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REVIEW

Bibliometric Review for Prefabricated Steel Frame Replaceable Structures

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ABSTRACT: The paradigm in seismic design is shifting from preventing structural collapse to enabling rapid post-earthquake functional recovery, positioning replaceable structural components as a key development trend. These components offer a significant advantage: following an earthquake, only the pre-designed replaceable elements need to be swapped out to restore the building's overall functionality, thereby enhancing seismic resilience and reparability. This study conducted a comprehensive literature review utilizing databases such as Web of Science and China National Knowledge Infrastructure (CNKI). This study retrieves and analyzes relevant literature from the Web of Science and China National Knowledge Infrastructure (CNKI) databases. Utilizing CiteSpace, a visualization analysis is performed on key elements including keywords, publication timelines, authors, and institutions. Specifically, keyword co-occurrence maps, high-frequency keyword lists, and clustering network diagrams are generated to map the distribution of authors and research institutions, thereby revealing the primary characteristics and research hotspots of the field. The paper reviews the current research status of major joint configurations and systematically analyzes the research directions of critical lateral-force-resisting units. Furthermore, the impact of hazards on structural survivability is explored, and the application prospects of Digital Twins and Physics-Informed Neural Networks (PINN) in precision assessment and decision-making are evaluated, aiming to provide a theoretical foundation and technical framework for the construction of resilient cities.

KEYWORDS: Prefabricated structures; replaceable; CiteSpace; seismic performance; connection nodes

1 Introduction

The conventional construction paradigm, characterized by excessive resource consumption, high emissions, and substantial pollution, is increasingly inadequate to meet the demands of modern societal advancement. This is driven by rapid urbanization, rising labor costs, and a growing imperative for sustainable development. In response, prefabricated building techniques are emerging as a transformative force, dynamically reshaping the industry's future. Prefabricated construction is an industrialized building method that involves the factory fabrication of standardized components, followed by their rapid on-site assembly. Supported by national initiatives, its advancement—particularly in concrete, steel, and wooden structures adapted to local conditions—has become a key developmental trajectory for China's construction sector. Based on construction techniques, connections in prefabricated buildings are primarily categorized as "wet" or "dry" [1]. In current practice, wet connections are guided by the "equivalent to cast-in-place"

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principle, meaning their strength should approximate that of monolithic concrete. This is typically achieved using grouted sleeves. However, wet connections involve extensive on-site pouring, which complicates construction and generates more pollution than dry methods. Consequently, the industry is shifting from wet to dry connections [2] to better leverage the advantages of prefabrication, such as accelerated timelines, simplified processes, and reduced environmental impact.

Dry connections refer to techniques that join prefabricated load-bearing components using mechanical methods, thereby eliminating the need for cast-in-place concrete. Primary types include welded, bolted, prestressed, and corbel connections. By avoiding on-site casting or grouting, this method offers a more straightforward and efficient alternative to wet connections, aligning with the trend toward construction industrialization. Moreover, the development of dry connection technology coincides with a design philosophy that prioritizes repair over demolition following structural damage. This synergy makes dry connections particularly suitable for replaceable structures, which form the core of this research within prefabricated construction. Accordingly, this study began with a comprehensive review of literature from databases including Web of Science and the China National Knowledge Infrastructure (CNKI), provided an overview of two prevalent dry connection types: welded and bolted connections.

Welded connections facilitate the metallurgical fusion at the interfaces of prefabricated elements, resulting in continuous and dependable joint nodes. The primary advantage of these connections is the formation of monolithic rigid joints that demonstrate superior load-bearing capacity, structural stiffness, and sealing effectiveness, eliminating the necessity for supplementary fastening components. For instance, Gao [3] conducted an investigation into welded longitudinal reinforcement and steel beam-column joints. Ketiyot and Hansapinyo [4] developed steel beam-column joints featuring T-shaped cross-sections embedded within the structure, Guo et al. [5] introduced interlocking concrete beam-column joints. Li et al. [6] fabricated joint components assembled through welded steel tubes. Additionally, Hu et al. [7] examined fully welded joint configurations within beam-column connection regions, as shown in Fig. 1.

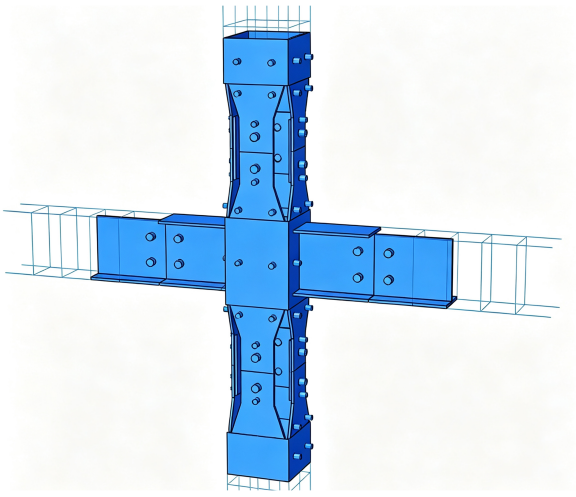


Figure 1: Bolt-assembled steel connection joint.

Bolt connections, conversely, facilitate the mechanical fastening of components by means of the pretensioning of high-strength bolts and constitute the most prevalent method of dry connection currently in use. These connections provide significant benefits, including rapid assembly, quality control, elimination of hot work, and the ability to be disassembled, thereby rendering them particularly well-suited to the principles of modular construction. In recent years, the performance of bolted connections has been progressively

enhanced through the utilization of higher-strength materials, the development of energy-dissipating connection devices, and the advancement of modular integrated connection systems. Consequently, the application of these connections has increasingly extended to structures subjected to more stringent seismic design criteria. For example, Ghayeb et al. [8] introduced an innovative dry connection node and assessed its seismic performance, as shown in Fig. 2. Similarly, Yang et al. [9] proposed steel-concrete composite joints aimed at enhancing both load-bearing capacity and seismic resilience. Additionally, Yang et al. [10] developed bolted prefabricated joints that link welded extended steel plates with embedded bolts, thereby significantly improving energy dissipation capabilities.

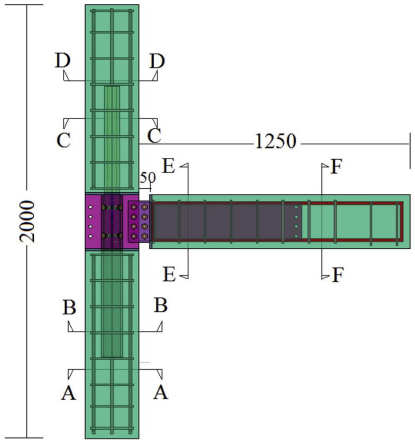


Figure 2: New type dry connection node.

Comparative analyses have demonstrated that the load-bearing capacities of these dry connection types typically exceed those of cast-in-place joints.

In summary, both welded and bolted connections effectively exemplify the distinct advantages inherent to prefabricated construction, which include rapid on-site assembly and robust structural load-bearing performance. Among the diverse connection methodologies currently employed in prefabricated buildings, dry connection techniques have attained a notably advanced and mature level of technological development. Nevertheless, as a direct result of the inherent uncertainty associated with structural damage during major seismic events, prefabricated buildings frequently experience significant and widespread structural impairment in the aftermath of earthquakes. Subsequent field investigations and detailed analyses conducted following the 2008 Wenchuan earthquake [11,12] revealed that the prefabricated components situated at the epicenter often sustained comparatively less damage, whereas the connection joints themselves proved to be far more vulnerable. The subsequent post-earthquake restoration and reconstruction efforts consequently posed substantial technical and logistical challenges, as the majority of the affected building frameworks required complete dismantling and reconstruction, thereby incurring considerable economic costs and increased energy expenditure. Consequently, the systematic investigation into improving the reparability and resilience of prefabricated buildings has emerged as a central and critical area of emphasis in the contemporary advancement of prefabricated construction engineering.

This systematic review examined the literature concerning “replaceable”, “prefabricated”, and “steel frame” structures. The current state of prefabricated building development was reviewed, along with representative types of prefabricated connections. The research methodology was then outlined, followed by an evaluation of search results, which synthesizes specific research conditions and emerging trends in recent years. Subsequently, CiteSpace was employed to analyze the collected articles, with a focus on authorship,

institutional affiliations, and keywords, leading to the generation and interpretation of visualized knowledge maps. The paper concluded by summarizing the present research landscape on replaceable nodes and offered a critical assessment of existing replaceable structural systems.

2 Data Sources and Research Methods

This section presented a review of the literature employed for data analysis, outlined the research questions, described the research methodologies, and addressed other pertinent aspects.

2.1 Research Questions

In this study, drew upon the reviewed literature and the established research methodologies, the following research questions were proposed for investigation:

- What are the primary research areas concerning replaceable structures in both domestic and international contexts?

- What are the different types of replaceable structures?

