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REVIEW

Overview of Prefabricated Segmental Pier Column Connection Technology

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ABSTRACT

With the acceleration of urbanization, prefabricated bridges have become a significant choice for transportation infrastructure construction due to their environmental friendliness, efficiency, and reliable quality. However, existing connection technologies still face shortcomings in construction efficiency, seismic performance, and cost control. This paper summarizes the process characteristics of commonly used connection technologies such as socket connections, grouted sleeve connections and corrugated pipe connections, and analyzes their seismic capacity and mechanical performance. In response to existing issues, two new technologies—separated steel connection and multi-chamber steel tube concrete connection—are proposed, and their comprehensive performance and economic efficiency are analyzed. The new connection technologies outperform traditional methods in construction efficiency, economic efficiency, and structural stability, with more reasonable force distribution, clearer load transfer paths, and significantly reduced overall costs. Existing technologies, such as socket connections, perform well in seismic performance but are complex to construct; grouted sleeve connections are mature in technology, but the quality of grouting is difficult to inspect. The separated steel connection and multi-chamber steel tube concrete connection technologies offer significant advantages. With the increasing demands for energy conservation and emission reduction, coupled with the rising labor costs, prefabricated bridge piers are undoubtedly poised to become one of the preferred technologies for bridge construction in China in the future. Therefore, in light of the

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current research landscape, this paper concludes by offering a forward-looking perspective on the development directions of connection methods for prefabricated bridge piers and identifying key areas for future research.

Keywords: Prefabricated Bridges; Construction Efficiency; Structural Stability; Separated Steel Connection; Multi-Chamber Steel Tube Concrete Connection

1. Introduction

Bridges serve as critical hubs in the transportation network, playing a vital role in urban development and infrastructure construction. Particularly in rapidly developing cities and complex mountainous terrains, prefabricated bridges have become an effective solution due to their fast construction speed, environmental friendliness, and ability to achieve high-quality standardized production [1–3]. Practical cases demonstrate that prefabricated modular bridges offer significant advantages in improving construction efficiency and reducing environmental impact [4–7]. However, prefabricated bridge piers face numerous challenges, including insufficient overall performance, significant design and construction difficulties, complexity of on-site construction, and the need for quality assurance. Particularly in mountainous areas, due to the rugged terrain, complex geological conditions, limited construction sites, and confined spaces, traditional prefabricated bridge pier construction techniques encounter issues such as complicated procedures, the need for temporary supports, difficulty in precision control, undetectable grouting quality, poor construction quality in cold regions during winter, weak joint stress or force transfer performance, lack of integrity, unsuitability for high seismic zones, and high costs. Therefore, there is an urgent need to develop a new type of bridge pier joint design that features no welding, no bolting, and no need for precise alignment of holes, while meeting requirements for construction efficiency, structural stability, and environmental adaptability.

The design of joint connections involves theories of connection, seismic design, material performance, and construction process simulation. The successful application of these theories reveals the challenges in design and execution, such as seismic issues, material properties, and construction techniques. Solving these problems depends on theoretical research, material innovation, and advancements in construction technology.

This article analyzes the advantages and disadvantages of commonly used joint connection forms (such as plug-in, bellows pipes, and grout sleeves) in terms of seismic resistance, mechanical performance, construction efficiency, cost-effectiveness, and environmental adaptability. Based on this, the article will comprehensively evaluate the possibility and feasibility of technological innovation and propose forward-looking solutions. The aim of this article is to promote the advancement and development of prefabricated bridge technology while providing innovative solutions and references for similar engineering challenges. Finally, a summary and outlook of connection technology are provided, believing that with the development of related technologies in the future, joint connection technology will be more innovated and perfected.

2. The Development of Prefabricated Pier Column Connection Technology

The technology of prefabricated pier column connection has become an important component of the global construction industry due to its efficiency and environmental protection characteristics. With the acceleration of industrialization and urbanization, the application of this technology is becoming increasingly widespread, having a significant impact on promoting the modernization of the construction industry.

The technology for prefabricated pier and column connections first emerged in the 1970s in Western countries [8], with the Linn Cove Viaduct in the United States being the world's first bridge to utilize this technique when construction began in 1978 [9]. In 1991, the Monterrey Light Rail Transit Project in Mexico marked the first large-scale use of prefabricated segmental bridges globally. The Pont St-Benezet Bridge in France, completed in 2000, was the pioneering project to employ an externally prestressed structure with a moving scaffold for cantilever assembly using prefabricated segments [10]. As research progressed, the technology for prefabricated pier and column connections has been widely promoted, leading to comprehensive handbooks and extensive studies and applications in the United States [11].

