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Bibliometric Analysis of Structures and Connection Types Widely Used in Prefabricated Construction in China

Modern construction is increasingly turning to prefabricated technologies to enhance the efficiency and environmental sustainability of projects. This trend is particularly evident in China, where prefabricated construction is becoming a key element of the sustainable urban infrastructure development strategy, showcasing impressive growth rates. This study aims to analyze the types of building structures and connections widely used in prefabricated construction in China, focusing on their efficiency, cost, environmental impact, and sustainability. The methodology includes a bibliometric analysis of scientific literature and statistical data from recent years to identify key trends and development directions in this field. The main findings indicate that China leads in the research and application of prefabricated technologies, particularly in reinforced concrete and steel structures. Various types of prefabricated structures and connection methods are analyzed in terms of their application and effectiveness. Based on the analysis, the study identifies major challenges and prospects for the further development of prefabricated construction, including the need for standardization and improvement in the quality of connection elements. The research underscores the significant potential of prefabricated construction to promote sustainable development and the efficient use of resources in the construction industry.
Keywords: *prefabricated construction, China, building structures, connections, sustainable development, prefabricated connections, building technology*

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INTRODUCTION

In the current state and trends of the global construction market, traditional construction methods face numerous challenges such as inefficiency, irrational use of resources, and long construction timelines. As a significant development trend in the global construction industry, prefabricated construction is actively studied and researched by various countries to address the current issues facing the construction sector [1, 2]. Research has shown that building with prefabricated structures can significantly improve resource efficiency, reduce carbon emissions, and effectively decrease construction waste, thereby ensuring ecological efficiency and supporting the principles of sustainable development [3–5]. Moreover, studies also indicate that compared to traditional monolithic construction, prefabricated structures offer the advantage of higher construction speed [6, 7]. This significantly reduces project construction time, lowering overall costs. Due to these advantages, prefabricated construction becomes a preferred option for projects with tight deadlines or in regions experiencing significant climate changes. Prefabricated construction technology plays an increasingly important role in improving the efficiency, quality, and eco-friendliness of buildings, and its development and application provide new ideas and solutions for addressing some problems associated with traditional construction methods.

The durability of fully prefabricated buildings largely depends on the quality of embedded parts and connections between them [8]. The specificity (seismic rating) affecting the structural connections of building frames is one of the main factors determining the development of structural and technological solutions for prefabricated construction in East Asian countries [9]. Many existing prefabricated construction projects still demonstrate a high degree of vulnerability to seismic impacts, so the seismic characteristics of prefabricated structures remain a key research priority [10]. As a unique feature of prefabricated construction, the design of connections significantly determines the structural strength and seismic characteristics of prefabricated buildings [11]. Therefore, analyzing the existing widely used types of prefabricated construction and connection designs is of great importance.

MATERIALS AND METHODS

According to the statistical data from the CEPII-BACI database, the total global export volume of prefabricated structures amounted to USD 12.2 billion in 2022. The largest exporters were China, the Czech Republic, Estonia, the USA, and the Netherlands, with Europe being the continent with the highest share of exports (Fig. 1)[1]. Currently, Russia holds a small share of this market.

As shown in Fig. 2, we conducted a comparative analysis of the export shares of several countries with the highest indicators starting from 2000. Since 2004, China's share of prefabricated building exports in the global volume began to grow rapidly and maintained a leading position for many subsequent years. Meanwhile, the export share from the USA