- What are the prevailing developmental trends associated with replaceable structures?

2.2 Research Methods

The development of research methodologies adheres to a structured process grounded in a dual framework that encompasses the delineation of the research scope and the analysis of research questions [13–17]. This approach facilitates the construction of a flexible methodological system. To conduct a thorough and systematic review of the existing research both domestically and internationally, and to guarantee the comprehensiveness and precision of the literature retrieval process, this study adopts a dual-database search strategy encompassing both Chinese and English sources. Corresponding search keywords are established for core databases in each language. By standardizing the search topics and cross-referencing the Chinese and English search terms [18–22], the approach effectively mitigates the risk of literature omission associated with monolingual searches, thereby ensuring a complete and objective assessment of the research landscape at home and abroad. The specific Chinese and English search terms utilized in this study are shown in the Table 1.

Table 1: Comparison of Chinese and English search terms.

Chinese	English
装配式建筑	Prefabricated building
可更换结构	Replaceable structure
钢结构	Steel structure

Within this literature review, the research methodology incorporated the use of the CiteSpace software to perform a visual analysis of the selected literature [23], thereby elucidating the application and developmental trends of the framework. The methodologies examined in the literature review involve utilizing online academic databases to retrieve articles pertinent to the research domain, while systematically excluding irrelevant materials. The specific methods are shown in Fig. 3.

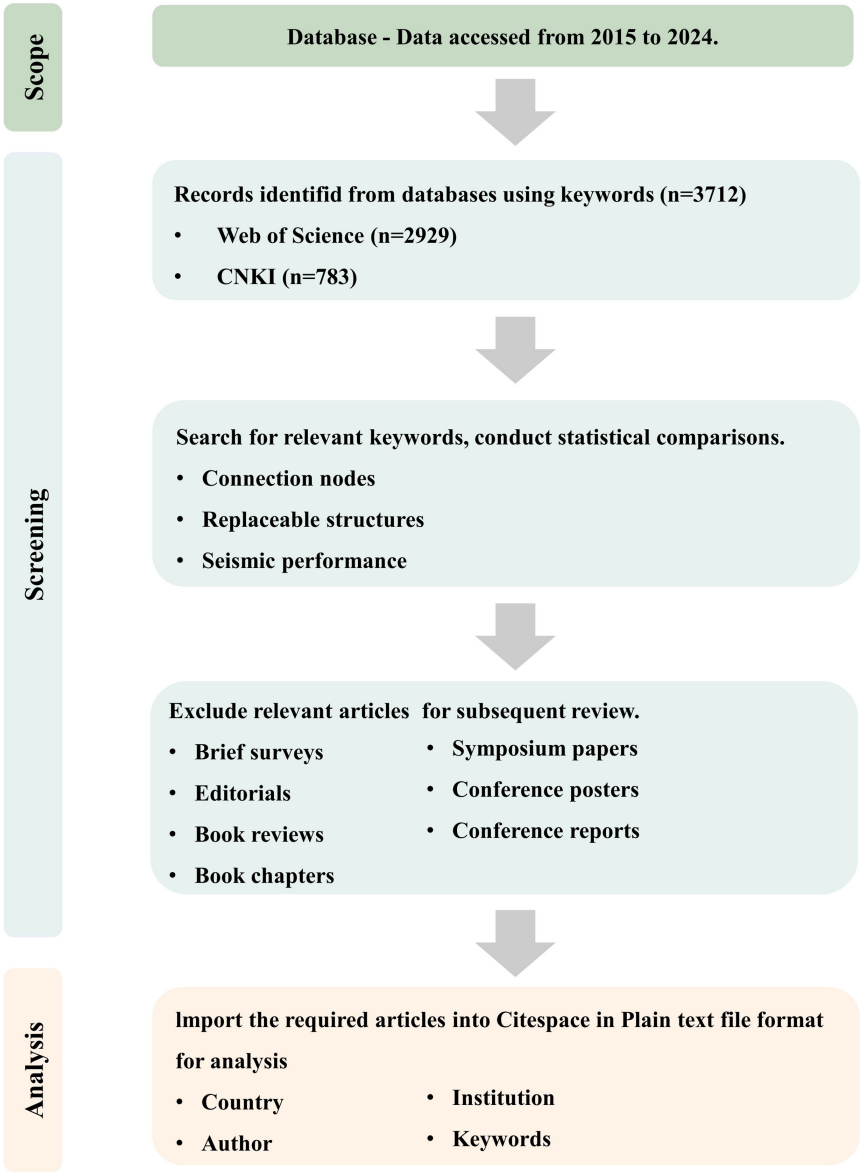


Figure 3: Visual analysis flowchart.

2.3 Literature Search Process

In the process of conducting the literature review, this study predominantly employed online databases, including Web of Science and the China National Knowledge Infrastructure (CNKI). Initially, the Web of Science database was utilized to identify articles published from 2015 to 2024 using the keyword TS = ("prefabricated buildings"), yielding a total of 2929 records [18–23]. The temporal variation in publication volume is depicted in the bar chart presented in Fig. 4. Subsequently, the CNKI database was utilized to retrieve articles from the corresponding time frame using the keyword TS = ("prefabricated buildings"). The document source categories were restricted to Peking University Core, SCI, EI, among others, while the discipline was specified as Architectural Science and Engineering. This query resulted in a total of 783 records. A bar chart illustrating the variations in publication volume over time is provided in Fig. 5.

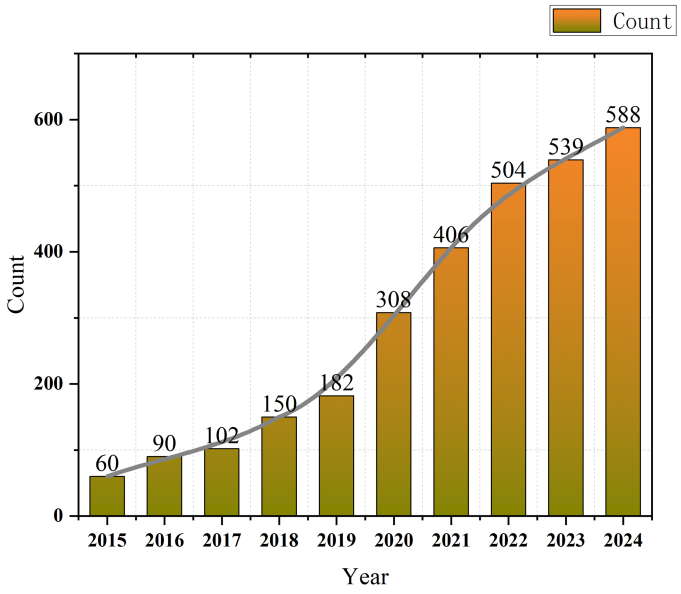


Figure 4: Annual publication volume of prefabricated building research papers from 2015 to 2024 (Web Data).

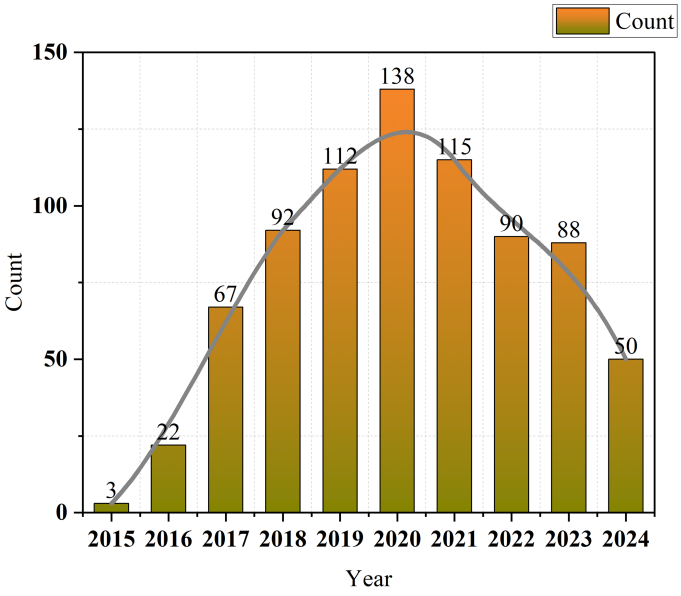


Figure 5: Annual publication volume of prefabricated building research papers from 2015 to 2024 (CNKI Data).

The analysis revealed that, as illustrated in Fig. 1, the quantity of publications pertaining to prefabrication indexed in the Web of Science database from 2015 to 2024 exhibits a linear increasing trend. Nations including China (2016 "Guiding Opinions on Vigorously Developing Prefabricated Buildings" [24]), the European Union ("Green New Deal" [25]), and the United States ("Infrastructure Investment and Jobs Act" [26]) have integrated prefabricated building into their frameworks for sustainable development. The advancement of the prefabricated building sector is primarily driven by industry transformation initiatives, including subsidies, tax incentives, and regulatory mandates. Notably, the growth rate of this sector accelerated from 2020 onward, culminating in a peak in 2024. Consequently, research on prefabrication continues to represent a significant area of scholarly interest within the global architectural community.