In China, the development of prefabricated piers and columns started in the 1990s [12]. However, initial engineering practices involved cast-in-place wet joint connections, which resulted in significant on-site workload and challenges in ensuring construction quality, thereby limiting their wider adoption. Since 2000, inspired by international advancements in prefabrication technologies, a series of systematic studies on prefabricated bridge technology have been conducted domestically. These studies primarily focused on connection techniques for bridge substructures using grouted sleeves and metal bellows. In 2012, the S6 Highway project in Shanghai was the first to trial this technology, which was subsequently promoted in the Jia Min Elevated Road project in Shanghai in 2014, yielding notable overall benefits [13]. To further promote the development of prefabricated pier column connection technology, the Nanjing Municipal Transportation Bureau has advanced the industrialization and informatization of bridge construction through multiple engineering applications. Units such as the Jiangsu Provincial Transportation Engineering Construction Bureau have also achieved technological breakthroughs, enhancing construction efficiency and quality.

3. The Current Status of Precast Assembly Pier Column Connection Technology

The overall mechanical performance of prefabricated bridge piers depends on the stable connection between the prefabricated segments. Therefore, the form of joint connection plays a decisive role in ensuring the quality and safety of the structure [14, 15]. Currently, the main forms of pier column connections include socket connection, grout sleeve connection, corrugated pipe connection, bolt flange connection, and mortise-tenon connection.

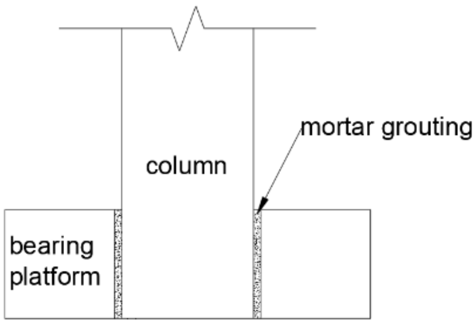
3.1. Socket Connection

The socket connection method involves pouring concrete or mortar into the pre-reserved holes of the pile cap to connect components. Prefabricated bridge piers and pile caps use this method for connection. Since there are no rebar connections at the joint nodes, to enhance the stability of the connection, concrete is typically poured around the bottom of the prefabricated bridge piers, and the contact surfaces are roughened (**Figure 1**).

Mashal and Palermo [16] conducted pseudo-static tests on Plug-in assembled pier columns, showing that Socket connections have good seismic performance. Their load-bearing capacity and ductility are comparable to those of cast-in-place components. Chen, Fu and Zeng [17] designed two scaled models of Plug-in assembled pier columns and cast-in-place pier columns, and conducted pseudo-static experiments and numerical simulations. The results indicate that the axial compression ratio and Grout depth significantly affect the connection performance; when the strength of the grout is not lower than that of the concrete, its impact can be neglected. In the numerical simulation section, the constitutive relationship of concrete is modeled using the Concrete Damaged Plasticity (CDP) model available in ABAQUS to simulate the nonlinear behavior of concrete.During the elastic stress stage of concrete, the CDP model directly describes the material's mechanical properties through the initial elastic modulus. When the concrete enters the damage stage, the expression for the elastic modulus changes to $E = (1 - d_c)E_0$ and $E = (1 - d_t)E_0$, where d_c and d_t are the compressive and tensile damage factors, respectively, and E_0represents the initial elastic modulus. Han et al. [18] studied the effects of pier column insertion depth and grout strength on the performance of assembled pier columns, indicating that with reasonable insertion depth and grout strength, the seismic performance of plug-in assembled piers can approach that of cast-in-place piers. Stephens, Lehman and Roeder [19] conducted cyclic loading experiments to investigate the mechanical behavior of embedded concrete-filled steel tube columns with two different embedment depths, 0.6 D and 0.9 D. The experimental results indicate that the embedment depth significantly influences the failure mode and hysteretic performance of the structure. Specimens with smaller embedment depths exhibited poorer energy dissipation capacity during hysteresis.

In the application of new materials and structures, Wang et al. [20] set shear keys in the grooves of the pier body and foundation platform, using ultra-high-performance grout material. This improved connection method has seismic performance and stiffness similar to those of cast-in-place columns. Leng[21] installed mounting cups on the foundation platform, utilizing the cups to connect the pier columns to the foundation platform, proposing two structural forms: steel plate shear studs connection and trapezoidal shear key connection. The results show that both connection forms meet safety requirements, and the trapezoidal shear key connection performs better.

Currently, socket connections have been widely applied in bridge engineering, such as the I/C Bridge and the Interstate 5 Bridge of the SR520 Highway in Washington State[22], the Conway Bypass Highway Bridge in Southern California[23], the Shuijiatan Bridge in Beijing from 1992[24], the Anhui Zhongpai River Bridge and the Huai River Bridge[25], the Beijing-Xiongan Expressway Viaduct, and the North Section II of the Shanghai Jiamin Elevated Road project[26].