1 CEPII-BACI. URL: http://www.cepii.fr/CEPII/en/bdd_modele/bdd_modele_item.asp?id=37 (access data: 20.03.2024).

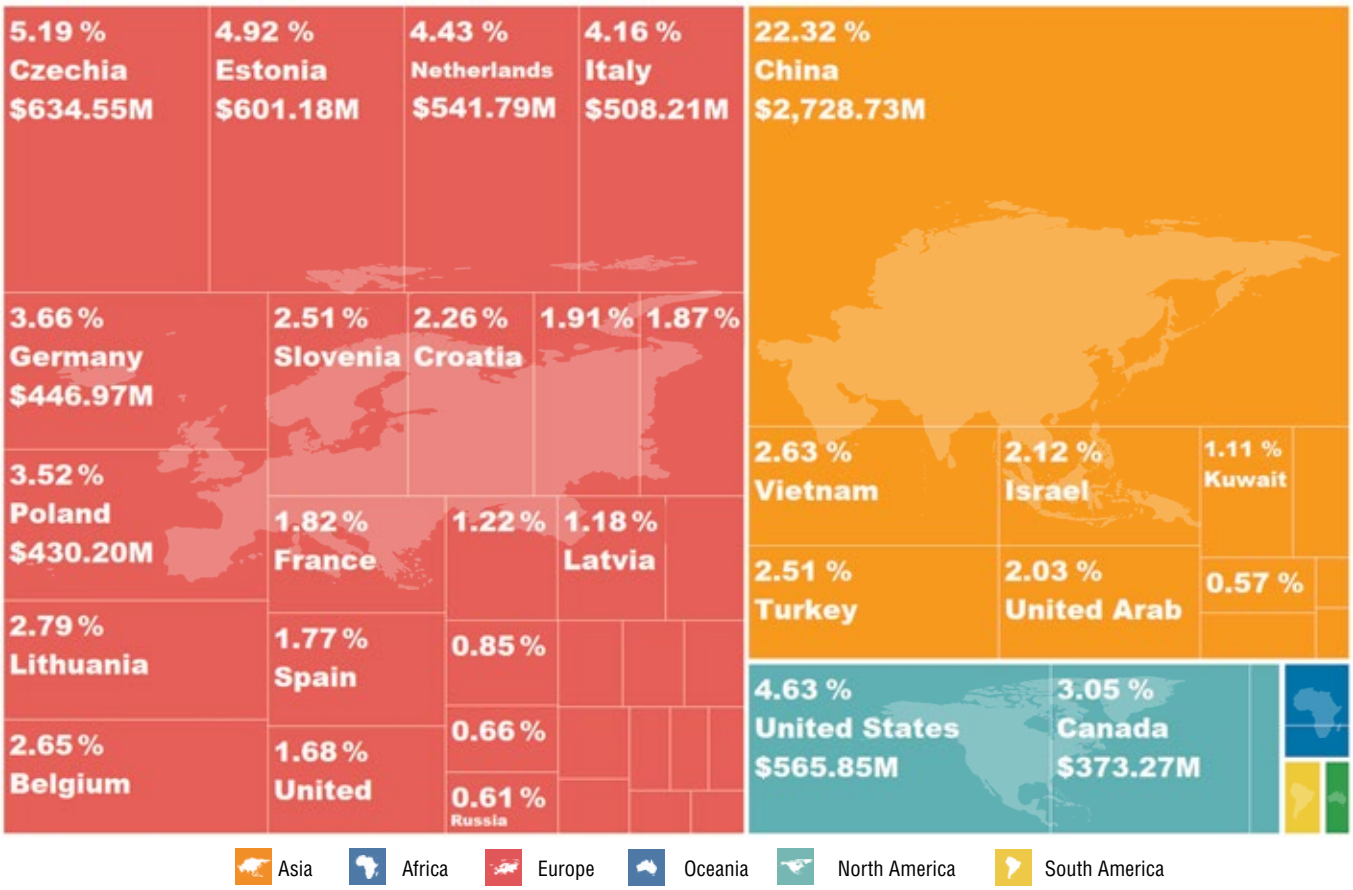

Fig. 1. Analysis of prefabricated structures export volume in the world in 2022

and Canada gradually decreased, while in European countries such as the Czech Republic, Estonia, the Netherlands, Italy, and Germany, the export share remained relatively stable.

Using the search formula "TI=(Prefabricated building) OR TI=(Prefabricated structure) OR TI=(Precast building) OR TI=(Precast structure) OR TI=(Prefabricated construction) OR TI=(Precast Construction)" in the Web of Science core collection database and filtering for materials published since 2015, we obtained 1505 search results. Of these, 76.54 % were journal papers and 17.41 % were conference materials. As shown in Fig. 3, the analysis of the results indicates that since 2015, China has been the country associated with the highest number of research outcomes and the highest level of cooperation between research organizations across different countries, with 827 publications. Australia ranks second in terms of cooperation with 105 works, while the USA ranks third both in terms of cooperation and the number of publications.

It is undeniable that against the backdrop of the global development of prefabricated construction, China stands out as one of the countries with the fastest-growing prefabricated construction industry. In recent years, the country has accumulated an extensive research base, and its practical experience and technological solutions in the field of prefabricated construction deserve detailed study. The analysis of widely used types of prefabricated buildings and connection structures in China can serve as a valuable source of experience and recommendations for practical engineering and future research.

RESULTS

Prefabricated structural systems in China are categorized by materials into steel, concrete, wood, and mixed structures. According to the Ministry of Housing and Urban-Rural Development of the People's Republic of China, reinforced concrete prefabricated structures remain the leading choice in the country's construction industry, accounting for approximately 66.22 %, while steel structures constitute 28.38 %[2].

