistical method that enables the visualization of scientific research's structural and dynamic aspects. One crucial technique within this analysis is bibliometrics, which helps represent the knowledge domain and elucidate the relationships between articles, journals, and keywords [27]. The systematic review, on the other hand, facilitates the extraction, integration, and comparison of topics, methods, and theories. It allows for the comprehensive exploration, analysis, interpretation, and summarization of all available research about a specific domain [26]. Combining these two approaches can give a holistic view of the reviewed topics, ensuring a thorough and comprehensive review. This approach guarantees an in-depth examination of the subject matter and provides a complete understanding of the research landscape.

This study undertook a literature review in multiple stages to address predefined research questions concerning the latest research topics in PCB. Fig. 1. provides a comprehensive overview of the various stages employed in this research. Firstly, a data collection process was conducted. Secondly, a scientometric analysis was performed to obtain an overview of knowledge in the field. This analysis encompassed aspects such as publication trends over time, article distribution, geographic cooperation, co-authorship, citation analysis to identify influential articles and co-occurrence of keywords. In the third stage, a systematic literature review was carried out. The objective was to analyze themes and sub-themes based on the groups identified through the scientometric analysis. This comprehensive examination resulted in recommendations for future research directions about PCB.

2.1. Stage one. Data recovery

The comprehensive collection of bibliographic data forms the foundation for conducting a state-of-the-art study within a particular domain. Initially, research questions are defined, and keywords are established to initiate the search process. These keywords align with the subject's main criteria under investigation, encompassing the research object, scope, and specific topics of interest. Furthermore, terms that are not relevant to the objectives of this study are identified for exclusion. This systematic approach aids in determining the precise set of keywords that will constitute the search algorithm.

For the search process, two databases were chosen: Web of Science and Scopus. It is worth noting that some researchers believe that Scopus covers a broader range of journals and includes more recent publications [28]. This study combined both search engines to create a comprehensive database. An iterative search process was initiated to develop a practical algorithm scheme that would yield optimal results. The algorithm employed in both search engines was as follows: "TITLE-ABS-KEY ((prefabricated concrete building) or (precast concrete structural system for building) or (prefabricated industrial building) or (offsite construction building) or (precast RC structural system for building) or (prefabricated RC building) or (prefabricated modular building)) and (seismic or earthquake or connection or wall or resilient or resilience or 'shear wall' or joint or 'shake table') not (bridge or management or 'steel building' or tunnel or thermal)." In the case of Scopus, a slight variation was made with the inclusion of quotation marks around the terms "shear wall" and "shake table," along with the addition of the term "not." The search was conducted in early May 2023.

The data collection process consisted of four stages [29]. In the first stage, 370 documents were identified in the Web of Science, while 470 were found in Scopus. These results underwent initial filtering based on document type, with only research articles being selected in both cases. The articles chosen from the Web of Science were limited to civil engineering, construction technology, engineering geology, and multidisciplinary geosciences. As for Scopus, articles within the field of engineering were included.

Additionally, only articles written in English were considered, and the search was restricted to the period from 2012 to 2023. This timeframe was chosen to focus on recent topics and research trends, with a minimum of ten years deemed sufficient for selecting the most up-to-date articles [21]. The search results were consolidated in the second stage to eliminate duplicate articles. Following that, a thorough review

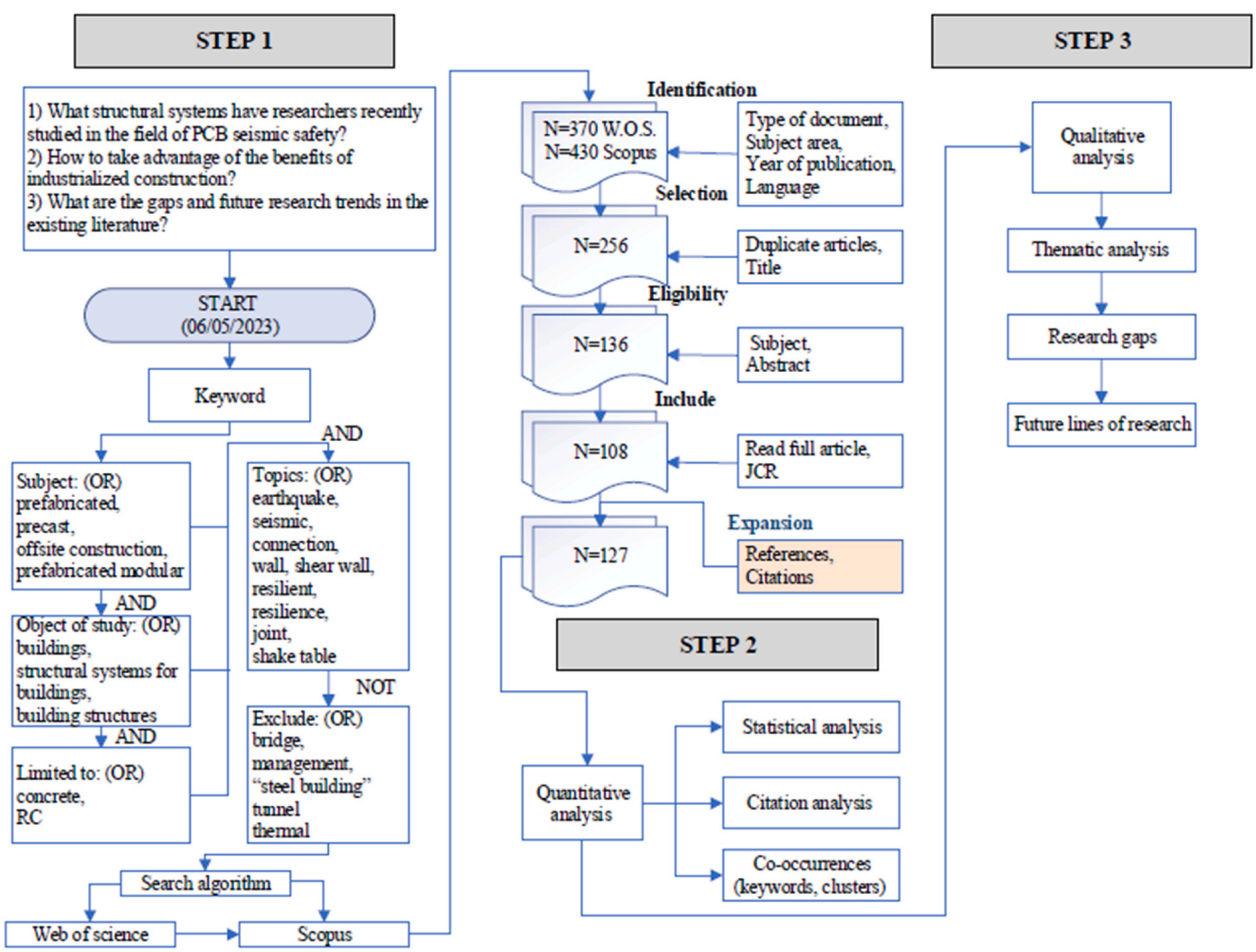


Fig. 1. Research stages of this study.

of the article titles enabled the elimination of irrelevant articles, resulting in a selection of 256 articles. The third stage involved assessing the eligibility of the documents by ensuring their alignment with the topic of seismic safety in PCB, taking into account the scope of the present study. As a result, 136 documents were considered relevant. Finally, in the fourth stage, all selected documents underwent an extensive reading to refine the literature further. The final database was determined by considering each document's relevance to seismic safety in PCB.

Consequently, a total of 108 documents were retained. Furthermore, after completing the four stages above, additional articles of interest were identified by reviewing citations and references within the final set of documents. This process resulted in a final database of 127 articles for the literature review research.

2.2. Stage two. Quantitative analysis

In the bibliographic search, a total of 127 articles were extracted. Subsequently, the statistical analysis of the bibliometric characteristics of the literature was performed using the VOSviewer software [27]. This freely available software is specifically designed to generate scientific maps and establish connections between bibliometric parameters based on distance. Citation analysis is a fundamental measure to quantify the influence of scholarly works. By examining these parameters, the overall structure of the literature and the relationships between different domains can be determined. VOSviewer is a valuable tool for conducting literature reviews across various fields, including construction engineering and project management [30]. VOSviewer was utilized to perform several vital tasks. Firstly, it was employed to import the literature sources and subsequently calculate the influence of journals, scholars, and influential publications. Additionally, VOSviewer was employed to examine geographic cooperation, analyze the co-occurrence of research keywords, and generate clusters based on these parameters. These analyses collectively provide an overview of the current research landscape within the domain, facilitating qualitative discussions and addressing the research questions at hand [30].

2.3. Stage three. Qualitative analysis

The third stage comprises the qualitative literature evaluation through a systematic analysis. This assessment aims to foster a comprehensive discussion on the identified research topics, aiming to identify knowledge gaps. Subsequently, recommendations and future directions can be formulated based on these findings to guide the research community and contribute to the existing body of knowledge. A meticulous analysis of the 127 selected articles was carried out to ensure the reliability and relevance of the findings, taking into account their quality and appropriateness to the scope of this study. It should be noted that this procedure is commonly employed in previous studies of a similar nature [31].

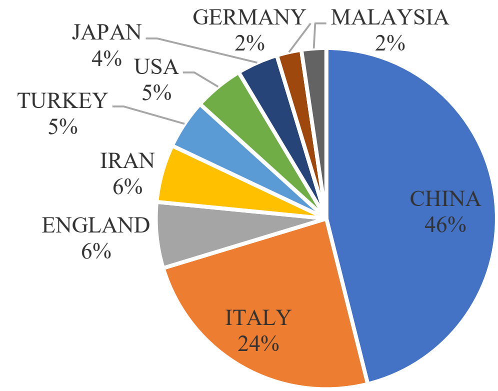


Fig. 3. Geographical location of the investigations.

3. Quantitative analysis

3.1. General characteristics of the database

A comprehensive analysis was conducted on the 127 selected documents to uncover the sample characteristics. The selected documents were published between 2012 and May 2023 to focus on recent topics and research trends. Fig. 2 illustrates the annual distribution of the published articles, highlighting a general increasing trend; it is anticipated that research in the field of seismic safety of PCB will continue to grow in the forthcoming years. The advantages associated with prefabricated structures, such as rapid construction, high efficiency, and environmental protection [32], may contribute to the researchers' inclination toward this subject.

Fig. 3 presents the research contribution by country, with China (46%) and Italy (24%) leading the way. The remaining 30% of publications are distributed among several countries, including England, Iran, Turkey, the United States, Japan, Germany and Malaysia.

3.2. Geographic cooperation

It is essential to remember that various factors, such as the development of local industries, materials, products and specific needs, influence research activities in each country. Fig. 4 shows the analysis of the most research-active countries, where the font size and the nodes' variation represent the volume of publication, allowing us to identify the critical regions of contribution and their interaction (thickness of the links). Table 1 shows quantitative measures of the countries. Link strength, number of articles and total citations are positively correlated, suggesting that any of these parameters can be used to assess the research productivity of a region. Average and normalized sources do not correlate, indicating that a country's influence and contribution to research do not depend only on the number of publications.