Fig. 5 depicts the number of academic publications related to prefabricated buildings in China, as retrieved from the CNKI database. Beginning in 2015, the publication volume exhibited a significant upward trend, reaching a maximum of 138 articles in 2020, followed by a decline thereafter. Significantly, by 2020, the technological readiness level (TRL) of prefabricated precast concrete (PC) structural technology had attained TRL 8. Concurrently, the quantity of patents integrating Building Information Modeling (BIM) with prefabrication technologies exceeded 20,000, while the domain for foundational theoretical research became increasingly limited. The emphasis of scholarly articles transitioned from broad "feasibility studies" to more granular subjects, including "node optimization." In 2022, the capacity utilization rate for PC components remained below 60%. Concurrently, market research increasingly emphasized cost control measures. Additionally, the effects of the COVID-19 pandemic contributed to a decline in the number of publications within this domain. More importantly, the pandemic brought an important revelation for the construction industry [27,28]: it is imperative to boost the development of prefabricated construction, as its low on-site workforce characteristic can well avoid mass personnel aggregation and improve the emergency response capacity of the construction industry. The published study provides a comprehensive overview of the developmental trajectory, current challenges, and practical accomplishments associated with prefabricated building in China. The theoretical significance of this work is primarily demonstrated in two key areas: firstly, it examines the developmental trajectories of the construction industry through a multi-faceted analytical approach; secondly, it formulates a comprehensive theoretical framework encompassing design, construction, and management, thereby offering foundational theoretical support for the sustainable advancement of the industry. The synergistic progression of scholarly research and technological innovation has significantly facilitated the sustained and robust development of prefabricated building in China.

Since 2016, there has been a consistent increase in scholarly interest in the domain of prefabricated buildings [29–35]. Numerous researchers have identified through their investigations that no definitive solution currently exists to address the challenges associated with structural repairs of prefabricated buildings following seismic events. Consequently, a novel research trajectory has gained prominence within the academic community: replaceable structures. The concept of replaceable structures was initially developed within the field of mechanical engineering. However, with the rapid advancement of prefabricated building methods, numerous researchers have extended this principle to building structures as a strategy to mitigate earthquake-induced damage. Grounded in the design philosophy of damage localization, this method entails the predetermined establishment of plastic hinge regions or the incorporation of replaceable energy-dissipating elements. By applying the capacity design principle, structural damage is deliberately confined to predetermined regions. During seismic events, these energy-dissipating components initially undergo plastic deformation via a controlled yielding mechanism, thereby efficiently dissipating seismic energy and maintaining the primary structure within its elastic performance range. Following an earthquake, the replacement of solely the components that have sustained local damage is sufficient to promptly reinstate the building's operational functionality, thereby improving the seismic resilience of the structure over its entire life span.

3 Research and Analysis of Replaceable Structures

This study utilizes the scientometric software CiteSpace (version 6.3.R1) to conduct a visual analysis. The temporal scope of the research spans from 2015 to 2024, segmented into annual intervals. The analysis focuses on nodes representing Authors, Institutions, Keywords, and Countries. Regarding parameter configuration, the node threshold is determined using the G-index algorithm, while the Pathfinder algorithm is employed to prune the network. This approach is intended to effectively elucidate the core knowledge structure [36].

Utilizing the Web of Science database, a search was conducted employing the advanced search parameter TS = ("replaceable structure") and restricting the publication date range from 01 January 2015,

to 31 December 2024. Articles published within this specified timeframe were subsequently retrieved. The dataset was exported in plain text format and subsequently imported into CiteSpace for visualization analysis. Given the importance of threshold selection in subsequent analyses, an initial examination was performed using a threshold value of k = 25. The resulting visualization exhibited excessively dense nodes, redundant connections, and severely overlapping cluster boundaries, indicating that this threshold was too low to effectively filter out low-frequency noise and obtain a clear modular structure.

To achieve a more structurally meaningful visualization, we tightened the threshold to k = 20. This adjustment follows the principles of the Truncated Power-Law Distribution and Network Sparsification in complex networks. In bibliometric networks, the degree distribution of nodes typically follows a power-law relationship P(k)~kγ, with most nodes falling in the low-frequency tail. Reducing k from 25 to 20 removes approximately 20% of peripheral nodes in each time slice, which mathematically corresponds to sparsifying the adjacency matrix. Letting the original network density be ρ_0 and the adjusted density be ρ_1, the sparsification process satisfies:

$$\rho_1 = \frac{E_{k=20}}{N_{k=20}} < \rho_0 = \frac{E_{k=25}}{N_{k=25}} \tag{1}$$

where E denotes the number of edges and N denotes the number of nodes. By increasing the threshold, the average degree (k) of the network is effectively reduced, thereby improving the Modularity Index (Q). According to Newman's definition:

$$Q = \frac{1}{2m}\Sigma_{ij}\left[A_{ij} - \frac{k_i k_j}{2m}\right]\delta\left(C_i, C_j\right) \tag{2}$$

As redundant connections decrease after tightening k, the network converges from a fully connected state to a core-periphery structure, significantly reducing cross-cluster edges (noise terms in A_{ij}) and driving Q closer to 1. The results show that at k = 20, the network maintains connectivity while substantially improving cluster separation and silhouette coefficients, revealing a more accurate knowledge structure.

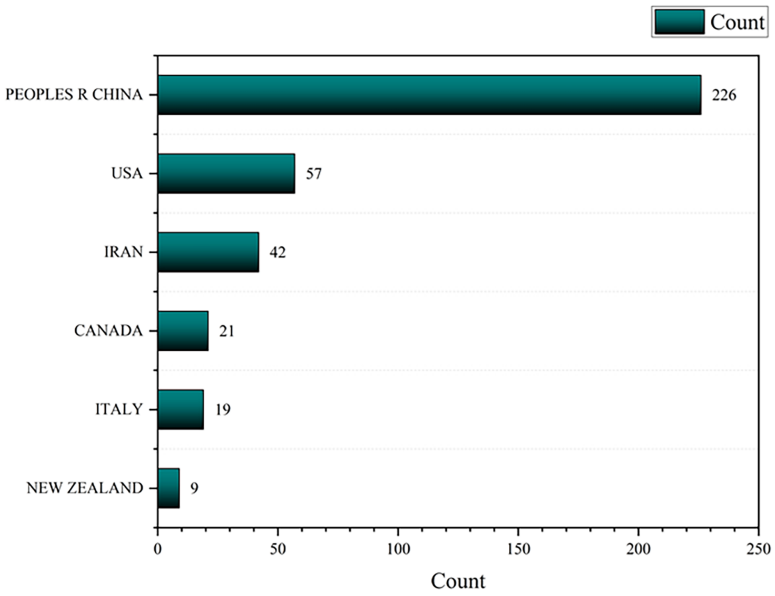
3.1 Analysis of Literature by Country

Configure the node classification to "Country" and define the temporal scope from 2015 to 2024. Employ the g-index with a parameter of k = 20 as the threshold criterion, and apply the "Pathfinder" technique for network pruning, specifically utilizing the "Pruning the merged network" approach. The resultant network visualization is presented in Fig. 6a.

As illustrated in Fig. 6b, China leads in the number of published articles in the domain of replaceable structures, with a total of 226 papers published during the specified period. This suggests that in recent years, China has introduced the concept of "resilient functional structures" within the context of disaster prevention and mitigation [37], highlighting the importance of constructing buildings that possess the capacity for swift restoration following seismic events. This concept has been integrated into various national standards and research protocols, thereby encouraging researchers to investigate design methodologies for interchangeable components. At the research level concerning replaceable structures, domestic investigations predominantly concentrate on localized structural innovations and technical enhancements. In contrast, international research tends to adopt a more macro-level perspective, prioritizing the integration of structural design within the broader context of overall engineering goals. This "demand-driven and technology integration" approach has conferred a competitive advantage to China in terms of the volume of published scholarly articles.



(a)



(b)

Figure 6: (**a**) Network map of countries with published papers in the field of replaceable structures, (**b**) Comparison of the number of publications by countries in the field of replaceable structures.

3.2 Analysis of Literature Authors

The node type was designated as "Author", with the temporal scope defined from 2015 to 2024. The threshold criterion was established using the g-index with a parameter of k = 20. Additionally, the network pruning technique employed was the "Pathfinder" method, applied specifically through pruning the merged network. The resulting network is depicted in Fig. 7. This network comprises 253 nodes and 263 edges, where each node corresponds to an individual author, and each edge represents a collaborative relationship between

authors. As illustrated in Fig. 7, Lian et al. [38], Wang et al. [39] along with five additional researchers [40–50], have contributed a substantial volume of publications within the domain of replaceable structures.