Construction elements are primarily divided into two types: horizontally positioned elements and vertically positioned elements. Horizontally positioned elements include beams, slabs, etc., while vertically positioned elements comprise columns, diaphragms, prefabricated supports, etc. These primary elements, through the use of various materials, cross-sectional shapes, positioning methods, and construction techniques, can form different structural solutions that meet diverse usage and performance requirements. For instance, depending on the material, beams can be made of reinforced concrete, steel, mixed reinforced concrete, or a combination of steel and reinforced concrete. Various combinations and shapes provide a rich selection of design solutions and flexibility in prefabricated construction.

All types of building systems are also formed by combining various primary elements. Prefabricated building structural systems

2 Special topic on affordable housing: The core of new housing reform. URL: https://pdf.dfcfw.com/pdf/H301_AP202401161617522492_1.pdf (access data: 20.03.2024).

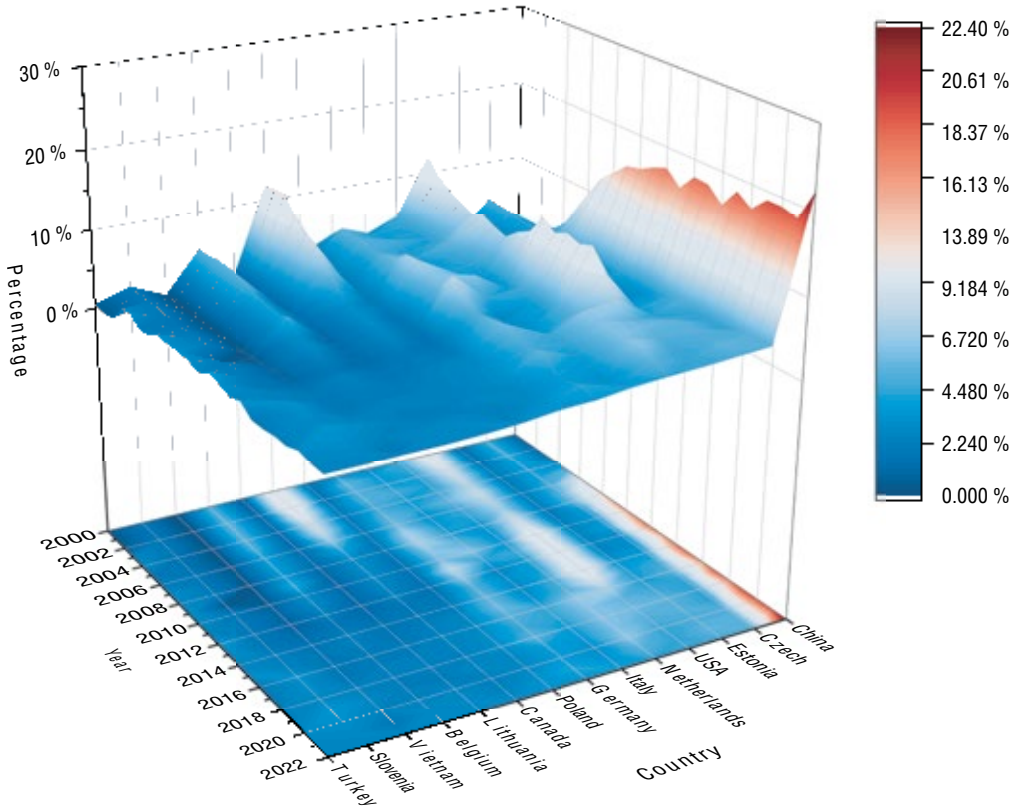

Fig. 2. Analysis of exports of prefabricated structures of countries of volume change from 2000 to 2022