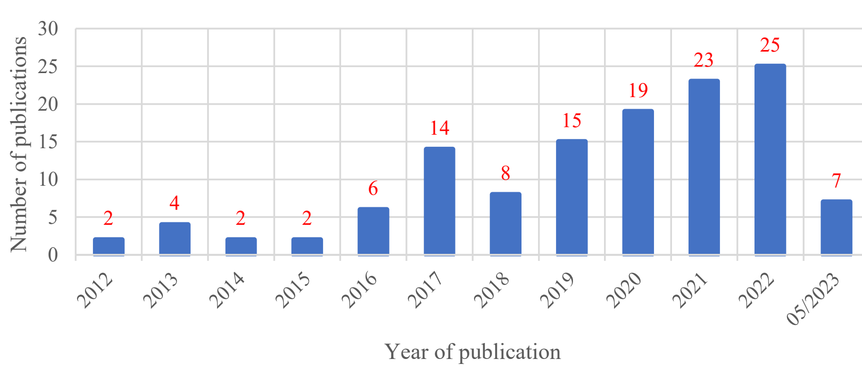


Fig. 2. Number of articles per year (2012–05/2023).

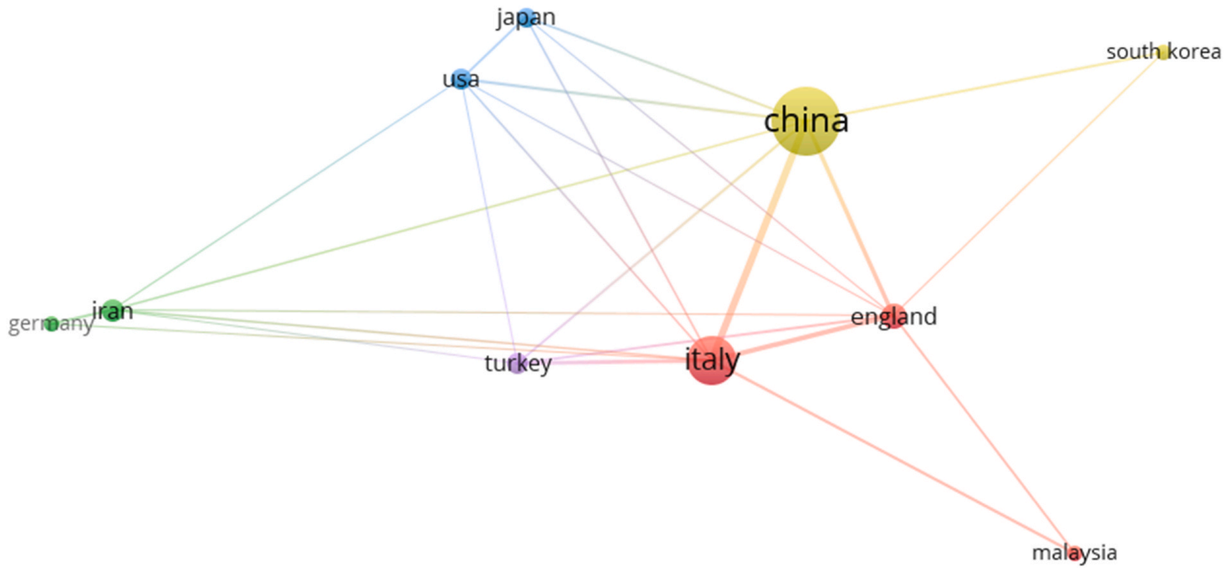


Fig. 4. Countries active in research.

Table 1
Countries active in research.

Countries	Total Link	Documents	Citations	Avg. Pub. Year[a]	Avg. Citations[b]	Norm. Citations[c]	Avg. Norm. Citations[d]
China	76	59	553	2021	9,37	92,33	1,6
Italy	86	31	906	2018	29,23	82,36	2,7
England	41	8	260	2018	32,50	28,89	3,6
Turkey	21	6	52	2021	8,67	13,00	2,2
United States	13	6	171	2018	28,50	19,00	3,2
Iran	11	7	54	2020	7,71	13,50	1,9
Japan	9	5	76	2018	15,20	10,86	2,2
Malaysia	8	3	32	2016	10,67	3,20	1,1
Germany	5	3	34	2020	11,33	8,50	2,8
South Korea	4	3	46	2018	15,33	5,75	1,9

[a] Average year published,[b] Average citations,[c] Normalized citations,[d] Average normalized citations

China and Italy emerge as the leading countries in terms of number of publications; in terms of citations, Italy stands out as the most active country. When considering the generation of relevant research results (average number of sources) and of high influence and current research position (average number of normalized citations), England, Italy and the United States come out on top. These results are because England possesses a great tradition in building construction using modern construction methods [33], Italian researchers have gained relevance due to the scientific response given to the occurrence of earthquakes in their territory in recent years, and finally, some authors agree with the fact that the genesis of industrialized construction cannot be dissociated from the United States [6]. It should be noted that although the People's Republic of China generates many publications, a situation congruent with the recent large-scale urbanization of China that seeks sustainable development [34]; however, it is essential to mention that their results have not yet reached a considerable number of citations, which prevents them from positioning themselves as highly relevant and influential in the field.

3.3. Source analysis

Based on the number of publications and citations, the top-ranked journals are Engineering Structures, Bulletin of Earthquake Engineering, and Journal of Building Engineering.

Regarding influence per publication, the journals with the highest average number of citations per article are Earthquake Engineering & Structural Dynamics, Structural Concrete, and Engineering Structures. Furthermore, the average normalized citation reflects the journals' strong average influence per year, indicating a current and continuous impact. The best-positioned journals in this regard are Earthquake Engineering & Structural Dynamics, Structural Concrete, and Engineering Structures. Notably, despite having a low total or average citation count, Soil Dynamics and Earthquake Engineering demonstrate their current influence through the average normalized citation. (Table 2).

3.4. Co-author analysis

Table 3. provides information on the number of documents where each author is mentioned, the total number of citations they received, and their average year of publication, which indicates their productivity and the period during which they were most active. "Dal Lago (2018)" contributed nine articles with 220 citations, producing an average of 24.44 citations per article; this highlights the impact of his work on advancing knowledge. However, authors such as "Toniolo (2016)," "Negro (2017)" and "Biondini (2016)" achieved higher average citation counts of 52.20, 48.40, and 34.60, respectively. These figures underscore the relevance of their research. Regarding the current position measured by the average normalized citation, the authors "Negro (2017)", "Toniolo (2016) and "Yu (2020)" are at the forefront of the list, indicating their influential standing in the field.

3.5. Most cited articles

Table 4. presents the 15 most cited papers. The article with the most citations [35] is the oldest. It explores the challenges of seismic design in precast concrete structures, focusing specifically on the impact of the

Table 2
Source analysis

Journal	Total Link	Documents	Citations	Avg. Pub. Year[a]	Avg. Citations[b]	Norm. Citations[c]	Avg. Norm. Citations[d]
Engineering Structures	80	33	769	2019	23,30	85,44	2,59
Bulletin of Earthquake Engineering	51	14	253	2018	18,07	25,3	1,81
Journal Of Building Engineering	27	14	85	2021	6,07	21,25	1,52
Structural Design of Tall and Special Buildings	8	10	114	2018	11,40	11,4	1,14
Structures	12	7	61	2021	8,71	15,25	2,18
Journal of Earthquake Engineering	5	4	30	2022	7,5	6,00	1,50
Journal of Structural Engineering	6	4	72	2018	18	10,29	2,57
Soil Dynamics and Earthquake Engineering	22	4	70	2021	17,5	11,83	2,96
Structural Concrete	29	4	147	2018	36,75	13,36	3,34
Computers and Concrete	14	3	14	2018	4,67	1,75	0,58
Earthquake Engineering & Structural Dynamics	9	3	124	2017	41,33	13,78	4,59
Structural Control & Health Monitoring	1	3	25	2020	8,33	2,6	0,87

[a] Average year published, [b] Average citations, [c] Normalized citations, [d] Average normalized citations

Table 3
Co-author Analysis.

Author	Total Link	Documents	Citations	Avg. Pub. Year[a]	Avg. Citations[b]	Norm. Citations[c]	Avg. Norm. Citations[d]
Dal Lago, Bruno	91	9	220	2018	24,44	22,00	2,44
Toniolo, Giandomenico	73	5	261	2016	52,20	23,73	4,75
Negro, Paolo	61	5	242	2017	48,40	26,89	5,38
Biondini, Fabio	59	5	173	2016	34,60	17,30	3,46
Lamperti Tornaghi, Marco	46	4	60	2020	15,00	8,57	2,14
Pan, Wei	23	5	60	2021	12,00	15,00	3,00
Wang, Zhen	23	5	60	2021	12,00	15,00	3,00
Brunesi, E.	12	5	89	2019	19,80	16,50	3,30
Nascimbene, Roberto	12	5	89	2019	21,00	17,50	3,50
Yu, Zhiwu	9	3	63	2020	21,00	12,60	4,20
Baghdadi, Abtin	8	3	34	2020	11,33	8,50	2,83
Wu, Hao	5	5	23	2021	4,80	6,00	1,20
Pan, Peng	4	3	44	2018	14,67	8,80	2,93
Nagae, Takuya	2	3	59	2017	19,67	8,43	2,81
Heristchian, Mahmoud	8	3	34	2022	11,33	8,50	2,93

[a] Average year published, [b] Average citations, [c] Normalized citations, [d] Average normalized citations

Table 4
Most cited articles in the field of seismic safety of PCB.

Title	Authors	Public. Year	Source Title	Citations	Average per Year	Ref.
Precast concrete structures: the lessons learned from the L'Aquila earthquake	Toniolo, Giandomenico	2012	Structural Concrete	107	8,92	[35]
Precast concrete wall with end columns (PreWEC) for earthquake resistant design	Sritharan, Sri	2015	Earthquake Engineering & Structural Dynamics	94	10,44	[36]
Pseudodynamic tests on a full-scale 3-storey precast concrete building: Behavior of the mechanical connections and floor diaphragms	Bournas, Dionysios A.	2013	Engineering Structures	91	8,27	[11]
Damage and collapses in industrial precast buildings after the 2012 Emilia earthquake	Savoia, Marco	2017	Engineering Structures	86	12,29	[37]
Pseudodynamic tests on a full-scale 3-storey precast concrete building: Global response	Negro, Paolo	2013	Engineering structures	73	6,64	[10]
Beam-column joints in continuous RC frames: Comparison between cast-in-situ and precast solutions	Breccolotti, Marco	2016	Engineering Structures	64	8,00	[38]
Role of wall panel connections on the seismic performance of precast structures	Biondini, Fabio	2013	Bulletin Of Earthquake Engineering	63	5,73	[115]
Friction-based dissipative devices for precast concrete panels	Dal Lago, Bruno	2017	Engineering Structures	58	8,29	[117]
Seismic performance assessment of low-rise precast wall panel structure with bolt connections	Guo, Wei	2019	Engineering Structures	49	9,80	[108]
Seismic response of precast structures with vertical cladding panels: The SAFECLADDING experimental campaign	Negro, Paolo	2017	Engineering Structures	42	6,00	[12]
Experimental investigation of prefabricated beam-to-column steel joints for precast concrete structures under cyclic loading	Li, Zuohua	2020	Engineering Structures	40	10,00	[65]
Experimental and numerical investigation of the seismic response of precast wall connections	Brunesi, E.	2017	Bulletin Of Earthquake Engineering	40	5,71	[110]
Seismic design and performance of dry-assembled precast structures with adaptable joints	Dal Lago, Bruno	2018	Soil Dynamics and Earthquake Engineering	35	5,83	[52]
Experimental study of a fabricated confined concrete beam-to-column connection with end-plates	Li Shufeng	2018	Construction and Building Materials	34	5,67	[53]
Experimental study of a novel multi-hazard resistant prefabricated concrete frame structure	Lin, Kaiqi	2019	Soil Dynamics and Earthquake Engineering	33	6,60	[123]

2009 L'Aquila earthquake in Italy. The second most cited article [36] investigates using precast concrete walls as an earthquake-resistant system. The third paper [11] conducts an experimental study on a full-scale precast concrete building, particularly on the mechanical connections.