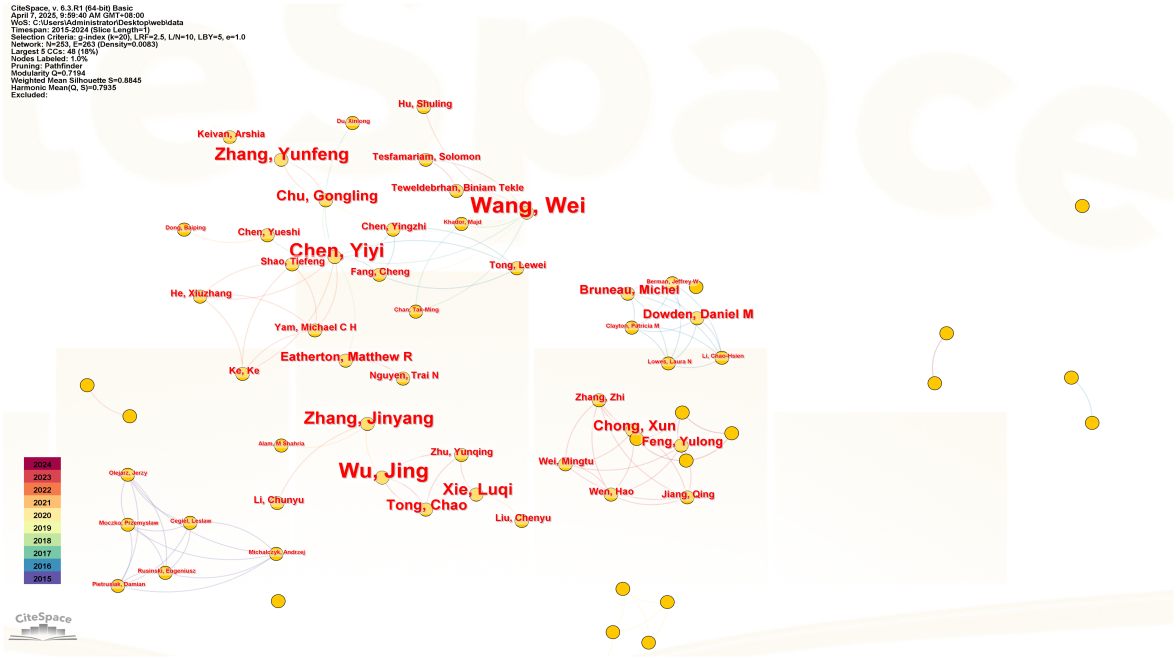


Figure 7: Network map of authors in the replaceable structural domain.

3.3 Analysis of Research Institutions

The node type was designated as "Institution", encompassing the time frame from 2015 to 2024. The threshold was determined using the g-index with a parameter of k = 20, in order to construct the knowledge network of institutions within the domain of replaceable structure. The network comprises 160 nodes and 180 edges, with each node representing an institution and each edge denoting a collaborative relationship between institutions. As illustrated in Fig. 8, the primary institutions engaged in research on "replaceable structure" were examined. The analysis distinctly indicates a concentrated pattern of research activity within this domain. The findings presented in Table 2 indicate that Chinese institutions have demonstrated notably significant contributions within this field. Tongji University leads with a total of 52 publications, followed by Xi'an University of Architecture and Technology with 41 publications, and Southeast University with 29 publications. Collectively, these three universities have played a pivotal role in advancing civil and earthquake engineering in China, underscoring the country's strategic emphasis on this area of research.

It is important to highlight that the list also encompasses research projects affiliated with the China Earthquake Administration. This suggests that investigations into structural resilience transcend purely academic inquiry and are closely aligned with national objectives aimed at mitigating earthquake risks and advancing the construction of disaster-resilient infrastructure. Furthermore, institutions including the University of Canterbury in New Zealand and the University of California system in the United States, both situated within regions characterized by high seismic activity, underscore that the issue of "replaceable structures" constitutes a significant global challenge within the field of earthquake engineering. The discrepancy in publication output highlights China's present position as a pivotal center for knowledge generation in this vital domain, demonstrating the country's strategic investment in research focused on improving structural reparability and resilience following seismic events.



Figure 8: Knowledge graph of the network of replaceable structures in the domain.

Table 2: Number of institutions published in the field of replaceable structures (top 10).

Number	Institutions	Counts
1	Tongji University	52
2	Xi'an University of Architecture & Technology	41
3	Southeast University-China	29
4	Islamic Azad University	18
5	Chang'an University	12
6	University of Canterbury	11
7	Beijing University of Technology	11
8	University of California System	10
9	China Earthquake Administration	10
10	Hong Kong Polytechnic University	9

3.4 Analysis of Research Hotspots

By configuring the node type to "Keyword", specifying the time frame from 2015 to 2024, and applying a threshold based on the g-index (k = 20), alongside employing the network pruning techniques "Pathfinder" and "Pruning the merged network," a co-occurrence map of keywords within the domain of replaceable structures was produced, as illustrated in Fig. 9. Applying the same methodology, data obtained from CNKI were processed accordingly, and the resulting keyword map is presented in Fig. 10, Table 3 presents the frequency rankings of the associated keywords. Subsequently, utilizing the parameters of the co-occurrence map, a cluster analysis of the keywords was performed, resulting in the generation of the keyword clustering map, as illustrated in Fig. 11.

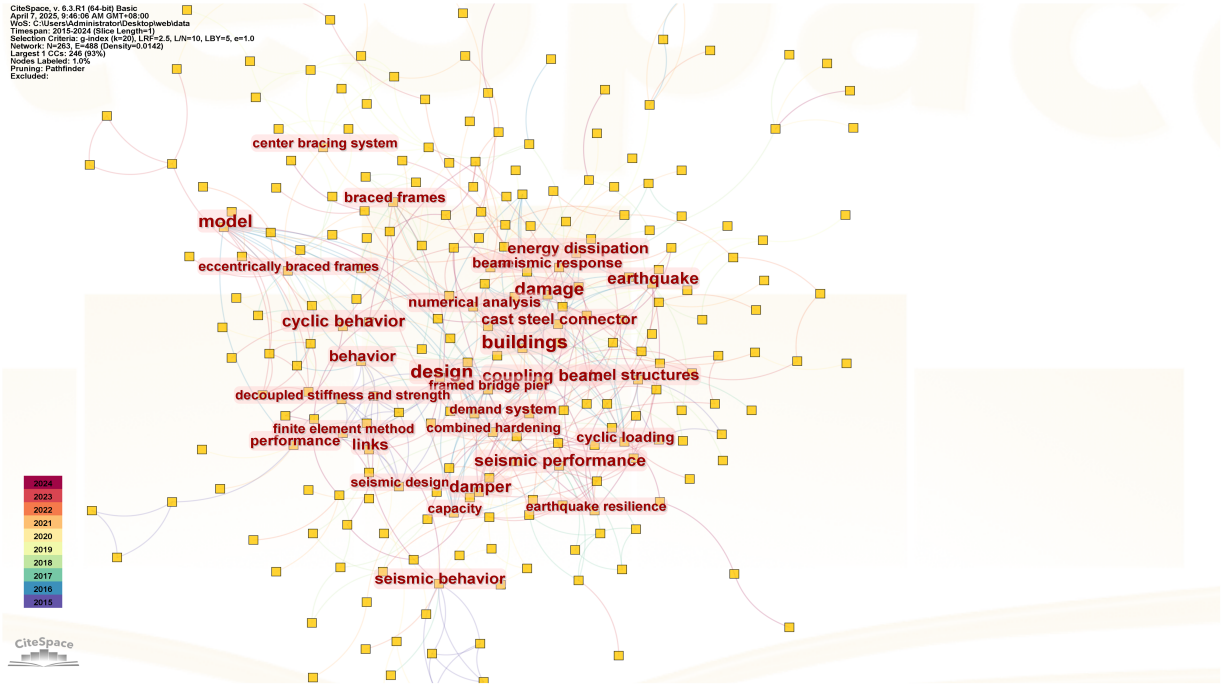


Figure 9: Keyword co-occurrence map of replaceable structure domain (Web).