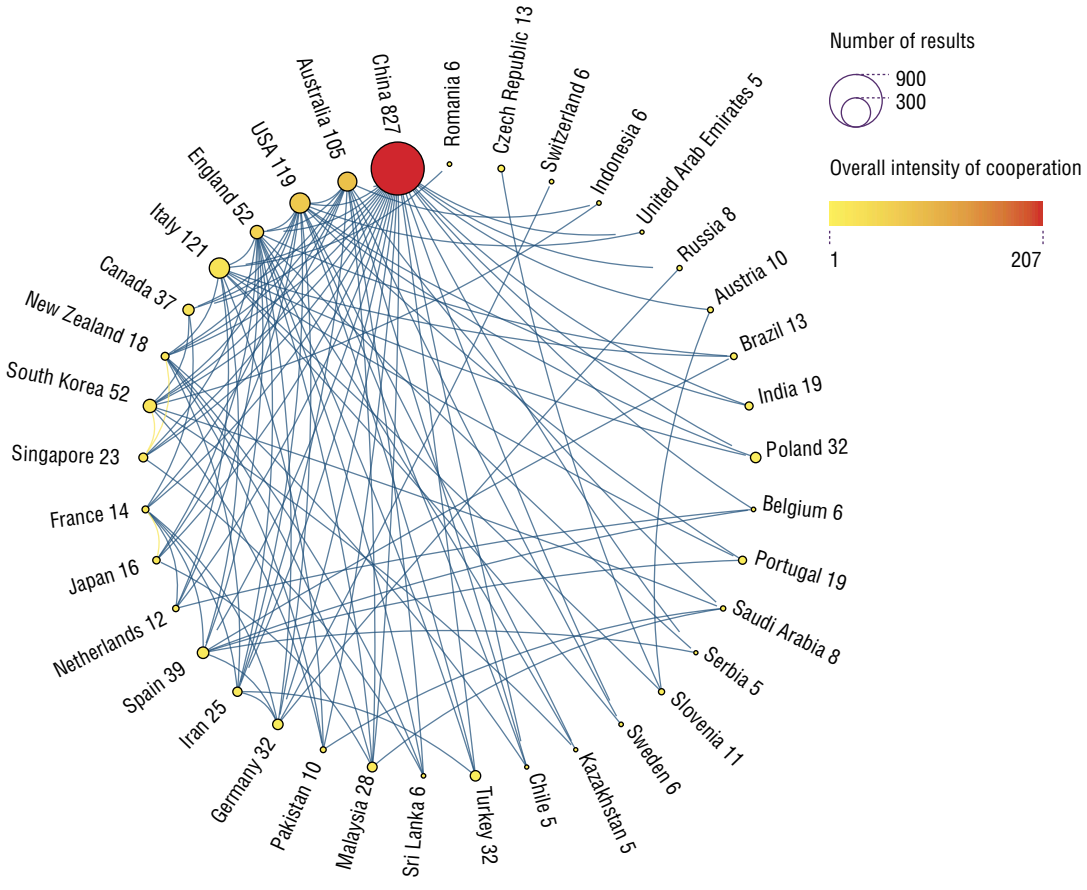

Fig. 3. Analysis of the number of results and the level of cooperation between research organizations in different countries

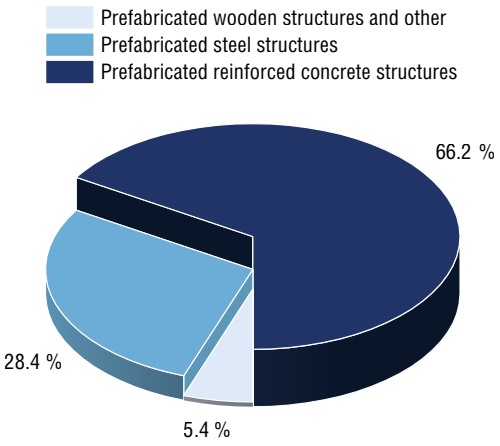

Fig. 4. Proportion of material types for prefabricated structures in China

currently used in China include frame structures, wall structures, frame-wall structures, frame-support structures, girderless slab systems, and so on (Fig. 4). Different structures have different ranges of applicable buildings and geographic regions. Through interviews and surveys of 10 engineers holding various positions in design and construction in the Chinese construction industry, the corresponding ranges of application for these different types of structures in the construction industry in China were identified (Table 1).

By conducting a search in the China National Knowledge Infrastructure (CNKI) using relevant keywords for various structural systems, we obtained a diverse number of results, including patents, dissertations, journal papers, and conference materials (Fig. 5). This allows us to understand the current research trends in prefabricated construction types. It is evident that prefabricated wall structures are the most popular among the research topics, followed by prefabricated frame-wall structures and prefabricated frame structures. Since 2015, with changes in government policy