The article with the most decisive influence on the scientific community (12.29), written by Savoia, Marco [37], examines the damage inflicted on industrial precast concrete buildings due to the 2012 Emilia earthquake in Italy. These results highlight the significant impact of Italian researchers in seismic safety research, especially in response to earthquakes experienced in their region.

3.6. Co-occurrence of author keywords

Keywords are crucial for summarising existing research and highlighting areas explored within a specific domain. A keyword network provides information on the relationships between research topics, patterns, and intellectual organization [38]. Fig. 5 shows the patterns observed in the field of PCB seismic safety and sheds light on the issues investigated. This tool has been used by previous researchers [31] to obtain valuable information on scientific keyword mapping, which is generated by analyzing co-occurrences and author keywords. A minimum occurrence threshold of three individual words was set, resulting in 36 author keywords exceeding this limit out of 482. A synonym file was incorporated to clean and consolidate words with similar semantic meanings. For example, terms such as prefabrication - prefabricated, seismic behaviour - seismic behaviour - seismic performance, and shear walls - shear wall were accumulated in their synonyms categories. As illustrated in Fig. 5, the most frequently mentioned keyword is "seismic behaviour". Other often repeated keywords are "precast concrete," "cladding panels," "precast buildings," and "shear wall," among others. The main keyword categories were identified by analyzing the most frequent keywords, their co-occurrence and visualization. In addition, the criteria established by this study's authors were considered during the categorization process. The resulting map consists of six groups, each representing a different field conceptually related or relevant to the study area.

1) Cluster Red (C-1): Frame system (beam-column connection, beam-to-column connection, cyclic loading, ductility, finite element analysis, monolithic-like connections, precast structure, prefabricated, seismic behaviour) References [35,37,38,44–48,50–59,62–71,73,74,173–191].
2) Cluster Green (C-2): Shear wall (beam-column joints, dry connections, lightly reinforced wall, precast concrete structures, prefabricated structure, seismic response, shear wall, wall-to-wall connection) References [10,11,36,77–80,82–93,98–103,107–113,192–203].
3) Cluster Blue (C-3): Cladding panels system (cladding panels, connection devices, connections, industrial buildings, precast buildings, seismic design) References [12,114–122,204–208].
4) Cluster Yellow (C-4): Progressive collapse (energy dissipation, experimental testing, incremental dynamic analysis, moment connection, progressive collapse) References [123,125–129].
5) Cluster Purple (C-5): Modular building (high-rise building, modular building, numerical simulation, precast concrete) References [4133–137,209].
6) Cluster Cyan (C-6): Emerging methodologies (optimum design, precast, residual drift, self-centering) References [139,141–145].

Table 5 provides statistical insights into the keywords used in the analysis. The total link strength represents the connections between a specific keyword and the other keywords in the dataset. Among the keywords, "seismic behaviour," "precast concrete," and "precast buildings" exhibit the highest degree of interrelation with other keywords and also have the highest occurrence frequency within the sample. The average year of publication column in Table 5 indicates the topicality of the keywords. Notably, the keywords "high rise building," "modular building," "cyclic loading," "finite element analysis," and "optimum design" emerge as the most current and relevant in the field of seismic safety of PCB. The average and normalized average citations shed light on specific keywords' significance and present influence. For instance, keywords such as "wall-to-wall connection," "lightly reinforced wall," and "experimental testing" demonstrate notable relevance and current impact based on their average citation counts and normalized average citations.

4. Qualitative analysis

This section presents a thematic analysis conducted to understand the current trends in research related to the seismic safety of precast concrete buildings (PCB). A categorization consisting of six main themes and eight subthemes was established that effectively organizes the various lines of research within the field. The sample encompassed all 127 articles, carefully selected to represent the topic comprehensively. The articles considered in this analysis covered 2012 to May 2023.

4.1. Frame system (number of articles=49)

The precast concrete frame plays a crucial role in the precast

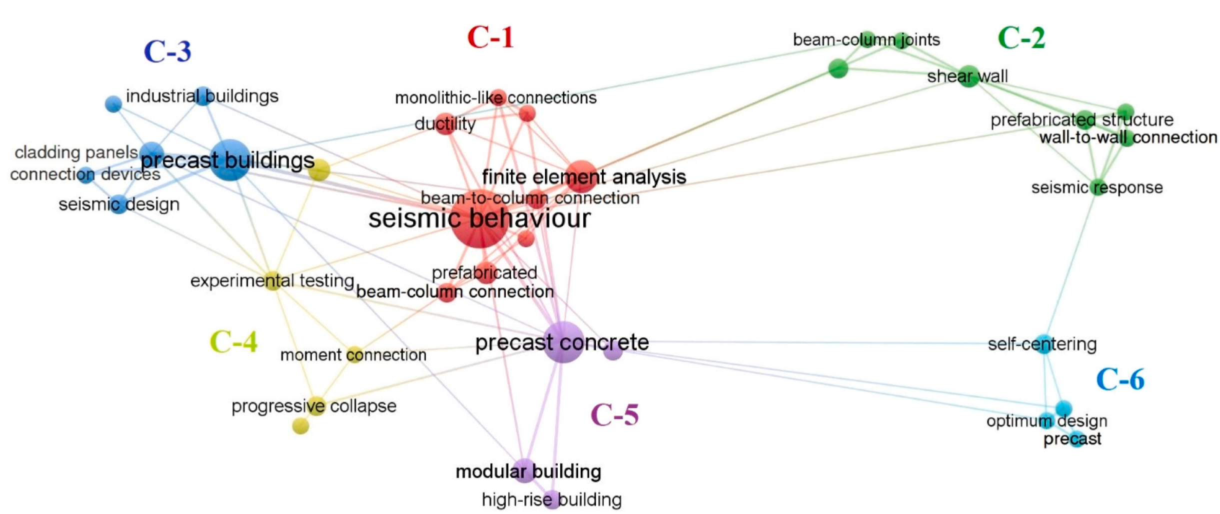


Fig. 5. Map of scientific analysis of author keywords

Table 5
Summary of most studied keywords.

Keyword	Clusters	occurrences	Total Link Strength	Avg. Pub. Year	Avg. Citations	Avg. Norm. Citations
seismic behaviour	1	34	39	2020	16.0	2,5
precast concrete	5	17	33	2020	11,9	2,1
precast buildings	3	17	27	2017	14,3	2,3
cladding panels	3	6	16	2019	14,3	2,2
finite element analysis	1	11	14	2021	4,6	1,3
shear wall	2	5	12	2019	17,5	2,6
cyclic loading	1	3	11	2021	6,9	1,9
experimental testing	4	4	11	2018	28,5	4,6
modular building	5	6	11	2021	12,5	3,4
ductility	1	5	10	2021	5,67	1,8
seismic design	3	4	9	2015	33.0	3,6
beam-column connection	1	4	7	2020	9,3	1,8
wall-to-wall connection	2	3	9	2018	29,7	5,1
lightly reinforced wall	2	3	9	2018	29,7	5,1
high-rise building	5	4	8	2021	9,5	2,6
optimum design	6	3	7	2021	4.5	1,0

[a]Average year published, [b] Average citations, [c] Normalized citations, [d] Average normalized citations

assembly structure system as the primary structural form. However, the application of this system in seismic zones has been limited due to the challenges associated with meeting the demanding strength requirements of connections during earthquake events, leading to their unreliability [39]. Nonetheless, it has been demonstrated that precast concrete frame structures can exhibit commendable seismic performance when the joints are designed with rationality, facilitating reliable connections. In the context of precast frame buildings, the primary challenge lies in identifying cost-effective and practical methods to connect precast concrete elements while ensuring sufficient stiffness, strength, elasticity, and stability [40].

Cast-in-place concrete structures offer the advantage of establishing continuous frames intrinsically resistant to bending moments. This behaviour, on the other hand, has to be deliberately implemented in precast structures. Therefore, the appropriate technology for the precast system is of great importance. The designer's goal is to achieve a solution that meets the required performance [41], which can be achieved depending on the connection between the structural elements, which can be emulative or non-emulative (hinged). Emulative links provide lateral stiffness and energy dissipation capacity similar to in-situ concrete structures. The system is designed to the usual standards for conventional concrete buildings [42], and assembly requires cast-in-place (wet) concrete, which can somewhat negate the advantages associated with prefabrication; the end product is a monolithic system. Articulated connections, on the other hand, are designed to allow non-linear rotations in the joint contour and avoid inelastic behaviour of the structural elements through the use of post-tensioning; their assembly avoids the use of cast-in-place concrete (dry connection), which leads to fast construction, maximizing the advantages of prefabrication. Another type of dry connection uses steel couplings and bolts, and mechanical and wet techniques can be combined. In addition, one kind of connection combines mild steel for increased energy dissipation and post-tensioned steel for self-centring; these connections are of the hybrid type [40].

Various research programs conducted in recent years have significantly advanced in understanding connection behaviour, thereby extensively promoting the development of precast structures [43].

4.1.1. Joint

The research community has acknowledged the significance of emulative connections through the wet assembly. However, limitations in the assembly process can lead to inconveniences such as prolonged waiting times, the need for scaffolding and concrete formwork, cold joint formation, and suboptimal bonding conditions, among others. These challenges have resulted in a decrease in the utilization of such connections [43]. Researchers have proposed several solutions for beam-column connection in precast construction. One approach focuses on reconfigurability by minimizing the volume of in-situ concrete, using fibre-reinforced concrete and employing geometric configurations for both section and reinforcement, thus eliminating the need for formwork [41]. Another study combines the concepts of dry and wet connections, facilitating assembly without scaffolding; this approach achieves elastic behaviour using a steel box anchored to the column, while the beams incorporate plastic hinges to improve ductility [44]. Using column and beam subcomponents establishes an economical and robust assembly pattern, which allows the connection point to be displaced and exhibits typical flexural behaviour [45],[46]. Researchers propose using new materials to solve the interface weakness resulting from segmented element connections and concrete quality. Ultra-high performance precast permanent concrete (UHPC) permanent precast forms, fixed by steel bolts, offer improved confinement of the central core [47]. In addition, a novel UHPC-filled joint geometry can significantly improve the mechanical properties of the interface, thus improving both execution and performance [48].