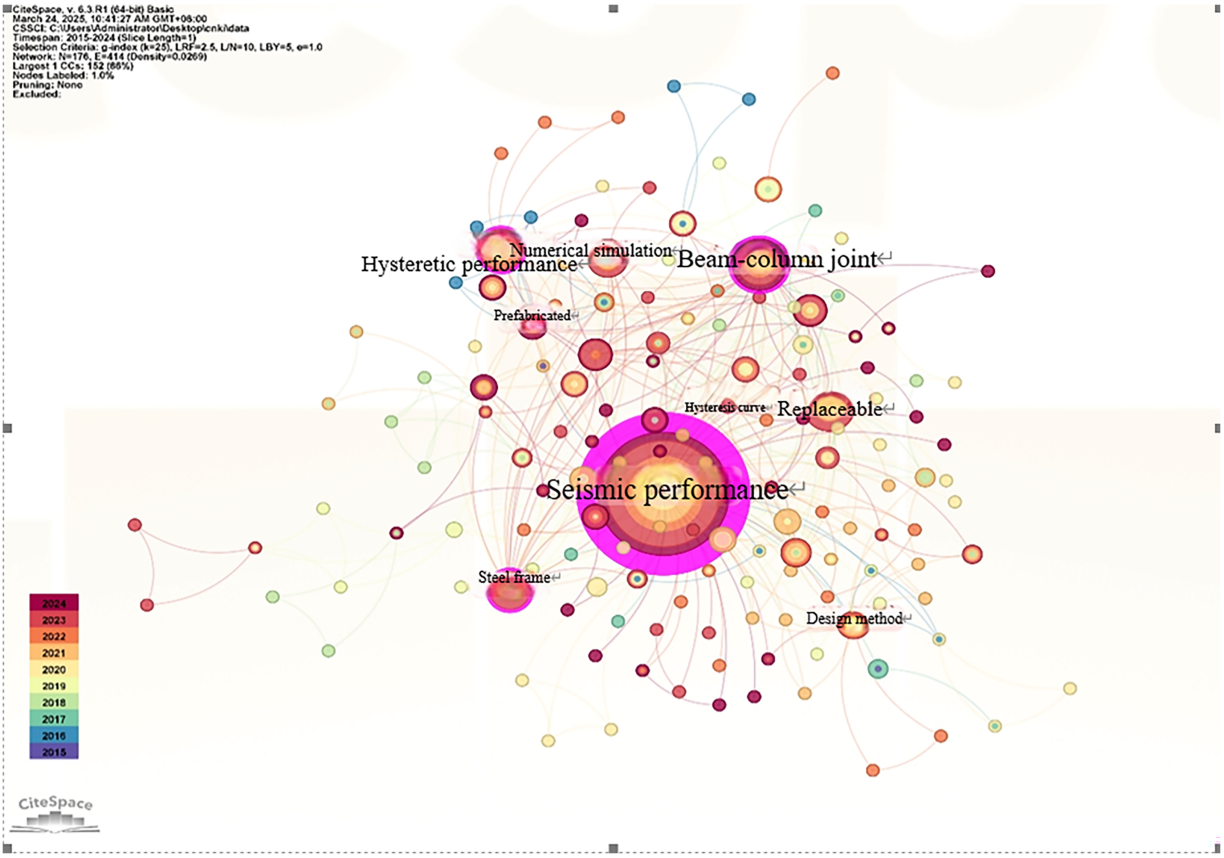


Figure 10: Keyword co-occurrence map (CNKI) in the field of replaceable structures.

Table 3: Ranking of keywords with replaceable structures.

Sorting	Domestic	International
1	Seismic performance	Behavior
2	Beam-column joint	Seismic performance
3	Hysteretic performance	Design
4	Replaceable	Performance
5	Numerical simulation	Connections
6	Steel frame	Buildings
7	Prefabricated	Seismic behavior
8	Hysteresis curve	Seismic design
9	Design method	Frames
10	——-	Eccentrically braced frames

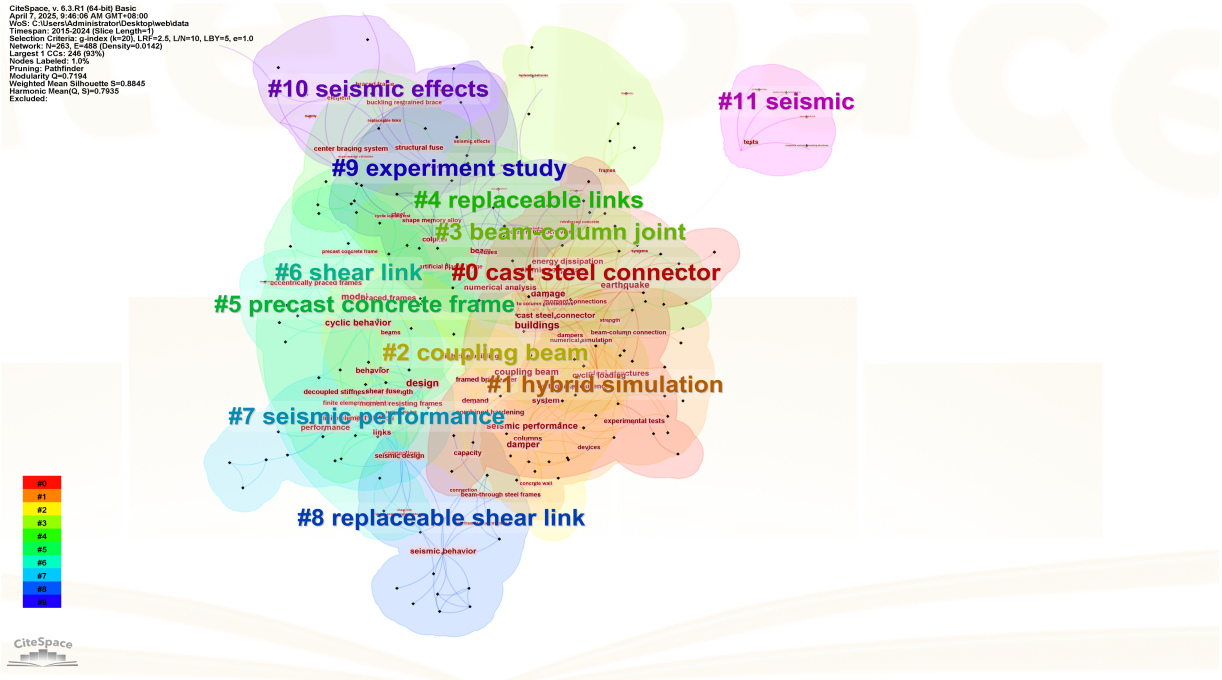


Figure 11: Keyword clustering map of replaceable structural domains.

To investigate the distinctions between Chinese and English literature concerning replaceable structures [51], this study utilizes two sets of keywords subjected to statistical analysis via Citespace The primary keywords identified in articles related to replaceable structures within the CNKI database from 2015 to 2024 encompass seismic performance, beam-column joints, hysteretic performance, and replaceable components. Concurrently, an analysis was conducted on the primary keywords featured in articles pertaining to replaceable structures retrieved from the Web of Science database. Nevertheless, given that the analysis of publication countries conducted with the Citespace tool indicated that the volume of domestic publications is among the highest, it was deemed inadequate to directly compare keyword variations between domestic and international literature. Consequently, following the exclusion of articles authored by domestic

researchers within specific research domains, the primary keywords [52–60] identified encompassed seismic performance, connections, steel structures, finite element analysis, among others. The observed divergence in research focal points underscores distinct developmental trajectories and methodological approaches between domestic and international scientific investigations. Domestic research commenced comparatively later and has been significantly shaped by the systematic engineering education models of countries such as Germany and Japan, with a strong focus on the comprehensive investigation of foundational theories and critical technologies. Concurrently, the national research assessment framework—encompassing metrics such as publication counts, impact factors, and the acquisition of funded projects—frequently incentivizes achieving breakthroughs at distinct, well-defined, and quantifiable junctures. Innovations occurring at these particular "points" are more prone to yield definitive and publishable outcomes. Conversely, the significance of conducting research internationally extends beyond theoretical advancements to encompass the resolution of practical engineering challenges and the influence on industrial practices. Variations in developmental stages result in divergent research trajectories. Numerous developed nations have surpassed their peak phases of construction activity, and the primary focus for advancements in engineering technology has consequently shifted towards maintenance, renovation, and improvement. Consequently, research carried out internationally is generally conducted within the framework of a comprehensive and well-established seismic structural system. The study concentrates on investigating the integration of replaceable structures within existing systems to enhance performance. The central research question is formulated as follows: "In what ways can replaceable structures be implemented within mature systems to improve the overall performance of the building?"

In summary, a comparative analysis of high-frequency keywords in Chinese and English literature [61] reveals distinct research emphases between domestic and international studies. Domestic research predominantly concentrates on the investigation of fine structural details and methodological innovations, whereas international research adopts a holistic perspective, prioritizing the integration and applicability of structures within overall engineering systems. These differing focal points collectively constitute a comprehensive framework guiding the development of replaceable structures. A thorough understanding of the interplay between component-level and system-level considerations, as well as between technological advancements and practical applications, is essential for scholars to attain a comprehensive understanding of the field, accurately situate their research, and facilitate more productive international academic exchanges.