Table 1. Types of prefabricated structures widely used in China

Number	Type of Structure	Main Load-Bearing Elements	Application Area	Applicable Geographic Region	Schematics
1	Prefabricated frame structures	Columns, beams, floor slabs	Widely used in multi-story and high-rise buildings such as residential, office, and educational buildings	Central and eastern provinces such as Henan, Shandong, Jiangsu, and regions with moderate seismic activity	
2	Prefabricated wall structures	Wall panels, floor slabsя	Suitable for high-rise residential buildings, hotels, office buildings, and other buildings with modest design requirements	Southwestern provinces such as Sichuan, Yunnan, and coastal areas prone to typhoons, such as Guangdong, Fujian. For high-rise residential and public buildings in seismic zones and areas prone to strong winds	
3	Prefabricated frame-wall structures	Columns, beams, wall panels, floor slabs	Suitable for multi-story and high-rise buildings, especially those requiring good seismic performance, such as residential buildings, offices, and hospitals	Northern and northeastern provinces such as Heilongjiang, Jilin, Liaoning, and regions with cold climates and high wind loads. For multi-story residential and public buildings in cold regions requiring good insulation and wind resistance	
4	Prefabricated frame support structures	Columns, beams, supports, floor slabs	Suitable for high-rise buildings and buildings requiring large open spaces such as sports halls, exhibition centers, etc.	Major cities across China such as Beijing, Shanghai, Guangzhou, and regions with high population density and limited construction space. For buildings located in areas with high wind or seismic loads	
5	Prefabricated girderless slabs structures	Prefabricated columns, prefabricated floor slabs	Suitable for rapidly constructed and long-span buildings such as multi-story factories, warehouses, public buildings, halls; can also be used in office and residential buildings for more flexible interior space planning	Coastal areas of southern China such as Guangdong, Hainan, and islands in the South China Sea. For resort buildings requiring maximum openness and natural ventilation	

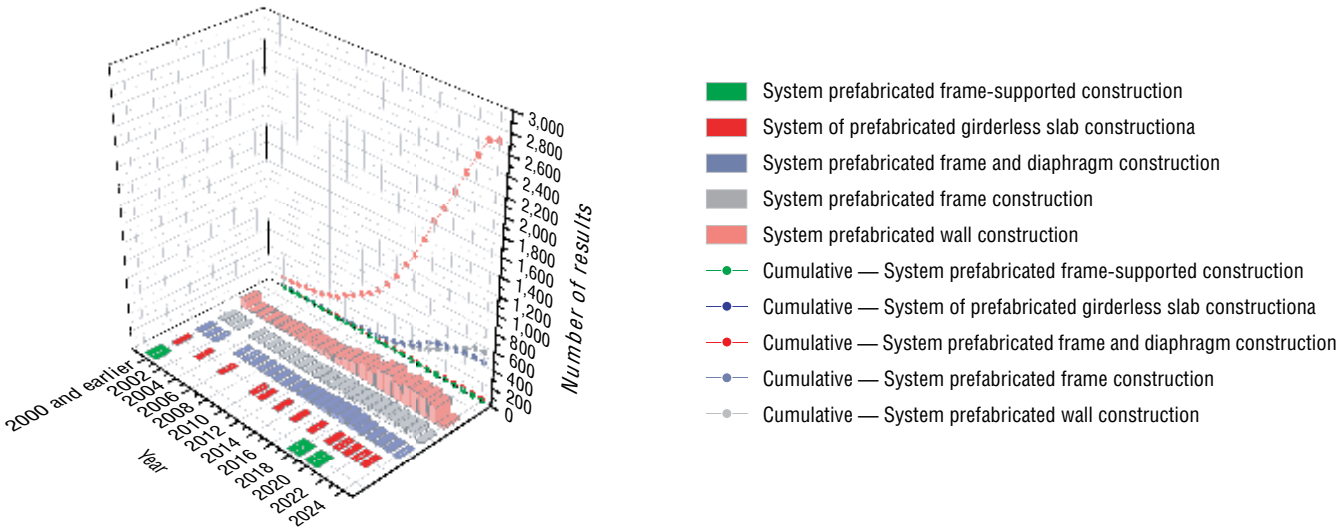

Fig. 5. Analyzing the number of results with different types of designs in search results

Table 2. Connection types for prefabricated structures

Number	Application Area	Connection Method	Types	Applied Elements
1	Frame structures where the building height does not exceed three stories or 12 meters [13]	Rebar lapping in grout-filled hole, Fig. 6	Rigid	Columns, walls, floor slabs, beams
2		Rebar lapping in grout-filledhole formed with metal bellow, Fig. 7	Rigid	
3	Stairs suitable for high-rise buildings of all structural systems. Structural elements for low-rise frame or wall structures	Bolt connection	Hinged	Stairs, wall panels, beams, columns
4		Element welding	Rigid	
5	High-rise buildings of various structural systems	Grout sleeve splicing of rebars	Rigid	Columns, walls
6		Threaded couplers	Rigid	Beams, floor slabs
7		Rebar lap-spliced connections	Hinged	Wall panels, beams, floor slabs, etc.
8		Welded reinforcement connections	Rigid	Beams, floor slabs
9		Connection of section steel	Hinged	Column
10	Frame apartments, office buildings	Modular joint	Rigid	Frame beams, columns
11	For masonry, wall structures, or frame-wall structures	HALFEN HBT Rebend Connection	Rigid	Block wall connection with structure