Dry assemblies leverage the advantages of prefabricated construction, employing techniques such as welding, bolted connections, dowel and dowel systems, or post-tensioning steel. These connections offer the potential for achieving articulated or monolithic behaviour. However, conducting a thorough analysis of such connections is crucial, as certain studies have reported inadequate seismic behaviour in hinged connections [49]. In the case of moment connections, complex geometries or specialized assembly techniques might be necessary, as the typical failure mode of the connection could be altered, requiring more sophisticated design approaches [50]. Researchers have proposed several alternatives to overcome the drawbacks associated with precast connections. One innovative approach is to modify fully restrained steel moment element connections using bolted plates in beams and columns [51]. Another solution researchers propose is to transform the hinged beam and column joints into rigid joints by activating mechanical connection devices after slab installation while maintaining the advantages of dry prefabrication [52]. To improve the seismic response of unbonded post-tensioned joints, steel face plates have been proposed as an alternative for confinement at the joints [53]. In addition, alternatives based on composite concrete and embedded steel structures have been explored and have demonstrated high load-bearing capacity and, more importantly, reliable and durable connections [54],[55],[56],[57]. Flange-type mechanical connections with plates and bolts have enabled fully restrained moment behaviour in segmented element connections [58]. In addition, researchers have successfully moved the plastic hinge from the column base to a lower moment zone by employing a steel box connection; this innovative approach aims to avoid brittle failure and achieve behaviour similar to that of a monolithic column [59]. In general, research efforts are focused on ensuring easy and fast construction, which provides significant advantages over traditional construction methods.

4.1.2. Damage control

The irreversible residual structural deformations produced by earthquakes in structures generate substantial economic costs in post-earthquake reconstruction [60]. Developing innovative high-performance structural systems with low damage and fast recovery allows for overcoming these deficiencies. Balancing, self-centring, replacement and addition of energy dissipation devices allow structures to minimize damage and recover building performance immediately after an earthquake [61]. Researchers have developed innovative beam-column connections that are reliable, simple to construct, easy to repair after an earthquake, and capable of damage control. Including a replaceable steel beam of reduced section located in the predetermined plastic hinge zone near the column allows concentration of the plastic damage in this zone so that the non-replaceable components remain in the elastic stage [62]. Following the same line in another study, a replaceable steel hinge and confined steel tube common core are used [63]. Other researchers proposed novel dual-function steel plate dampers working as energy dissipation hinge [64],[65]. Adapting the hinge joint by splice joint and connecting with energy-dissipating steel plates provides a joint that reduces residual deformation, is repairable and allows rapid recovery of building functions after earthquakes [66],[67]. Research has shown an increased interest in resilient structures; the losses caused by the many earthquakes worldwide over the years have marked this objective [67]. Table 6. provides a brief list of connections for frame systems proposed in the literature.

4.1.3. Rehabilitation

Significant progress has been made in enhancing the seismic safety of Prefabricated Concrete Buildings (PCB). However, many existing prefabricated buildings still exhibit high vulnerability to seismic activity, primarily due to inadequate seismic detailing, particularly at their connections; this vulnerability has been evident in earthquakes in southern Europe [35], where numerous structural collapses were attributed to using non-seismic standard dry friction beam-column joints [37],[68]. Retrofitting these structures to improve their seismic performance poses a considerable challenge for the engineering community and is a critical objective for public and private agencies. To address this limitation, researchers have proposed alternative approaches. One such technique is the implementation of monolateral dissipative bracing, which presents an innovative method for dissipating energy through tension and allowing free deformation during compression [69]. Another approach involves reinforcing dry friction connections using devices based on carbon-wrapped steel tubes, thereby facilitating the transformation of these connections [70]. Additionally, using three-hinged steel devices for multiple structural elements and configurations has been proposed as another viable alternative [71]. Since knowledge of seismic rehabilitation of PCB is scarce compared to cast-in-place structures, research efforts are essential.

4.1.4. Others

Precast concrete structures hold immense potential in the construction industry, not only for their advantages during the construction stage but also due to additional benefits associated with cost reduction and environmental impact. Moreover, researchers emphasize the importance of energy and resource conservation through the recovery and recycling of construction waste and the reuse of materials and buildings after demolition [72]. In light of these factors, researchers propose developing a structural system featuring a novel dry column beam connection that offers easy assembly, cost reduction, and a disassembly approach; the objective is to evaluate its environmental impact across various scenarios and assess its durability, potential for reuse, and cost-effectiveness compared to traditional cast-in-place reinforced concrete buildings [73]. Similarly, other researchers have introduced a probabilistic approach to evaluate structures' seismic performance and lifetime, considering the interaction between seismic and environmental hazards; this approach underscores the significance of adopting a comprehensive life-cycle perspective [74].

The research underlines the importance of wet connections. The proposed solutions include reducing in-situ concrete, using reinforced concretes and applying ultra-high-performance concretes. Using subcomponents for beams and columns improves the connection points, optimizing the execution and mitigating the use limitations. In contrast, dry connections employ steel plates, welding, bolting, doweling, or post-tensioning, seeking monolithic or hinged behaviour. Innovative dry approaches emulate the moment connections of steel structures, integrating mechanical devices to stiffen articulated systems, suggesting joint confinement, incorporating composite structures with embedded steel sections, and proposing flange-type connections. These wet and dry connections advances facilitate fast and simple construction, emphasizing economy and performance. Some researchers introduce damage control concepts, exploring techniques such as balancing, self-centering and energy dissipation. Beam-column connections introduce reduced steel beam segments, confined steel caissons, steel plate dampers and energy-dissipating steel plates within the plastic hinge zone, where damage is concentrated. These replaceable and removable devices retain non-replaceable components in the elastic phase, increasing the potential for reuse.

4.2. Shear walls (number of articles=43)

Shear walls are the primary components used to withstand seismic forces in buildings. However, in prefabricated structural systems, cast-in-place shear walls persist, despite inherent drawbacks such as high labour and resource requirements; these limitations hinder the progress of the technique [75]. Over the years, the scientific community has extensively studied the concept of prefabricated shear walls, resulting in rapid advancements. Nonetheless, significant challenges remain, including concerns about their integrity, performance uncertainties, implementation complexities, and the weakening effect of joints [76]. To overcome these obstacles, researchers have dedicated their efforts to developing innovative high-performance connection systems using various techniques; through these endeavours, they have successfully demonstrated and ensured excellent behaviour, achieving the design objective of equivalence to their cast-in-place counterparts.

4.2.1. Assembly

The size of precast concrete walls is limited by transportation and lifting considerations, which require reliable connections between the top and bottom precast walls and their adjacent counterparts. Consequently, the literature highlights several connection systems that aim to achieve satisfactory ductility and minimal damage during seismic events. One method that has shown promising results is casting-in-place structural elements as vertical connections between adjacent walls while using grouted jackets for horizontal coupling; this method forms a monolithic element that effectively supports internal loads [77],[78],[79]. The use of cast-in-place concrete, commonly referred to as "wet connection", has been established as the traditional connection method. However, other researchers propose a three-sided consolidation system that relies on a reliable cast-in-place concrete connection, omitting the connection at the base of the wall and using mortar backfill for ease of construction, cost-effectiveness, and predetermined performance [80]. The pursuit of enhanced stiffness, ductility, and energy dissipation has been a focal point in numerous investigations. Implementing bracing has yielded promising results in cast-in-place walls, particularly in high-rise buildings [81]. More recently, the introduction of steel plate bracing in precast shear walls has been proposed, ensuring mechanical characteristics that cater to high and low axial load ratios, thus meeting the requirements for lower floors [82]. Double-skin shear walls have been introduced to improve assembly conditions with lighter components.

Table 6
Summary of connections for frame systems proposed in the bibliography.

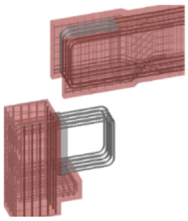
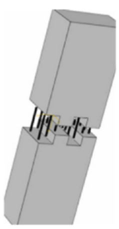
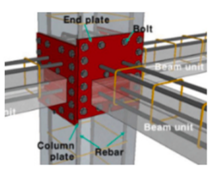
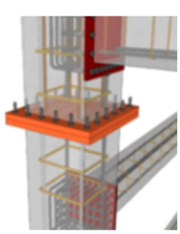
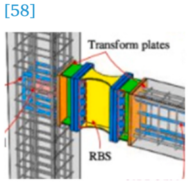
Type	Assembly	Illustration	Connection details
Emulative	Wet	 [38]  [48]	-Geometric variation of section and reinforcing steel[38].-Use of steel plates[44].-Use of subcomponents of structural elements[45,46].-Use of UHPC[47,48].
	Dry	 [51]  [58]	-Plates and bolts in beams and columns[51].-Joint stiffening with the rear slab[52].-Steel face plates at the joint[53].-Use of hybrid elements (steel and concrete)[54].-Flange type between elements[58].-Steel box at the base of the column[59].
	Dry	 [62]	-Damage control, preset plastic hinge[62].-Confined steel core[63].-Double function (hinge and energy dissipation) dampers[64,65].

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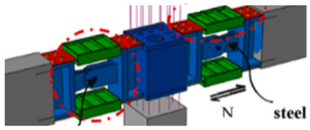
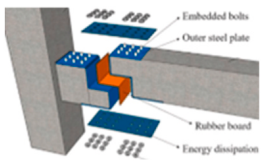
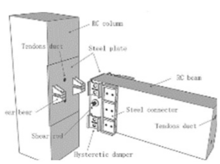
Table 6 (*continued*)

Type	Assembly	Illustration	Connection details
		 [64]	
Non-emulative	Dry	 [66]  [67]	-Steel plates for energy dissipation[66].-Hysteretic dampers for energy dissipation[67].

The combination of spiral-confined vertical overlap and horizontal loop connections has demonstrated favourable outcomes [83],[84]. In another study, effective load transfer was achieved through double-row spiral-confined vertical and rebar overlap connections [85],[86]. Following a similar approach, other researchers have proposed an innovative solution—a relieved wall featuring an interior hollow modular scheme that can be connected using in-situ concrete or mechanical devices [87].

The scientific community has recognized unbonded post-tensioned self-centring precast concrete walls as a high-performance seismic-resistant system capable of withstanding severe earthquakes with minimal damage; extensive research on this system has been documented in the literature [88],[89],[90]. In recent years, researchers have directed their efforts towards improving design guidelines, as the arrangement of unbonded steel impacts post-tensioning losses and shear friction [91]. Researchers have developed simplified design equations that align with the original system approach [92]. Furthermore, it has been determined that the design of post-tensioning and energy dissipation, known as the hybrid system, plays a crucial role in preventing system collapse, emphasizing the significance of the designer's control over these factors [93]. Fig. 6. summarizes the PCB assembly sequence.