To conduct a more in-depth analysis of research trends, the "Node Types = Keywords" setting was employed in CiteSpace to produce a keyword clustering map, which is presented in Fig. 11. The obtained Modularity Q value was 0.7194, exceeding the threshold of 0.3, which signifies a well-defined clustering structure. Additionally, the Mean Silhouette coefficient was 0.8845, surpassing the benchmark of 0.5, thereby indicating a high degree of internal consistency within each cluster. This indicates the robustness of the clustering map as demonstrated in reference [62]. T the cluster labels are assigned numerical identifiers ranging from #0 to #11, corresponding respectively to the following categories: #0 (cast steel connector), #1 (hybrid simulation), #2 (coupling beam), #3 (beam-column joint), #4 (replaceable links), #5 (precast concrete frame), #6 (shear link), #7 (seismic performance), #8 (replaceable shear link), and#9 (experimental study), #10 (seismic effects), #11 (seismic), resulting in a total of twelve distinct clusters. By conducting a thorough analysis of high-frequency keywords and nodes with high centrality [63], this study categorizes the cluster labels into three primary segments, each corresponding to key research focal points within the field of replaceable structures.

(1). Emphasizing the development and enhancement of replaceable components, specifically the "fuse" concept exemplified by "replaceable links" and "replaceable shear links", through comprehensive investigations into their hysteretic behavior, energy dissipation capabilities, and replacement procedures.

(2). Focusing on the seismic performance of prefabricated joints, this study emphasizes the seismic behavior of beam-column joints and coupling beams within precast concrete frame systems, particularly those employing advanced connection technologies such as cast steel connectors.

(3). The integration of experimental performance evaluations is achieved through the close combination of "experimental study" and "seismic performance", utilizing a range of methodologies such as quasi-static testing and shake table experiments. This approach systematically assesses the load-bearing capacity, ductility, and damage controllability of replaceable structural systems, thereby constituting the primary research directions within this domain.

This chapter employs CiteSpace software to conduct an analysis of the development within the field of replaceable nodes, focusing on aspects such as the research overview and the identification of research hotspots. Despite advancements in prefabricated building systems, ensuring seismic performance continues to be a primary focus in ongoing research. In response to the need to meet performance criteria, the concept of replaceable structural components has gained significant attention in the public domain.

4 Replaceable Structural Design Mechanism

To mitigate the critical drawbacks of conventional steel frames under seismic loading—namely the difficulty of post-earthquake repair, prolonged functional downtime, and substantial economic losses—the paradigm of replaceable structural components (RSC) has been introduced. The essence of this approach lies in the strategic concentration of inelastic deformation and structural damage within pre-designated replaceable regions, thereby facilitating controllable damage, rapid restoration, and sustainable utility. This methodology effectively safeguards global structural integrity, enabling expedited post-seismic repair and functional recovery. Central to this design philosophy is the principle of damage isolation: by incorporating "structural fuses"within the system, nonlinear excursions and hysteretic energy dissipation are confined to secondary, replaceable elements. Consequently, critical primary members, such as columns and joint panel zones, are shielded from damage and maintained in a near-elastic state.

In the field of structural joint design, strengthened nodes and weakened nodes serve as the primary seismic configurations for achieving plastic hinge relocation and preventing brittle failures. Strengthened nodes enhance load-bearing capacity, stiffness, and ductility through local structural detailing or material reinforcement. For instance, Wang and Ke [64] experimentally confirmed that cover-plate strengthened nodes significantly increase plastic rotation and energy dissipation capacity while inhibiting brittle fractures at the welds. Similarly, Jannesari and Tasnimi [65] utilized a combination of flange widening and cover plates to achieve plastic hinge relocation, thereby enhancing both hysteretic stability and stiffness. Landolfo et al. [66] also demonstrated that stiffening and reinforcing the joint panel zone in strengthened nodes can effectively control deformation and satisfy rotation demands during severe earthquakes.

Conversely, weakened nodes facilitate controllable energy dissipation zones through intentional section reduction. Qiu and Li [67] investigated the elastic shear buckling behavior of corrugated web girders with circular openings through finite element eigenvalue analysis, and proposed a reduction coefficient-based design formula that accounts for the effects of opening diameter, web height, web thickness, and opening eccentricity on the shear buckling capacity. Guo et al. [68] applied tapered weakening to high-strength steel nodes, successfully mitigating stress concentrations and enhancing low-cycle fatigue performance. Furthermore, Momenzadeh et al. [69] proposed weakened nodes with rectangular web openings, which exhibited no significant strength degradation even at a 4% story drift ratio, showcasing exceptional ductility and hysteretic performance.

4.1 Beam-to-Column Connections

Beam-column nodes serve as the primary seismic defense line for prefabricated structures. Modern research paradigms have evolved from conventional strength-oriented design to a sophisticated phase that emphasizes rotation capacity, damage control, hysteretic stability, and structural durability. Furthermore, critical phenomena such as panel zone shear deformation, bolt-hole bearing damage (often manifested as ovalization), stiffness degradation, and low-cycle fatigue are decisive factors in governing the failure modes and reparability potential of nodes under severe seismic loading. Addressing these issues necessitates a systematic control approach that integrates fundamental mechanical mechanisms with rigorous structural detailing.

4.1.1 Damage Control Mechanisms in Strengthened and Weakened Nodes

Farsi et al. [70] proposed a replaceable steel coupling beam featuring end-plate connections. By eliminating the conventional embedded segment of the coupling beam within the wall and adopting a double end-plate bolted configuration, the study successfully concentrated seismic damage within the detachable web of the coupling beam. Technical enhancements included the use of stiffening ribs to increase end-plate rigidity and 90° anchor bolt hooks to improve pull-out resistance. These modifications elevated the shear friction coefficient from 0.7 to 1.0, significantly boosting force transfer efficiency. In this configuration, the coupling beam web serves as the primary energy-dissipation component, ensuring that only the beam assembly needs to be replaced post-earthquake, thereby sparing the shear wall from demolition. This design conceptually integrates the reinforcement philosophy of strengthened nodes with the "structural fuse" mechanism characteristic of weakened nodes, ultimately achieving the objective of structural reusability.

A series of investigations by Wang et al. [71] and Tang et al. [72] indicates that strategic circular flange weakening and intentional web openings can markedly mitigate stress concentrations in the weld zones. This design effectively relocates plastic deformation away from the joint panel zone, thereby enhancing both nodal ductility and low-cycle fatigue life. In a similar vein, Mirghaderi et al. [73] conducted experimental research on a novel node configuration incorporating corrugated plates within the web region. Their findings demonstrated that this system successfully shifts the beam-end plastic hinge to the corrugated segment, exhibiting robust seismic performance. Furthermore, the corrugated plates effectively reduce the bending moment demand on the web at the connection interface while ensuring sufficient shear stiffness, which serves to postpone the onset of local flange buckling.

4.1.2 Replaceable Energy-Dissipating Hinges

To further facilitate rapid post-earthquake functional recovery, replaceable energy-dissipating components have been integrated into beam-to-column node systems, fulfilling the dual objectives of damage concentration and structural modularity for disassembly. Zheng et al. [74] developed a novel precast concrete beam-column node featuring replaceable energy-dissipating steel hinges. In this configuration, steel tubes are employed to confine the node core, while shear-yielding, low-yield-point (LYP) steel hinges are positioned at the beam ends to serve as artificial plastic hinges. Experimental results demonstrated that the nodes exhibit plump hysteretic loops without significant pinching effects. Furthermore, the load-bearing capacity and energy dissipation capacity were enhanced by approximately 50% and 100%, respectively, compared to conventional monolithic cast-in-place joints. Crucially, plastic damage was isolated entirely within the replaceable hinges, leaving the primary structural members with only negligible damage. Post-event restoration is achieved solely by replacing the damaged hinge components, effectively realizing the quasi-static decoupling of the energy-dissipation mechanism from the primary structure. A comparative

overview of different replaceable node configurations and their corresponding mechanical performance is summarized in Table 4.

Table 4: Classification and performance comparison of replaceable nodes.

Node Category	Core Mechanism	Performance Characteristics	Key Issues Addressed
Strengthened Nodes	Local structural detailing or material reinforcement + preset replaceable energy-dissipating segments; enhancing stiffness and load-bearing capacity.	High initial stiffness, substantial capacity, and superior plastic rotation; damage localized within replaceable strengthened components.	Joint panel zone yielding, column-end failure, brittle weld fracture, and post-earthquake repair challenges.
Weakened Nodes	Intentional section reduction at the beam end to create "structural fuses"; forced relocation of the plastic hinge away from the column face.	Exceptional ductility, plump hysteretic loops, and minimized stress concentration; negligible damage to the primary structure.	Uncontrollable plastic hinge localization, concentrated nodal damage, and inadequate low-cycle fatigue performance.
Self-Centering Nodes	Prestressing or rocking mechanisms providing restoring force + replaceable energy-dissipating components; controlling residual deformation.	Negligible residual drift and post-seismic lateral tilt; complete restoration of structural performance after component replacement.	Permanent residual lateral drift, inability to reset, and the requirement for hydraulic jacking or structural realignment during repair.
Hybrid Energy-Dissipating Nodes	Integration of yielding, friction, and shear energy dissipation mechanisms; fully bolted assembly with localized replaceable damage.	High energy-dissipation efficiency, stable stiffness degradation, expedited replacement, and superior construction tolerance.	Bolt-hole ovalization, uncontrolled slip, and rapid stiffness degradation under cyclic loading.