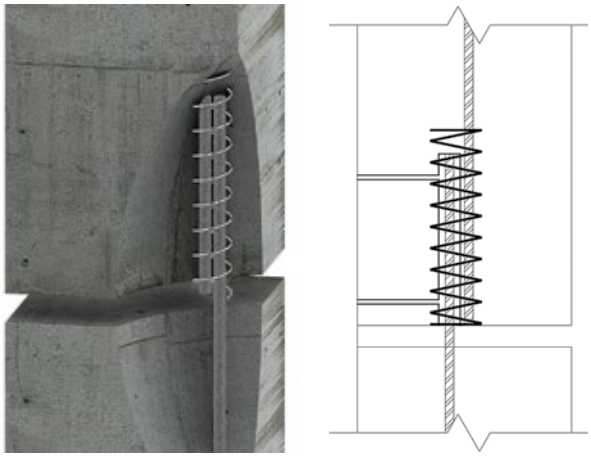

Fig. 6. Rebar lapping in grout-filled hole

and technological advancements, research on these three types of structures has entered a phase of active growth.

This trend indicates the increasing focus on and development of prefabricated construction methods in China, aligning with broader goals of efficiency and sustainability in the construction industry. The active growth in research also suggests a robust and ongoing effort to innovate and optimize prefabricated construction technologies, which will likely continue to influence the field significantly in the coming years.

Connections between prefabricated elements play a crucial role in ensuring the structural integrity and efficiency of the prefabricated construction system. They also enhance the multifunctionality and speed of the construction process [12]. As shown in Table 2, various types of connections are used in prefabricated constructions depending on the design of the structure and the materials used. Connection types can be classified according to the behavior of the connecting structure, mechanical properties, types of connected

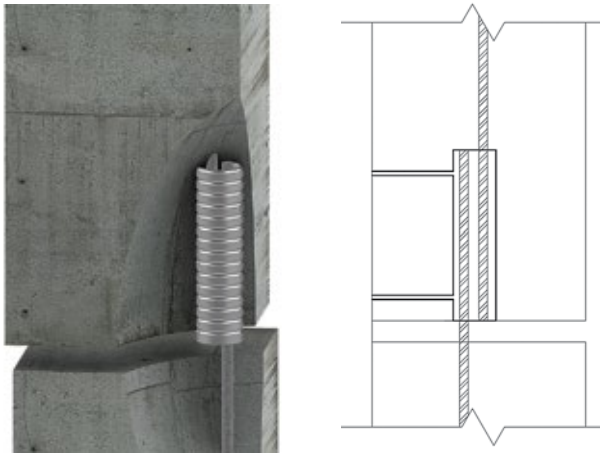

Fig. 7. Rebar lapping in grout-filled hole formed with metal bellow

elements, joint requirements, and the load-bearing capacity of components. Different types of connections are suitable for various types of buildings or structures.

Additionally, a search in the China National Knowledge Infrastructure (CNKI) using keywords related to various types of connections yielded a diverse number of results, including patents, dissertations, journal papers, conference materials, etc. (Fig. 8).

It can be noted that currently, the greatest interest among researchers is in grout sleeve splicing of rebars, followed by rebar lapping in grout-filled holes and bolt connections. Research on grout sleeve splicing of rebars began relatively late, but since 2014, the number of studies in this area has grown rapidly. Bolt connections had a certain research base and interest in the early stages, whereas interest in studies on rebar connections using grout-filled holes began to exceed interest in bolt connections from 2017 onwards.

DISCUSSION

Examining the current state of the prefabricated construction industry in China reveals its significance and enduring role in the global market for prefabricated structures. As the country with the largest export volume, China's systems of construction and connection design in the field of prefabricated construction undoubtedly deserve attention and study.

It is worth noting that Chinese research in the area of prefabricated structural systems began relatively early. By 2000, China had already accumulated a substantial body of research results related to prefabricated structures. These early studies laid a solid foundation for subsequent technological advancements and innovations. Research on types of connections between various prefabricated elements began relatively late, attracting significant attention from researchers and engineers starting in 2005. The study of connections between prefabricated elements, both traditional and innovative, gradually became a relevant topic. In particular, researchers focused on connection technologies that enhance structural safety, reliability, and construction efficiency.

In the context of structural systems in prefabricated construction, reinforced concrete structures predominate. In the area of connections, grout sleeve splicing of rebars has become the most actively researched area in China, demonstrating the fastest development rates. Bolt connections attracted research interest early on, which continues to this day. Additionally, rebar lapping in grout-filled holes remains an active area of current research.