4.2.2. *Resilience*

The design philosophy commonly adopted in cast-in-place reinforced concrete buildings primarily emphasizes life safety, tolerating structural member damage that can result in the loss of building functionality after a severe earthquake, often leading to inevitable demolition. However, in the case of Prefabricated Concrete Buildings (PCB), researchers have put forth alternative approaches that prioritize post-earthquake resilience and sustainability.

Tilting systems offer significant damage reduction, albeit with the trade-off of lower energy dissipation [95]; steel dampers have been proposed to compensate for the lower energy dissipation [96]. An alternative approach is to design demountable or repairable systems; these systems employ strong steel joints (dry joints) for the joints, thus maximizing the advantages of prefabrication, such as faster construction and better quality control [97]. Numerous studies have explored the development of precast concrete demountable buildings. Researchers have proposed a demountable shear wall of multiple slender walls in which strong steel connections interconnect the structural elements. In this system, the nonlinear behaviour is concentrated on the shear walls, preserving the integrity of the other elements [98]. In addition, other researchers have developed a method of joining walls using welded shear and shear steel keys; these keys, composed of low-yield strength steel plates, efficiently transfer loads and dissipate energy [99],[100]. To improve the coupled tilt-up walls by eliminating the interaction between components, a segmented wall for each floor connected by circular steel dampers that function as shock absorbers are presented [101]. Another study increases the efficiency of tilt-up systems by configuring the system with two end columns and linking adjacent walls with replaceable energy dissipative connectors [36]. The standing seam has also been addressed with a male-female connection using u-shaped acro channels and bolts that incorporate rubber that dampers and dissipates vibrations [102],[103].

4.2.3. *Modular wall systems*

The sustainability of structures has become a growing concern, with the current trend recognizing its significance alongside structural safety [104]—on-site activities involving in-situ concrete construction demand substantial time, extensive formwork, and a significant workforce; moreover, when these structures suffer severe damage or reach the end of their service life, they often require complete demolition; this process

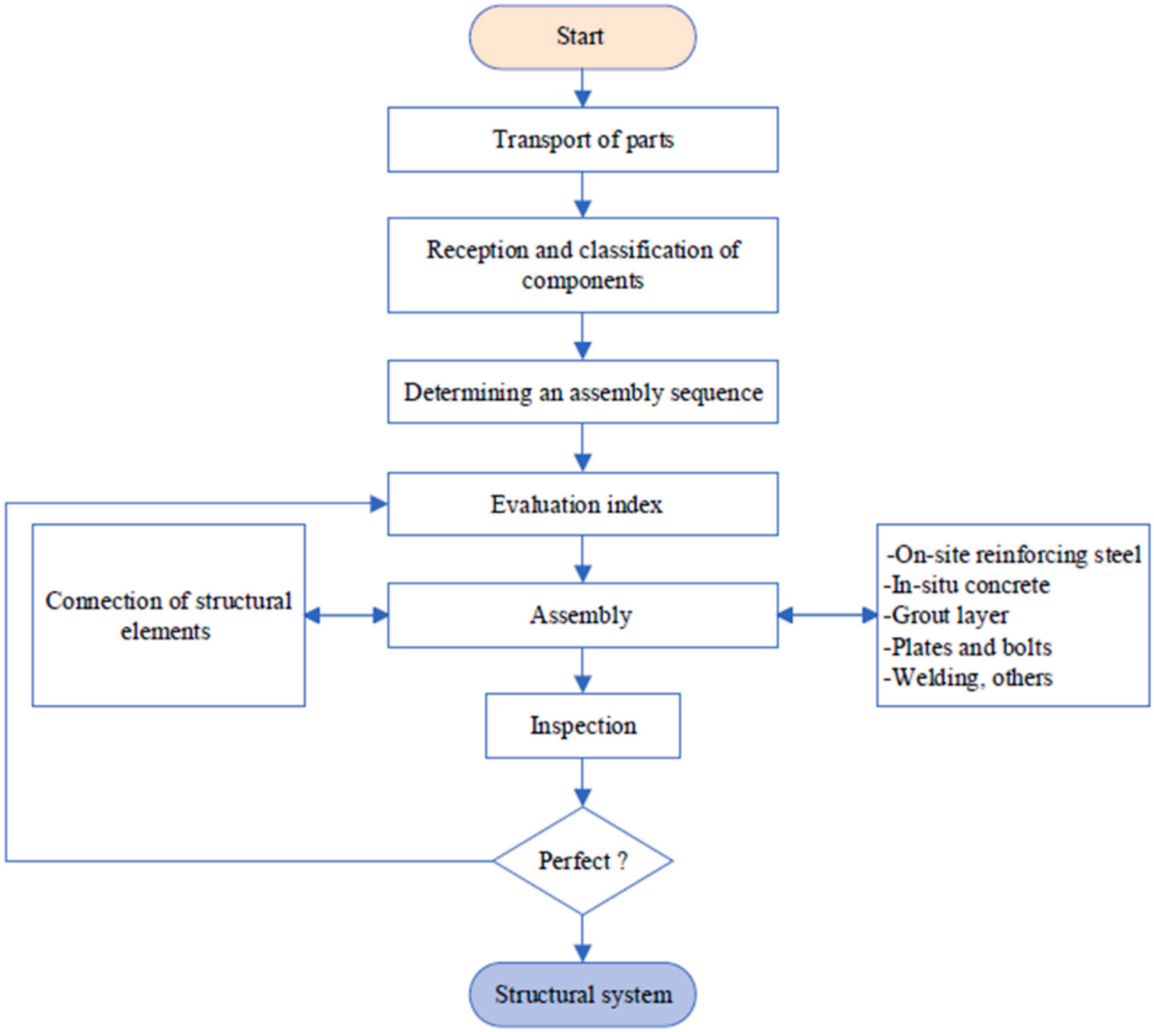


Fig. 6. Summary of PCB assembly sequence.
Modified from reference [94].

contributes to environmental issues and consumes significant amounts of energy [105]. In light of this scenario, researchers are exploring design approaches incorporating deconstruction concepts [106]. Precast concrete wall panel systems with bolted connections offer a compelling solution, particularly for low-rise buildings, owing to their straightforward assembly and disassembly. In this regard, a team of researchers has developed a lightly reinforced panel system featuring simple bolted connections designed to withstand tensile and shear forces; these panels are easy to fabricate and transport, and their joints can be readily replaced or upgraded to meet new requirements; the deconstruction process is also streamlined, presenting a straightforward procedure [107],[108]. In the realm of low-rise building typologies, other researchers conducted experimental investigations to determine the seismic behaviour of a particular configuration; the buildings were connected using felts and mechanical anchors, with their findings revealing that the weakest link in the system was the three-way connections [109],[110]. In a separate study, researchers conducted shaking table tests on an improved system version, showcasing its ability to withstand severe earthquakes and confirming its suitability for low-rise buildings [111]. Moreover, researchers have proposed alternative approaches for medium- and high-rise buildings; one proposal involves a prefabricated shear wall combined with various types of dissipative beams, demonstrating its feasibility while highlighting the ease of repairing possible damages [112]. Additionally, scholars analyzed the incorporation of a viscoelastic damped joint for the vertical connection of precast wall panels, yielding promising results; in a 24-story building, the system successfully dissipated 90% of the incoming seismic energy [113]. Table 7. provides a brief list of shear wall connections proposed in the literature.

4.3. Cladding panel system (number of articles=15)

The significance of sheathing panels on the seismic behaviour of precast concrete buildings (PCB) has been largely disregarded over the years. They are commonly viewed as non-structural elements that primarily contribute seismic mass, lack stiffness and are joined by dry connections. However, previous seismic events have demonstrated the need to reassess this approach. The interaction between the frame and the panels plays a crucial role in determining the seismic response of the structure [35]. To address this issue, researchers have proposed three general criteria. The first criterion involves considering an isostatic arrangement of the panel connections. In this approach, the seismic analysis focuses on the bare frame, and the panels contribute only their mass. However, when significant displacement occurs at the connections, the panels actively participate in the seismic response. The second criterion adopts an integrated support system where the panels are integral to the lateral resistance system. This hyperstatic assembly utilizes fixed connections designed based on seismic analysis. The third criterion entails the creation of a dissipative system by installing devices between the panels and the frame or between the panels themselves. These

Table 7
Summary of shear wall connections proposed in the literature.

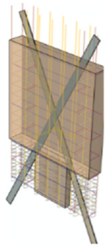
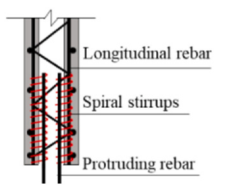
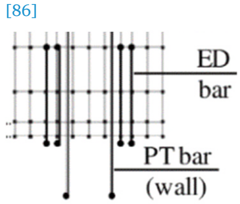
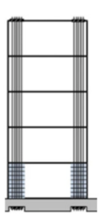
Type	Assembly	Illustration	Connection details
Emulative	Wet	 [82]  [86]	-Concrete-in-place (vertical coupling)-Grout coupler (horizontal coupling)[77–79].-Bracing with steel plates and lap joints[82].-Double skin walls, overlapping connections[83–86].-Lightened wall, caged coupling or mechanical devices[87].
Non-emulative	Dry	 [88]  [91]	-Post-tensioned unbonded self-centering[88–90].-Includes confinement region[91]-Hybrid action post-tensioned steel and mild steel[93].

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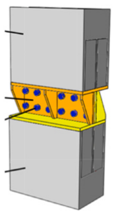
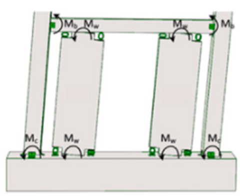
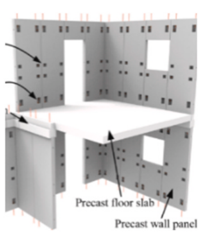
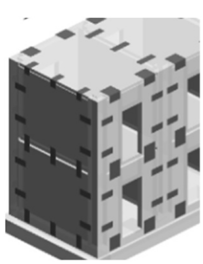
Table 7 (*continued*)

Type	Assembly	Illustration	Connection details
	Dry	 [98]  [101]	-Replaceable, mechanical connection[98].-Vertical assembly between walls with steel shear keys[99,100].- O-type steel dampers[101]- Vertical assembly to columns with O-type dampers[36].-Male-female connection with damping[102].
	Dry	 [107]  [111]	-Modular system with replaceable bolted joints[107].-Connection with felts and mechanical anchors[109]. -Plate and bolt connection[111].-Coupling with energy-dissipating beams[112].-Vertical connection with viscoelastic cushioned joints[113].

devices are responsible for dissipating energy within the system [114].