4.2 Bracing Systems

Bracing systems represent the primary source of lateral stiffness in prefabricated steel frames; however, brace buckling and connection failure under severe seismic loading are critical vulnerabilities that can trigger structural collapse. Replaceable bracing and link beam systems are centered on the core principles of damage concentration, sacrificial energy dissipation, maintaining primary structural elasticity, and facilitating rapid post-earthquake replaceability. By confining plastic yielding and failure to detachable 'structural fuse' segments, these systems have emerged as a pivotal technical trajectory in contemporary seismic resilience design.

4.2.1 Replaceable Links

Eccentrically Braced Frames (EBF), which employ replaceable shear links as "structural fuses" to dissipate seismic energy, represent one of the most established configurations within the spectrum of replaceable structural systems. As a seismic-resistant system characterized by both high initial stiffness and excellent ductility, EBF have attained significant research advancements in recent years across several critical domains, including dynamic characteristics, progressive collapse resistance, performance optimization, seismic response mechanisms, and the development of reparable structural detailing.

Young and Adeli [75] investigated twelve geometrically irregular EBF and proposed simplified formulas for the fundamental period based on vibration theory. By accounting for both vertical and horizontal irregularities, these formulas facilitate the rapid estimation of structural dynamic characteristics during the preliminary design phase. Utilizing the nonlinear static alternate path method, Salmasi and Sheidaii [76] conducted progressive collapse assessments on various EBF configurations, including inverted-V, eccentric V, and eccentric X patterns; their findings indicated that the synergy between eccentric bracing and moment-resisting frames significantly enhances structural redundancy and global stability. Fathali and Hoseini Vaez [77] integrated Performance-Based Design (PBD) with metaheuristic algorithms to optimize EBF structures for lightweight objectives and uniform deformation distribution, offering a novel pathway for highly efficient and economic design.

Furthermore, through nonlinear dynamic time-history analysis, Ashrafi and Imanpour [78] pointed out that excessively short energy-dissipating links in multi-story EBF might trigger non-uniform yielding, uneven inter-story drift distribution, and risks of out-of-plane column buckling, necessitating strict control over the slenderness ratio and rigorous verification of column stability. Significant advancements have been achieved domestically in the field of high-strength steel (HSS) EBF. Through shaking table tests, Lian and Su [79] elucidated the influence of critical parameters—such as the web height-to-thickness ratio, link length, and height-to-span ratio—on Y-shaped systems. They established PBD methodologies to realize an idealized failure mode where energy-dissipating links yield preferentially while the primary structure remains elastic. Based on Incremental Dynamic Analysis (IDA), Tian et al. [80] verified the superior seismic resilience and damage controllability of K-shaped HSS-EBF, confirming that PBD ensures plastic deformation is confined solely to the link beams under severe seismic events. Additionally, experiments by Shi et al. [81] demonstrated that bolted semi-rigid connections in EBFs exhibit better seismic performance than welded joints and offer superior convenience for post-earthquake replacement, with the end-plate thickness primarily governing the nodal failure modes, thereby providing a technical basis for the design of replaceable EBF systems.

4.2.2 Buckling-Restrained Brace

Beyond EBF, significant research efforts have been dedicated internationally to Buckling-Restrained Braced (BRB) systems. Junda et al. [82] introduced the Buckling-Restrained Knee Braced Frame (BRKBF) system, which features a streamlined configuration and lower post-earthquake repair difficulty compared to traditional bracing structures. Low-cycle cyclic test results indicated that this frame system possesses stable hysteretic performance and robust energy-dissipating capacity. Specifically, plastic damage can be entirely confined to the knee brace components, effectively shielding the primary frame structure. Guo et al. [83] conducted a comprehensive review of the 40-year evolutionary history of BRB, summarizing their mechanical mechanisms, failure modes, hysteretic fatigue performance, and critical design parameters. Their work also systematically organized provisions from various international design codes, providing a thorough theoretical foundation for the subsequent optimization and engineering application of BRB.

Furthermore, Wu et al. [84] performed cyclic loading tests on BRB-equipped concrete frames under varying stiffness ratios. The results demonstrated superior global energy dissipation performance, with structural load-bearing capacity increasing in proportion to the brace-to-frame stiffness ratio. However, an excessively high stiffness ratio was found to exacerbate damage at the brace connections. Under lateral loading, rotational deformation at the brace ends induces secondary bending moments, and this rotation exhibits a linear relationship with the story drift ratio. The study recommended strengthening the ductility detailing of the joints to ensure that the energy-dissipating potential of the BRBs is fully realized under severe seismic events.

By synthesizing the domestic and international research findings on the two primary categories of replaceable lateral-force-resisting systems—namely, replaceable links in EBF and BRB—a horizontal comparison was conducted from the core perspective of replaceable seismic design. This evaluation focuses on critical indicators, including damage control mechanisms, energy-dissipating components, and reparability characteristics. The detailed comparative results are presented in Table 5.

Table 5: Comparative analysis of seismic performance between EBF and BRB.

Indicator	EBF	BRB
Core Energy-Dissipating Component	Shear links: Serving as dedicated structural fuses.	Nternal steel core: The entire brace assembly acts as the energy-dissipating unit.
Damage Control Mechanism	Damage localized in links. Short links are prone to non-uniform shear yielding, potentially triggering uneven inter-story drift and out-of-plane column buckling.	Damage localized in the core. Brace-end rotation induces secondary bending moments, leading to localized failure at the connections.
Plasticity Distribution Pattern	Achieves preferential yielding of links; primary beam-column members remain elastic with highly controllable plastic zone localization.	Plasticity concentrated in the core; primary frame remains elastic, though node zones are susceptible to secondary damage.
Post-Earthquake Replaceability	Utilizes bolted semi-rigid connections, allowing direct replacement of links without altering the primary frame; high replacement efficiency.	Conventional BRBs require full replacement. Modular types allow core replacement, but repair procedures for connection nodes are relatively complex.
Design Plastic Rotation Capacity	≥0.08 rad (short links, AISC 341)	≥0.02 rad axial strain equivalent (AISC 341 qualification protocol)
Overstrength Factor Ω	Typically 1.5–2.0; may exceed 2.0 for short links	Typically 1.1–1.4
Equivalent Viscous Damping Ratio	20%–35%	30%–45%

4.3 Seismic-Resilient Structural Systems

Driven by advancements in construction technology and escalating societal demands, the paradigm of seismic design has shifted from a "survival-oriented" (life-safety) focus to one centered on functional recovery. Consequently, functional recovery has evolved beyond a mere qualitative narrative into a rigorous, metric-based evaluation framework. According to the FEMA P-58 [85–87], the quantitative criteria for measuring the performance of replaceable structures primarily include: (1) Residual Drift Ratio (RDR): Research indicates that when RDR exceeds 0.5%, conventional steel frames are prone to severe geometric nonlinear damage exacerbated by P-Delta effects, significantly complicating post-earthquake repair. Replaceable systems are designed to restrict RDR to below 0.2% through self-centering mechanisms or forced realignment techniques. (2) Cumulative Damage Index: The low-cycle fatigue life of energy-dissipating components under mainshock-aftershock sequences serves as the cornerstone for evaluating structural reliability. (3) Repair Duration and Economic Metrics: These indicators encompass the downtime required for component replacement, as well as the ratio of component reset costs to the total life-cycle cost (LCC) of the structure.

4.3.1 Self-Centering Structural Systems

Self-centering structures exploit the superelastic recovery effects of materials such as post-tensioned (PT) tendons and Shape Memory Alloy (SMA) to eliminate post-earthquake residual drifts, enabling autonomous re-centering without the need for external intervention. This paradigm represents a mainstream research trajectory within the field of seismic-resilient engineering. Ozbulut et al. [88] developed a hybrid self-centering damper by integrating the superelasticity of SMA with the advantages of viscous damping, effectively addressing the excessive residual deformation inherent in traditional damping systems. Zou et al. [89] focused on precast concrete frame nodes, confirming that the initial tension stress and the quantity of PT tendons are the decisive factors governing the re-centering capacity; their findings suggest that optimized reinforcement configurations can ensure that primary structural members remain within the elastic range even under large-drift conditions. Furthermore, Zhang et al. [90] proposed a prestressed steel frame system, with experimental evidence demonstrating that the structure satisfies the design objectives of remaining 'damage-free' under serviceability-level earthquakes and achieving "re-centering with energy dissipation" under design-basis earthquakes. Overall, its integrated seismic and re-centering performance significantly out-performs that of conventional steel frames.