CONCLUSION

With the deepening of research into connection technologies for prefabricated elements, various new connection methods have been proposed and optimized to overcome the limitations inherent in traditional connection methods. The application of prefabricated

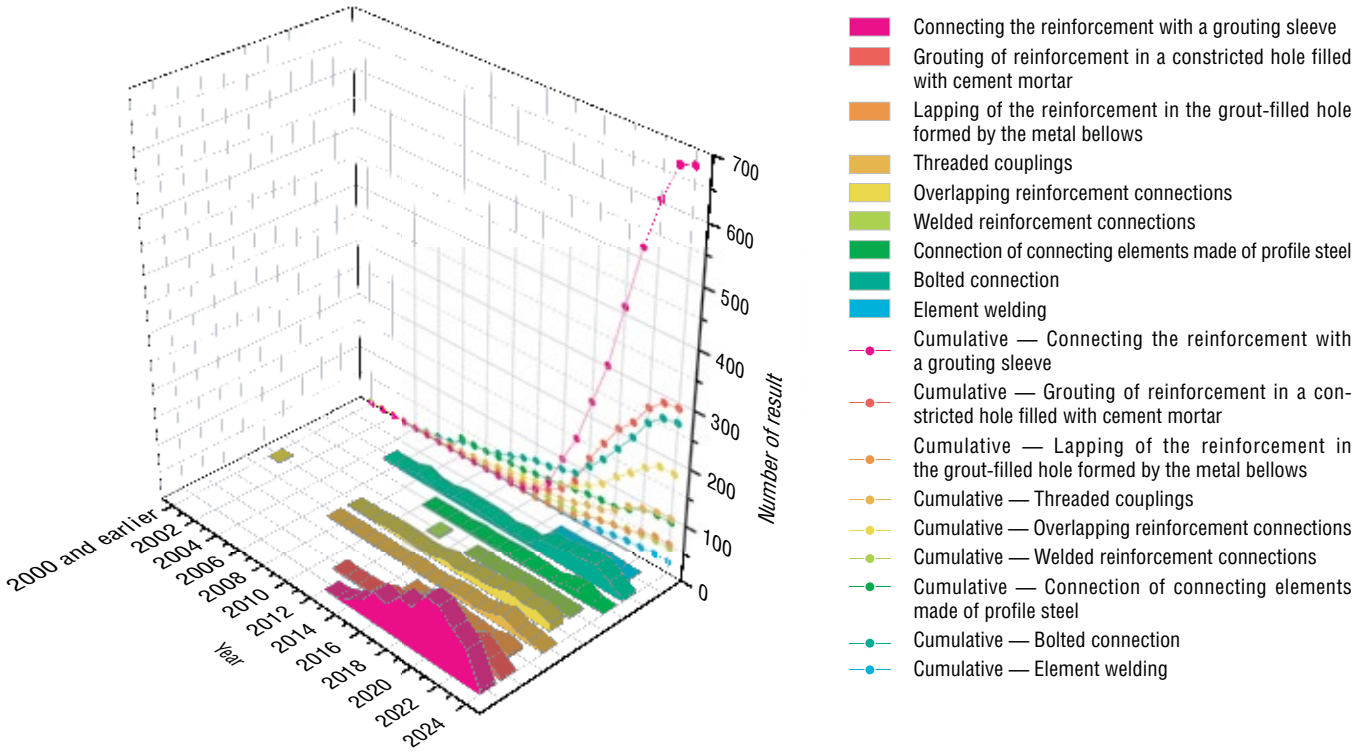

Fig. 8. Analyze the number of results related to different types of connections in search results

construction technologies in practical projects has shown good results and received positive feedback, which, in turn, has stimulated the development and application of these technologies. The development and improvement of these technologies have offered new approaches and solutions to the problems of traditional construction, increasing construction efficiency, reducing project timelines, and lowering construction costs.

However, despite significant achievements in the systems of construction and connection design in prefabricated construction, many challenges remain for scientists to address. For example, issues of seismic resilience in prefabricated structures remain a critically important research direction, requiring the development and study of structures and connections with high levels of seismic resistance.

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Библиометрический анализ конструкций и типов соединений, широко используемых в сборном строительстве Китая

Современное строительство все чаще обращается к сборным технологиям, стремясь повысить эффективность и экологическую устойчивость проектов. Особенно в Китае, где данное направление показывает впечатляющие темпы развития, сборное строительство становится ключевым элементом стратегии устойчивого развития городской инфраструктуры. Цель данного исследования заключается в анализе типов строительных конструкций и соединений, широко используемых в сборном строительстве в Китае, с акцентом на их эффективность, стоимость, влияние на окружающую среду и устойчивость. Методология включает в себя библиометрический анализ научной литературы и статистических данных, охватывающих последние годы, для выявления ключевых трендов и направлений развития в данной области. Основные результаты показывают, что Китай занимает лидирующие позиции в исследованиях и применении сборных технологий, особенно в области железобетонных и стальных конструкций. Различные типы сборных конструкций и методы соединений анализируются с точки зрения их применения и эффективности. На основе анализа определены основные проблемы и перспективы дальнейшего развития сборного строительства, включая необходимость стандартизации и улучшения качества соединительных элементов. Исследование подчеркивает значительный потенциал сборного строительства для содействия устойчивому развитию и эффективному использованию ресурсов в строительной отрасли.