4.3.1. *Energy dissipation*

The research community has verified the reliability of the dissipative criterion and its isostatic equivalent in kinematic terms [12]. Based on this criterion, several design strategies for the structural system have been investigated, focusing on developing reliable and easy-to-implement systems. These studies have explored different levels of interaction and the creation of a highly efficient dual frame/wall system [115],[116]. One approach was implementing a connection system using friction-based devices for horizontal or vertical connections. This system demonstrated significant results, exhibiting high energy dissipation capacity and offering replaceability in case of damage [117],[118].

Other researchers conducted experimental tests with various connected devices, including local tests, subassemblies, and full-scale prototypes, which confirmed the overall seismic behaviour within strength and displacement constraints [114]. In another study, multiple connection configurations were analyzed, and the effects of varying the location, quantity, and thickness of the steel damping devices were reviewed. The results indicate the proposed device allows high energy dissipation in panel-to-panel and panel-to-support connections [119],[120]. In addition, some authors propose an energy-dissipating cladding panel that incorporates U-shaped steel dampers; these dampers facilitate seismic energy dissipation through relative sliding displacement between the panels and the structure, thus providing effective damage control [121]. The horizontal configuration of the panels was examined, revealing that achieving an isostatic configuration can be challenging; therefore, when designing such a configuration, it is essential to consider correct connection details [122]. Fig. 7. shows a system of energy-dissipating cladding panels using U-shaped steel dampers.

4.4. Progressive collapse (number of articles=6)

Earthquakes, winds, fires, and the potential for progressive collapse resulting from accidental failures present significant technical challenges throughout the service life of structures. Consequently, the design and construction of structures that can withstand multiple hazards have garnered significant attention from the global research community in recent years [123]. In the context of reinforced concrete buildings, recent studies have identified seismic actions and progressive collapse as the most critical hazards affecting their safety [60]. *Progressive collapse* is the disproportionate chain reaction triggered by a localized failure resulting from extraordinary events such as fire, explosion, or overload [124]. Substantial advancements have been made by the scientific community in cast-in-place reinforced concrete buildings, particularly in achieving robust resistance mechanisms against column loss [125].

Building upon this progress, researchers have introduced innovative precast concrete structural systems that offer enhanced resistance to multiple hazards. Through cyclic and progressive collapse tests, an innovative frame incorporating post-tensioned tendons, steel angles, energy dissipaters, and shear plates was evaluated for its seismic performance and progressive collapse design impact, leading to the development of a comprehensive multi-hazard design approach [123,123]. The behaviour of precast systems is highly dependent on their connections. Given this, researchers have proposed a non-emulative moment connection detail that incorporates high-strength post-tensioned steel anchored to the parapets using bearing plates specifically designed to resist progressive collapse scenarios [126]. In another study, three types of connections were tested by pushout tests to evaluate their capabilities and resistance mechanisms in preventing progressive collapse [127],[128]. In addition, typological fragility curves have been established to assess the risk of progressive collapse in single- and multiple-risk environments [125]. It has been observed that masonry infill walls can help mitigate progressive collapse behaviours; however, panel openings and their location significantly affect structural strength [129]. Fig. 8. shows a schematic of the expected deformation in an accidental local failure scenario and the details of the beam-column junction region with the capacity for progressive collapse.

4.5. Modular buildings (number of articles=7)

Modular concrete buildings represent the pinnacle of precast construction, utilizing volumetric modular components instead of discrete structural elements like beams, columns, and walls commonly found in traditional precast concrete systems. This approach enables a greater level of prefabrication to be achieved, leading to numerous advantages [130]. Such structures are particularly well-suited for architectural spaces requiring repetitive units, such as hotels, offices, and residences, and have the potential for application in high-rise buildings [131]. While extensive research has been conducted on developing steel modular buildings [132], ongoing research is focused on advancing concrete modular building systems [4].

Scholars have researched modular concrete buildings to enhance their resistance against lateral wind and seismic forces. As part of this endeavour, hybrid coupled wall systems have been developed for high-rise modular structures. These systems incorporate replaceable steel coupling beams and precast concrete walls within the modules,

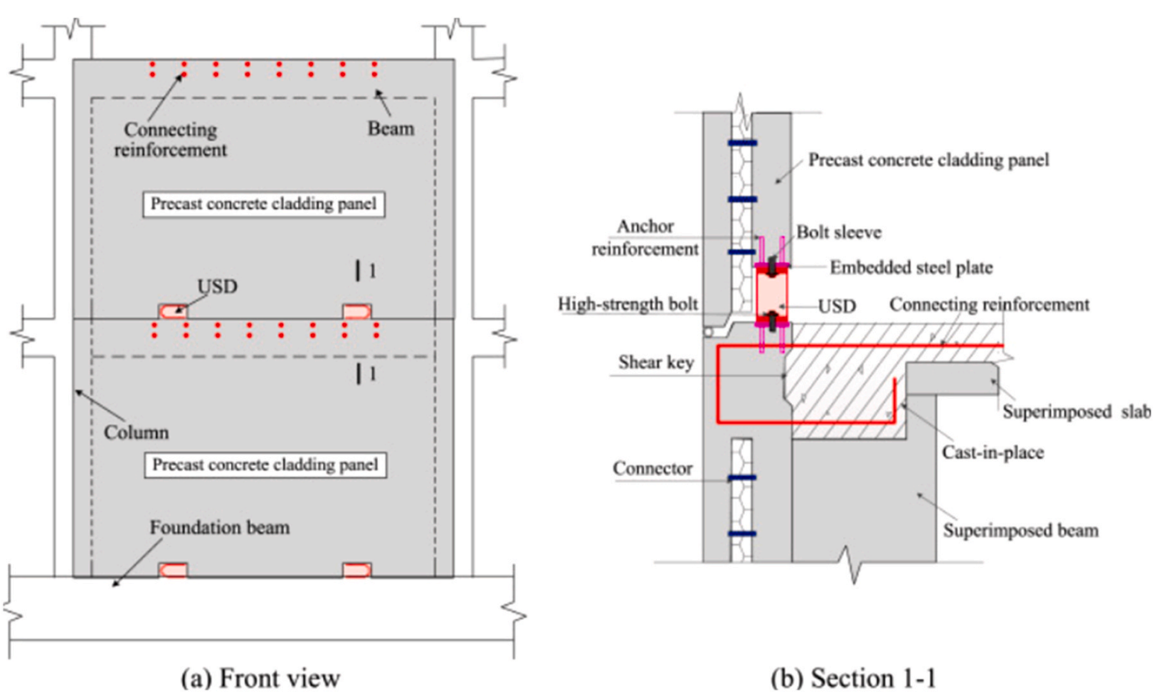


Fig. 7. Energy dissipative cladding panel system using U-shaped steel dampers. [121].

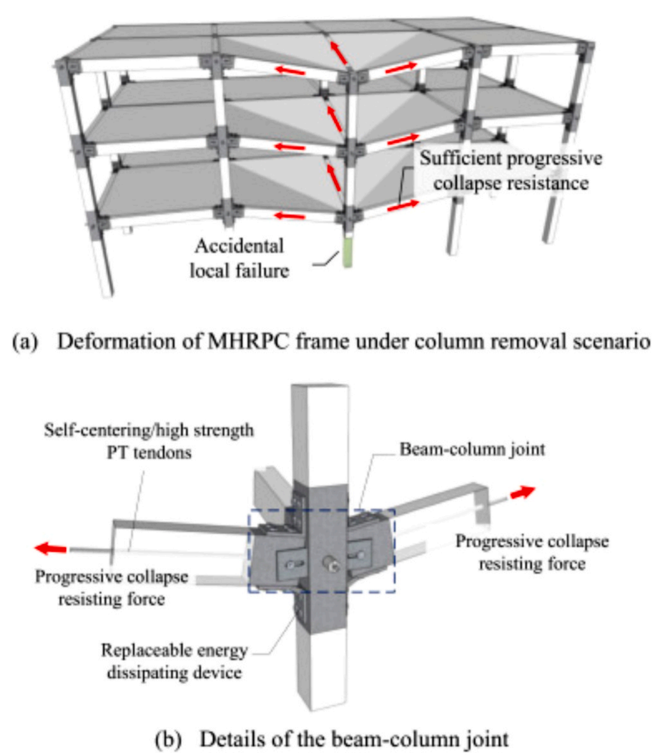


Fig. 8. Schematic of the expected deformation in an accidental local failure scenario and details of the beam-column joint region. [123].

substituting the need for in-situ concrete or steel cores [133]. Additionally, another study proposes the elimination of cast-in-place cores by utilizing a lateral force-resisting shear wall system, where shear walls are integrated into the precast modules. It has been confirmed through numerical modelling and multi-mode analysis that this system possesses sufficient strength to withstand seismic loads [134]. Similarly, another study has developed a discrete horizontal diaphragm system that eliminates the need for a cast-in-place concrete layer. This system incorporates innovative horizontal and vertical connection systems, and simulation was conducted using a spring model [135]. Furthermore, researchers have devised a modular prefabricated shear wall system, wherein volumetric modules are assembled using horizontal and vertical joints comprising steel studs and beams. This system enables rapid construction and offers the advantage of being demountable [4]. The role of cast-in-place cores in providing resistance against lateral forces was investigated, considering the interaction between the module core walls and the influence of vertical connections between modules. Horizontal connection is facilitated by an in-situ concrete layer in the slab [136]. A novel approach was proposed to recognise a knowledge gap in the structural design of modular buildings, emphasising that modules bear vertical loads and transfer lateral loads to cast-in-place cores to resist such forces [137]. Fig. 9. shows the assembly concept of a prefabricated volumetric modular building.

4.6. Emerging methodologies (number of articles= 6)

Industrialized construction is gaining traction in numerous countries, driven by government policies that advocate for enhanced automation and productivity within the industry [138]. As a result, the design phase is receiving increased attention regarding constructability, sustainability, and climate resilience. In a contemporary building environment, the focus is on long-term sustainability, aiming to minimize impacts such as carbon footprint and costs [139]. Extensive research has shown that geometry and material choices significantly influence the carbon footprint and cost of building construction [140]. It is widely acknowledged that novel approaches are needed to accurately predict, correlate, and optimize building geometry to minimize these impacts. Existing methods often fail to provide a comprehensive assessment, thus highlighting the necessity for new approaches to address this challenge effectively.

In line with these advancements, researchers have pursued a novel system approach incorporating Building Information Modeling (BIM) for three-dimensional geometric modeling of buildings, coupled with automatic generative design techniques, to optimize the carbon footprint and construction cost of precast buildings [139]. Another significant research focus revolves around the seismic optimization of precast concrete structural systems. Multi-objective optimal seismic design has been employed for precast concrete frames, utilizing hybrid semi-rigid connections to mitigate issues such as premature creep, excessive displacement, and unfavorable failure modes during severe earthquakes [141]. Additionally, a separate study has developed an automatic optimal design procedure applicable to unbonded prestressed shear wall frames and shear wall systems with damping. The objective is to identify the optimal combination of post-tensioning tendons and shear connectors, thereby ensuring moment capacity, while simultaneously achieving zero residual drift [142],[143]. Other researchers have focused on determining the optimal locations of connections within two- and three-dimensional areas, explicitly targeting the automation of prefabricated building processes [144]. In a separate study, scholars have introduced a novel construction approach for prefabricated floor-wall systems utilizing artificial intelligence (AI). This approach involves searching for optimal locations of wall and beam patterns, as well as proposing a range of suitable joints, elements, and associated assembly methods [145]. These research efforts highlight the ongoing endeavors to advance the field of precast construction through innovative design methodologies and optimization techniques.