Beyond advancements at the material and nodal levels, rocking-hybrid self-centering systems demonstrate substantial prospects for engineering application. Zhou et al. [91] proposed a self-centering brace-rocking frame (SCB-RF) system, which effectively integrates the re-centering capabilities of braces with the energy-dissipating merits of rocking frames. This configuration is particularly suited for meeting the stringent requirements of rapid functional recovery in high-intensity seismic regions. Furthermore, Lu et al. [92] conducted a comparative analysis of two types of hinge-controlled rocking concrete frames. Their findings indicated that rocking frames with column-end hinges facilitate concentrated energy dissipation and achieve autonomous re-centering through the synergistic action of structural self-weight and post-tensioning. Consequently, the global structure remains essentially damage-free following seismic excursions.

4.3.2 Functional Recovery Systems

Ji et al. [93] conducted quasi-static tests on replaceable steel coupling beams, demonstrating that shear-yielding energy-dissipating links possess substantial plastic deformation capacity. Their findings indicated that the mechanical performance redundancy far exceeds the requirements of current design codes, while

damage remains localized, controllable, and facilitates rapid assembly and disassembly. Chen et al. [94] applied these components to super high-rise shear wall structures, effectively mitigating inter-story drifts and reducing damage to the primary wall structures. Concurrently, researchers have explored the optimization of replaceable components using high-performance materials. Fan et al. [95] improved the global energy-dissipation level and effectively lowered structural responses under rare seismic events by optimizing the cross-sections and dimensions of the energy-dissipating segments in replaceable coupling beams. Furthermore, Zhang et al. [96] performed pushover numerical analyses on high-strength steel composite frame-tube structures equipped with HSS hybrid energy-dissipating links. The numerical results demonstrated that the proposed links effectively restricted lateral drifts and confined plastic damage to the replaceable elements, providing useful design guidance for high-performance replaceable bracing and connection components.

5 Development Prospects

While replaceable structural systems have achieved substantial advancements in the field of seismic resilience, bridging the gap between laboratory research and large-scale engineering implementation remains a formidable task. This transition continues to be beset by deep-seated challenges, including multi-hazard coupling, intelligent operation and maintenance (O&M), and practical feasibility.

5.1 Survivability under Multi-Hazard Coupling

Throughout their full service lifecycle, structures are susceptible to cascading multi-hazard sequences, such as fire and earthquakes. The coupled effects of fire and seismic events induce material property degradation, damage accumulation, and resistance attenuation, significantly diminishing both structural survivability and post-disaster recoverability. Consequently, understanding these interactions has emerged as a pivotal scientific challenge in the research of high-performance structures and resilient cities.

Liu et al. [97] conducted quasi-static cyclic tests on concrete-filled steel tubular (CFST) column-to-steel beam connections after fire exposure. The results indicated that, even after exposure to elevated temperatures, the joints exhibited relatively favorable ductile hysteretic behavior, characterized by significant beam-end plastic deformation and stable energy dissipation. However, weld fracture was observed as one of the ultimate failure modes, indicating a transition from ductile deformation to localized failure. Although the hysteretic loops remained relatively plump and stable, the load-bearing capacity declined significantly with increasing fire exposure temperature. The displacement ductility coefficient exhibited a distinct peak characteristic, initially increasing and subsequently decreasing, while both stiffness and energy dissipation capacity underwent pronounced degradation. Consequently, the structural safety margin was substantially reduced under coupled fire and seismic loading conditions.

Jin and Su [98] integrated PyroSim fire simulation with ABAQUS finite element modeling and Incremental Dynamic Analysis (IDA) to systematically investigate the seismic fragility of steel frames following fire exposure. Their study quantitatively demonstrated that fire exposure significantly elevates the exceedance probabilities of various structural damage states, making it difficult for post-fire structures to satisfy seismic design code requirements. Furthermore, by implementing retrofitting strategies with X-shaped and M-shaped steel braces, the structural fragility was substantially mitigated, and the seismic performance was restored to code-mandated limits. This approach effectively enhances both structural survivability and post-disaster reparability under multi-hazard coupled scenarios.

In summary, research on structural survivability under multi-hazard coupling has progressively shifted from isolated hazard assessments to the investigation of sequential fire-seismic actions, evolutionary damage accumulation, and probabilistic fragility assessments. Spanning multiple research scales—ranging from individual components and joints to global structural systems—these studies have systematically elucidated

coupled deterioration mechanisms, mechanical performance evolution laws, fragility evaluation methodologies, and retrofitting/enhancement technologies. The existing body of work provides robust experimental foundations and theoretical frameworks for quantifying structural safety margins and enhancing post-disaster survivability and functional recovery under complex multi-hazard environments.

5.2 Intelligent Monitoring and Digital Twins

Intelligent monitoring and digital twin technologies represent the pivotal methodologies for achieving rapid post-seismic assessment, precise decision-making, and efficient restoration of replaceable structures. By establishing a digital paradigm that integrates real-time sensing, intelligent evaluation, and closed-loop decision-making, these technologies significantly bolster structural resilience and the reliability of post-disaster remediation.

In the domain of structural health monitoring (SHM), fiber optic sensing and electromechanical impedance (EMI) techniques have emerged as pivotal methodologies for the damage perception of replaceable components. Chen et al. [99] developed FBG-based smart washers that achieve full-range linear monitoring of bolt preloads, providing a robust solution for the quantitative evaluation of nodal connection states. Leveraging the high-frequency electromechanical characteristics of PZT transducers, Wang et al. [100] utilized admittance peak frequency shifts to facilitate the early identification of micro-cracks, significantly enhancing monitoring sensitivity to incipient damage. Furthermore, Li et al. [101] integrated compressive sensing into piezoceramic impedance signal processing, effectively augmenting both the precision and efficiency of damage identification in steel structures. Collectively, these research trajectories—spanning bolt connection monitoring, crack identification, and signal processing—constitute a comprehensive damage perception framework. This framework provides foundational technical support for the post-seismic assessment, precision remediation, and intelligent decision-making of functional recovery structures.

In the domains of digital twins and intelligent decision-making, the synergy between deep learning and virtual mapping models is propelling post-seismic assessment toward a new paradigm of automation and real-time realization. Parola et al. [102] integrated digital twins with convolutional neural networks (CNNs), leveraging structural dynamic response data to achieve precise damage localization and severity identification. Notably, their approach maintains robust classification accuracy even under small-sample conditions.

Despite these advancements, intelligent monitoring currently confronts several critical bottlenecks, including the insufficient longevity of sensors, data dropout under extreme disaster scenarios, and the limited generalization ability of purely data-driven algorithms. To address these challenges, Feng and Liang [103] applied Physics-Informed Neural Networks (PINNs) to the identification of nonlinear structural parameters, effectively enhancing the inversion precision and robustness within complex damage fields. Looking forward, research should prioritize the development of data-physics hybrid-driven models. By establishing an intelligent evaluation framework that balances the efficiency of data-driven approaches with the mechanical consistency of physical constraints, we can provide stable and reliable technical support for the precision remediation of replaceable structures.

6 Conclusion

Current paradigms in seismic design are transitioning from “collapse prevention” toward “rapid post-earthquake functional recovery.” Replaceable prefabricated steel frames have emerged as a pivotal direction for enhancing structural resilience, leveraging their inherent advantages in damage localization, component replaceability, and primary structure protection. Based on a comprehensive bibliometric analysis and systematic review, this paper elucidates the current research status, key technologies, and developmental trends both domestically and internationally. The primary conclusions are as follows:

Replaceable structures effectively safeguard the primary frame and facilitate expedited post-seismic restoration by concentrating plastic damage within 'structural fuse' components, such as coupling beams, braces, and column bases. While node systems—including strengthened, weakened, self-centering, and hybrid energy-dissipating configurations—are increasingly refined, and applications of replaceable links and buckling-restrained brace (BRB) have matured, several bottlenecks persist. These include a reduction in systemic lateral stiffness, unclear synergistic load-bearing mechanisms, and practical difficulties in component disassembly and assembly caused by residual drift.

Multi-hazard coupling significantly accelerates performance deterioration. Specifically, the load-bearing capacity, stiffness, and energy dissipation of nodes decline markedly following fire exposure; however, bracing retrofits can effectively bolster post-disaster survivability. Furthermore, while intelligent sensing and digital twins provide technical support for precision remediation, challenges regarding sensor durability, data robustness, and algorithmic reliability remain to be addressed.

Future research on replaceable structures should evolve toward systematization, standardization, and intelligence. Priority should be given to the development of high-performance hybrid systems and breakthroughs in stiffness-strength coordinated design and active realignment technologies. By integrating intelligent monitoring with physics-constrained models, the field will move toward achieving comprehensive seismic resilience across entire structural systems.

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