Ключевые слова: *сборное строительство, Китай, строительные конструкции, соединения, устойчивое развитие, сборные соединения, строительная технология*

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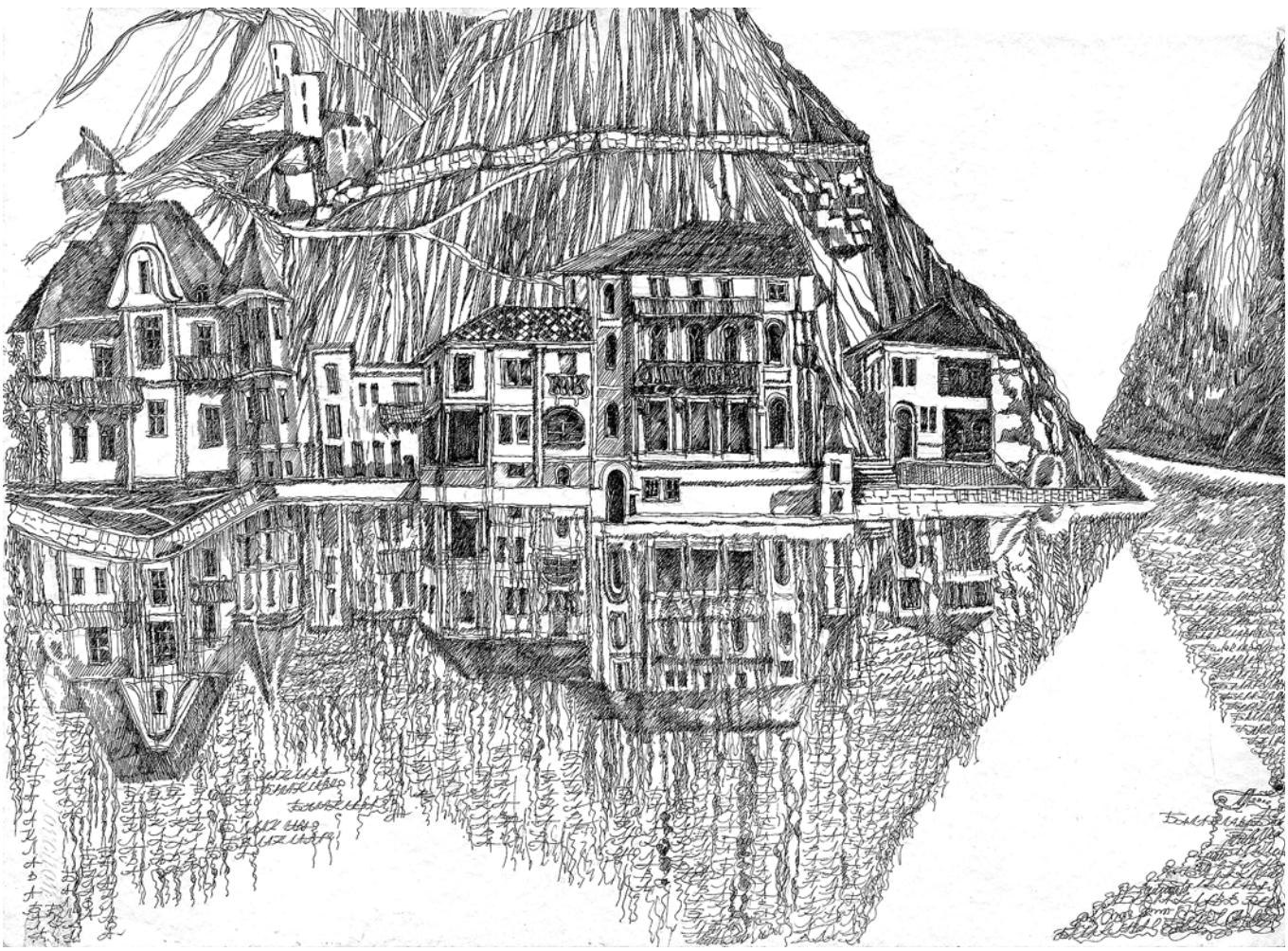

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