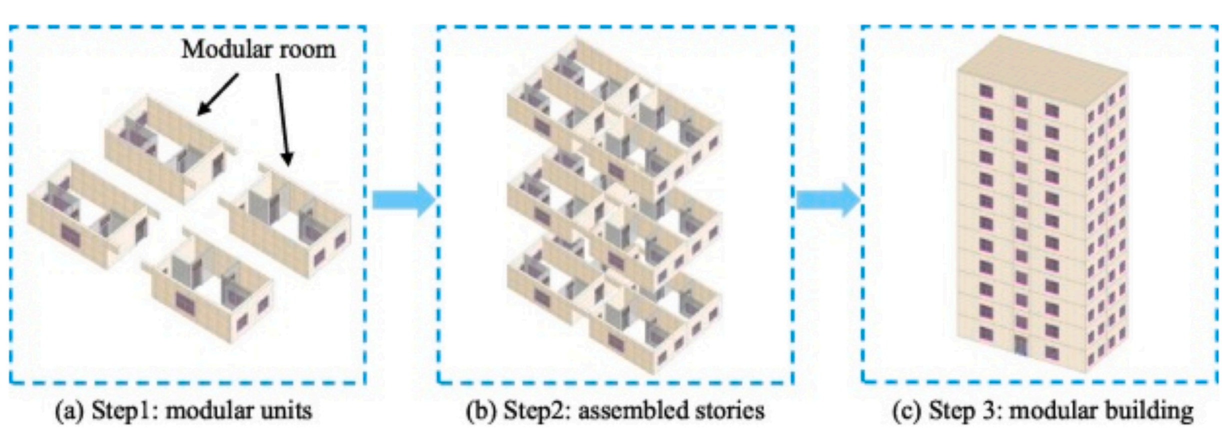


Fig. 9. Assembly concept of precast modular building. [4].

5. Discussion

This section examines trends and offers insights into future directions. The trends identified in this analysis stem from the classification performed in the preceding sections, which involve a critical analysis of the underlying factors driving these trends and the identification of key parameters. Furthermore, future directions are proposed based on identifying gaps in the analyzed literature. The aim is to provide recommendations on addressing these gaps and pave the way for future research in the field.

5.1. Trend analysis

Among the various categories of structural systems capable of withstanding simian forces, such as precast concrete frames and shear walls, they constitute 74% of the complete sample, as depicted in Fig. 10. This high percentage can be attributed to the extensive research conducted on precast concrete buildings over the past four decades. It is worth noting that most precast buildings are constructed using reinforced concrete, which has been prominently featured as the primary material in academic research and practical applications [21]. Considerable attention has been given to comparing precast concrete elements' structural and material performance with conventional cast-in-place concrete. The growing interest and trend towards precast concrete buildings are well-founded, as researchers widely acknowledge their numerous advantages over traditional structures. These advantages include reduced environmental loads, labour savings, enhanced quality, and increased efficiency in on-site construction, among others [146].

Beginning in the 1980 s, research on the seismic safety of PCB resulted in initial guidelines in New Zealand [8]. The PRESS design manual further reinforced developments in the early 1990 s [9], establishing standards for the use and design of precast concrete. Initial design guidelines were introduced by the National Earthquake Hazards Reduction Program (NEHRP) in 1994 [23]. The International Federation for Structural Concrete (Fib 2003) focused on seismic design philosophy [147]. In the USA, ACI 318 included seismic provisions for emulative systems in 2002, based on NEHRP. Guidelines for articulated connections and walls have been added; current structures are governed by the International Building Code IBC-15, which references ASCE/SIE 7–10 and ACI 318–14 [22]. The provisions of the Precast/Prestressed Concrete Institute (PCI) design manual and NEHPR are significant documents. In regions such as China and Hong Kong, the growth of the construction industry drives the evolution of standards to meet the 30% policy for new precast buildings [34]. The Indian code outlines joint and wall design with constructability and fire resistance in mind. Similarly, European standards incorporate safety concepts, wall provisions and stress analysis [148]. The codes aim for seismic behaviour similar to that of in-situ structures. Compliant PCB can be designed in areas of high seismic risk [22], [23], [148].

The research community acknowledges that the connections of precast elements represent the weakest link in these structural systems.

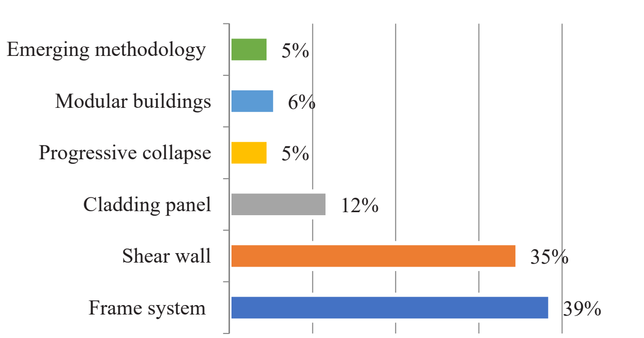


Fig. 10. Percentage of each category.

It has been demonstrated that these connections are susceptible to significant earthquake damage, highlighting their crucial role. Researchers have recognized the importance of understanding and addressing this vital aspect, making it one of the primary research topics within the field. Understanding and applying robust connections are critical to successfully implementing the precast system [149]. The significance of connections in precast concrete construction has been widely recognized and extensively discussed in the research, even since its early stages of adoption [9]. The development of innovative connection systems, known for their excellent mechanical behaviour, has played a pivotal role in achieving robust structural system integrity. A prevailing trend in these structural systems involves the creation of connections that prioritize ease of assembly, cost-effectiveness, utilization of new materials, and the avoidance of formwork, additional equipment, and the need for custom fittings.

The literature reveals lower percentages of studies addressing issues such as the structural behaviour of cladding panels (12%); the authors highlight the importance of taking into account nonstructural components during the design phase and seismic evaluation to embroider the failures evidenced in past earthquakes, current design approaches focus on the structural system, often neglecting the potential impact of nonstructural elements [150]. Seismically safe volumetric module systems (6%) emerge as the highest level in prefabricated systems. Research is scarce, and studies have demonstrated the feasibility of their application. However, structural elements and high percentages of cast-in-place concrete still predominate, undoubtedly an obstacle to their development. In addition, complex connection systems may affect their practical application; their behaviour still needs to be determined [4]. Studies addressing progressive collapse (5%) constructing multi-hazard structures is an important research topic worldwide, and the trend is developing multi-hazard designs [123]. Finally, the sample is completed by studies on the application of emerging methodologies in creating structures (5%); the authors agree that these methodologies at the method level can complement and improve problem-solving approaches. Their application may allow the consideration of other variables with equal importance for seismic safety in the design phase that traditional methodologies may not adequately address [26].

The substantial advantages of precast concrete technology are widely recognized [151]. However, within the scientific community, there is consensus that their market share in building construction remains comparatively limited [152], [153]. Researchers have identified numerous critical factors influencing the use of prefabricated systems, adopting a life-cycle approach, which is summarized as follows: (1) During the study and feasibility phase, several apprehensions arise, including high costs [42], [154], lack of social acceptance [155], fluctuations in preferred policies and market conditions, limited industry experience leading to poor design, poor management and production practices, as well as inadequate assembly [156], [157]. (2) In the design phase, problems may arise in accommodating architectural prerequisites, establishing component standardization and compatibility, addressing structural design constraints, earthquake-related concerns regarding building performance, and developing comprehensive technical specifications [152], [158]. (3) Problems in the manufacturing and transportation phase encompass the demand for skilled labour and expert handling of advanced equipment [34]. During transportation, complications such as stacking constraints, excessively long distances, suboptimal track conditions, restricted loading capacity, and inadequate vehicles can result in additional costs and delays [159]. (4) During construction, key parameters revolve around human resources and machinery requirements, operating radius, and limited crane capacities. Safety risks from connection failures and lifting operations [160], the lack of inspection techniques and connection verification technologies, and the use of non-standardized and untested accessories have been highlighted [153]. (5) Finally, in the operational phase, concerns focus on the need for more expertise to maintain components properly [161] and the absence of evidence that the life-cycle performance of prefabricated structures exceeds that of traditional buildings [162].

Significant progress has been made in research on the seismic safety of PCB. However, this study has identified several critical points that deserve attention. A research consensus must be established to formulate or improve design guidelines and standards that effectively incorporate these advances, instilling the confidence necessary for safe and widespread adoption. Given its recognition as the pinnacle of prefabrication, the scientific community must expand its research on volumetric modular structures. Integrating state-of-the-art methodologies in the search for optimal solutions can elevate the quality of solutions by reducing computational time. Research advocates for structural systems designed with disassembly capabilities, driven by the fundamental objective of mitigating the environmental impact during the end-of-life phase of the building, i.e., its demolition. Finally, the effective integration of the often contradictory parameters determining seismic safety and the economic, environmental and social pillars of sustainability in constructing precast concrete buildings must be demonstrated.

5.2. Future directions

Based on the scientific mapping and qualitative analysis of current research categories within PCB seismic safety, a comprehensive framework is established in Fig. 11, linking existing studies to future directions. This diagram illustrates the interplay between three columns: current research, research topics, and research trends, all of which contribute to the alignment of current and future research efforts. In the first column of Fig. 11, the current research is identified based on the scientific mapping conducted in previous sections. These findings are then linked to this study's relevant research topics or categories. The third column delineates future research directions by synthesizing the research findings from columns one and two. These directions naturally stem from the existing research themes explored above, forming a cohesive roadmap for further investigations into the seismic safety of precast concrete buildings. It is important to note that the specific keywords used in this analysis are exclusively derived from the scientific mapping process, ensuring that the recommendations for future research are grounded in the existing literature and its identified areas of

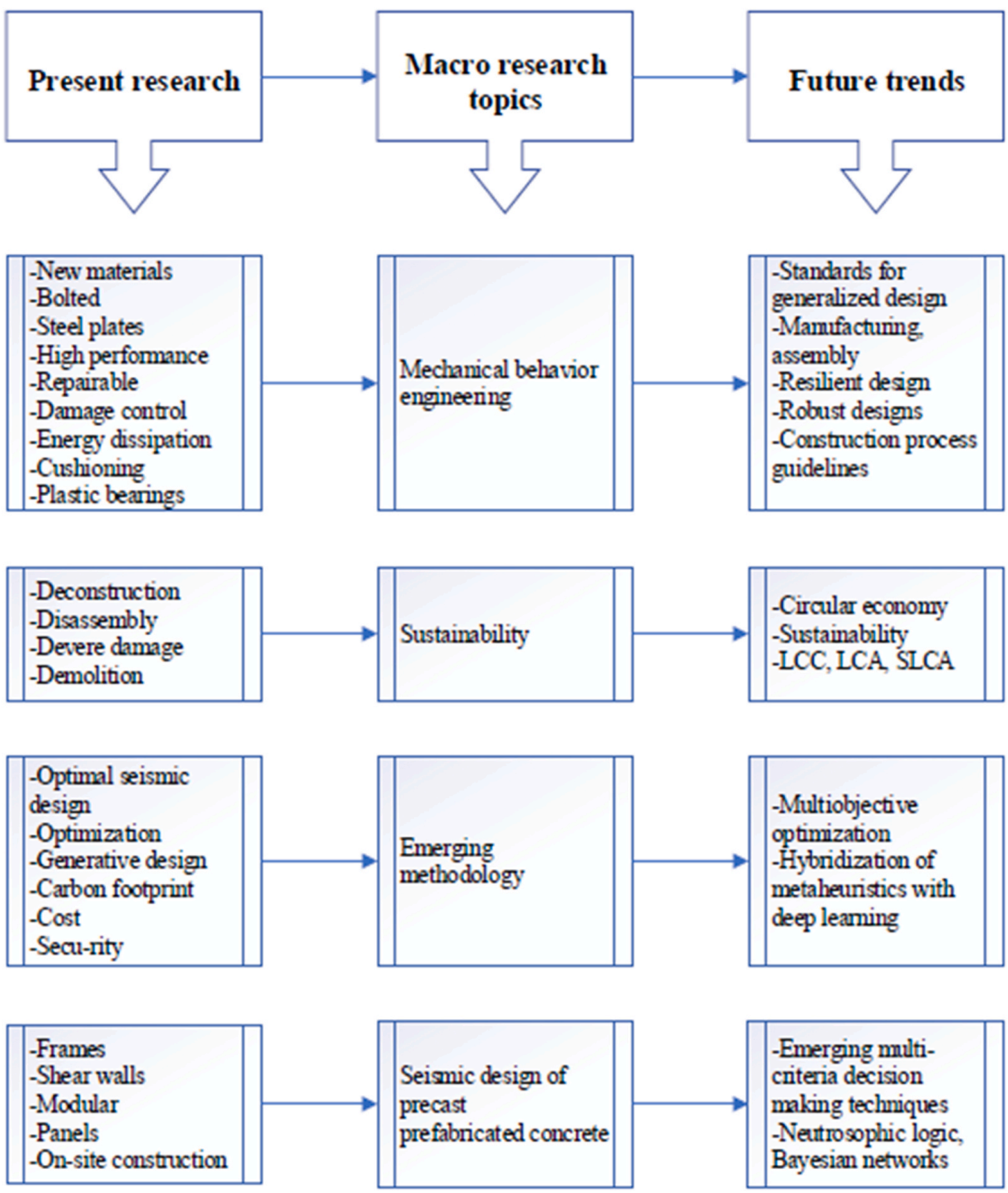


Fig. 11. Framework for linking current research areas to future research directions.

focus.

For instance, within the broader research topic of mechanical behaviour engineering, there is a need to focus on developing new design standards. These considerations should guide designers in selecting the appropriate structural approach, components, and, most importantly, an effective connection system; this ensures that the individual system components and the overall structure meet the required performance criteria. It is crucial to address the issue of irreversible residual structural deformations that occur during earthquakes, as these deformations lead to significant economic costs in post-earthquake reconstruction. Additionally, the design process must consider extraordinary actions or multiple hazards. To tackle these challenges, the development of innovative, robust, and high-performance structural systems that exhibit minimal damage and enable rapid recovery or repair is emerging as a promising strategy for achieving resilience-based engineering principles. The existing design of precast concrete buildings heavily relies on the original design system used for traditional cast-in-place buildings. However, it lacks a comprehensive approach considering the fabrication and erection stages [163].

The sustainability of structures has gained significant importance and is now regarded as equally crucial as ensuring structural safety. In addition to prioritizing structural integrity, a growing emphasis is on adopting sustainable practices throughout the construction process; this includes facilitating clean construction methods, optimizing transportation, and enabling easy assembly and disassembly to minimize the environmental impact. The goal is to reduce the carbon footprint and overall energy consumption, thereby enhancing the sustainability of new buildings over their entire life cycle. In recent years, cradle-to-grave environmental life cycle analysis studies have been increasingly used for different infrastructure projects. For instance, researchers evaluated the environmental impacts and total life-cycle costs associated with prefabricated and cast-in-place buildings in the United States [164]. Furthermore, another research team conducted a study to assess the environmental impacts of four different retaining walls, aiming to identify the optimal solutions for minimizing environmental harm [165]. In addition, a separate study focused on determining the environmental impacts of corrosion preventive designs for a prestressed concrete bridge deck exposed to an environment with high chloride content [166]. Researchers have recognized that the sustainability paradigm needs to be revised to mitigate environmental impacts. It is now imperative to consider economic and social factors alongside environmental considerations. The conventional "recycle, reduce, and reuse" approach is being reevaluated, with a shift towards the principles of "restore, renovate, and replace" [167].

Optimisation has been listed as an emerging structure methodology and studied extensively for several decades [168]. It offers a scientific approach to improving structural designs by considering multiple objectives, such as cost minimisation, reduction of CO_2 emissions, and embodied energy. Recent advancements have leveraged integrating deep learning techniques with metaheuristics to enhance solution quality and convergence speed. For instance, a study proposed a hybrid algorithm that combined the particle swarm optimisation method with the DB-scan clustering technique to design retaining walls, to optimise both carbon emissions and cost [169]. This hybridisation approach was also applied in optimising a steel-concrete composite bridge, where cost and embodied energy were treated as single objective functions using hybrid swarm intelligence [170]. Researchers can find optimal solutions that balance economic considerations, environmental impact, and energy efficiency in a structural design by incorporating advanced optimisation techniques and considering multiple objectives. These advancements open new avenues for creating more sustainable and efficient structures.

Given the inherent complexity of reconciling often conflicting criteria related to safety and sustainability, multi-criteria decision-making methodologies (MCDM) have gained significant attention in recent years. Specifically, multi-attribute decision-making methodologies (MADM) have proven valuable tools for addressing discrete problems with pre-defined alternatives. Advancements in decision-making techniques have facilitated the integration of sustainability principles into engineering practices through the use of hybrid approaches. For example, a study assessed a house's sustainability performance throughout its life cycle by considering four different structural design alternatives. The evaluation was conducted using various combinations of pairwise comparison and superior performance methods from the MCDM (Multiple Criteria Decision Making) fields [171]. Another research effort utilized neutrosophic criteria theory and the TOPSIS technique to evaluate the sustainability of concrete bridge decks in coastal environments [172]. These and similar advancements enhance the quality of decision-making solutions in uncertain environments.

The current challenge of the construction industry, in addition to structural safety, is to apply very restrictive budgets that minimize environmental impacts considering social and functional parameters. Therefore, we are facing a very complex problem with many restrictions and subject to significant uncertainties, which represents a major scientific challenge that can hardly be explored with traditional analytical tools. The use of state-of-the-art optimization methodologies, as well as multi-criteria decision-making that includes in their development the life cycle analysis from the design, manufacturing, assembly, use and maintenance phase and the end of life, will allow us to meet this challenge.

6. Conclusions

This study conducts a comprehensive and systematic review of the literature on advancing research on PCB' seismic safety. The analysis is carried out in three distinct stages. First, thoroughly identifying and compiling the relevant literature is carried out, ensuring a meticulous selection of appropriate sources. Next, a quantitative literature assessment is conducted, scrutinising various parameters and indicators to extrapolate insightful conclusions. Finally, a qualitative review of the sample is shown to delve deeper into the literature, uncover trends, and point out possible avenues for future research. A total of 127 articles published between 2012 and May 2023 were reviewed. The most salient findings are as follows:

1. The scientometric assessment presents a statistical overview of current developments in PCB seismic safety. This assessment reviews annual productivity, sources, authors, geographical collaborations, and notably cited articles. It highlights a remarkable increase in research output, discernible since 2019. In particular, it is discerned that most (70%) of the literature emanates from China and Italy. The bibliometric analysis systematically pinpoints and structures the prominent themes within the research, encapsulating six main categories: framing systems, shear walls, cladding panels, progressive collapse, modular buildings and emerging analytical methodologies. Finally, the qualitative review delineated the predominant trends and discerned gaps in the research landscape.
2. Frame and shear wall systems are the predominant focal points, comprising 74% of the investigations. This substantial proportion is well justified, given that the benchmark for performance is derived from structural systems used in site-built buildings. A considerable part of the research effort has been directed at improving connections. The current trend revolves around creating inventive, robust, high-performance structural systems designed with damage mitigation, recovery and rapid repair capabilities. Proposals have emerged for connection systems that facilitate deconstruction to improve the environmental impacts of building end-of-life processes. To a lesser degree, research has delved into volumetric modular structural systems, hailed as the epitome of prefabricated systems, along with the conceptualization of structures endowed with multi-hazard resistance.

3. This research meticulously examines the gaps in existing research; its approach is articulated in a proposed research framework intended to guide future research. These future avenues of exploration span a spectrum of efforts, including conceptualizing pioneering structural systems equipped with damage control and repair capabilities, establishing standardized structural protocols, and developing comprehensive design principles encompassing all facets of PCB realization. In addition, the framework advocates for a holistic sustainability assessment by delving into impacts that span the entire PCB life cycle. It also supports the integration of state-of-the-art methodologies, such as optimization and multi-criteria decision-making (MCDM), to seamlessly harmonize seismic safety and sustainability considerations. Impending research efforts face a formidable challenge: to address the crisis within the sustainability paradigm and pivot toward achieving structures that seamlessly intertwine seismic robustness and sustainable attributes. It is an intricate problem, navigating a series of constraints and uncertainties that transcend conventional conceptual frameworks.
4. The key findings of this research are summarized in three main points: (1) The structure of current knowledge is established, and central themes and sub-themes addressed by the research and related to obtaining seismically safe PCB are determined. (2) It determines the structural systems most studied at present, where the evolution of connection systems is highlighted, and the concepts that dominate their design. (3) This review identifies the challenges of research keeping sustainability at the forefront for conceiving seismic-resistant PCB from a holistic perspective and provides suggestions for future lines of research. As industrialized construction methods are emerging as the future of the construction industry, there is a growing worldwide interest in this construction approach. This study may help researchers to develop new research proposals by providing valuable insights. However, it attempts to outline the most recent research and reflects the general trend; it is possible that some approaches, drawbacks or practices still need to be considered. Additionally, this study has been based only on literature published and written in English.

The outcomes of this study stand out from prior reviews due to their comprehensive approach and methodological rigour. This study encompasses the formulation of novel propositions aimed at advancing seismic-resistant PCB, aligning them with contemporary societal imperatives related to fostering sustainable development goals. The study undertakes a thorough analysis, unearths previously uncharted research voids, and presents pathways to further research in this domain.

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