(**a**)

(**b**)

Figure 1. Socket connection: (**a**) socket connection diagram, and (**b**) Shanghai Jia Min elevated highway.

The integral socket connection method for prefabricated bridge piers has significant advantages and disadvantages. On the positive side, this method offers high bearing capacity and good energy dissipation performance. It requires relatively low precision in prefabrication, allows for longer continuous rebar sections, and involves a large concrete pour area for the connection region, resulting in good overall performance. However, there are also challenges with this method, such as a relatively large amount of cast-in-place work, the need for temporary measures to fix prefabricated segments, an incomplete shear failure mechanism, varying optimal insertion depths for different structural forms[27–30], poor self-recovery performance, and potential issues with grouting compactness inspection. These factors can affect construction progress and structural safety.

Based on the above content, future research directions for socket connection methods should first focus on studying the impact of insertion depth on connection performance. By optimizing the insertion depth, the stability and seismic resistance of the connection can be enhanced. Secondly, optimizing the interface structure is also crucial. By improving interface design and material selection, the durability and bearing capacity of the connection can be increased. Additionally, improving construction technology is equally important. Exploring more efficient and precise construction methods can reduce the amount of on-site work, improving construction efficiency and quality. The optimization of temporary fixation measures should also not be overlooked to ensure structural stability and safety during construction. At the same time, enhancing the strength of grout has a significant effect on improving the overall performance of the connection. Developing high-strength, high-performance grout is one of the future research directions. Finally, exploring the combination of socket connections with other connection methods to form a composite connection system can integrate the advantages of multiple connection methods, further improving the performance and application effects of prefabricated bridge piers.

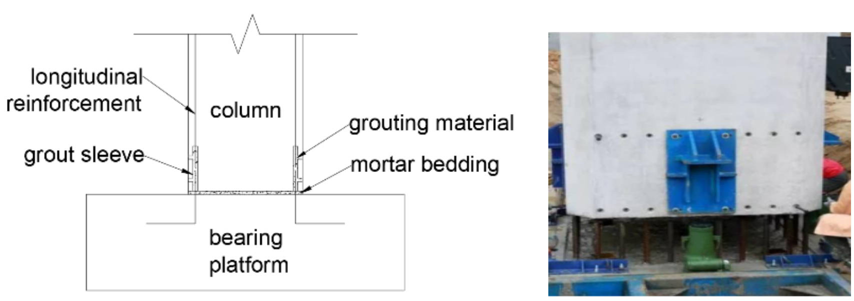
3.2. Grout Sleeve Connection

Grout sleeve connections refer to the method of connecting rebar by inserting longitudinal rebar into a specially made metal or plastic sleeve and then injecting fast-setting[31, 32], non-shrink grout material (**Figure 2**). The average bond strength between grout and reinforcement can be calculated using the following formula: $\tau = \frac{F}{\pi D l_a}$, In the formula: τ is the average bond strength; F is the axial force of the reinforcement; D is the diameter of the reinforcement; l_a is the anchorage length, The radial and circumferential stresses of the grout and the sleeve are $\sigma_r^{'} = \frac{a^2b^2}{b^2-a^2}\frac{S_2-S_1}{r^2} + \frac{a^2S_1-b^2S_2}{b^2-a^2}$ and $\sigma_\theta^{'} = \frac{a^2b^2}{b^2-a^2}\frac{S_1-S_2}{r^2} + \frac{a^2S_1-b^2S_2}{b^2-a^2}$, where a is the inner diameter of the sleeve and b is the outer diameter; S_1 and S_2 are the uniformly distributed stresses experienced by the grout and the sleeve; $\sigma_r^{'}$ is the radial stress; $\sigma_\theta^{'}$ is the circumferential stress; $r$is a function of the radial coordinate. The connection is achieved through the adhesive bond and mechanical interlock between materials. In the 1960s, American engineer Dr. Zhan Shu Yu invented the grout sleeve connection technology, effectively solving the problem of connecting longitudinal rebar [33].

Wang, Ma and Chen [34] studied the seismic performance of precast bridge piers with grout sleeve connections. The vibration response of precast bridge piers with grout sleeve connections was similar to that of cast-in-place piers. Qu et al. [35] completed shaking table tests on precast bridge piers with grout sleeve connections. The precast components showed similar stiffness, ductility, and energy dissipation performance compared to cast-in-place components, meeting seismic design codes. Ameli et al. [36] analyzed the mechanical properties and seismic performance of grout sleeve connections through laboratory tests and numerical simulations, comparing them with traditional mechanical connection methods. The test results indicate that grout sleeve connections have good load-bearing capacity and seismic performance, exhibiting better energy dissipation under seismic actions.

In the application of new materials and structures, Ou et al. [37] conducted experiments on grout sleeve connections at the base of piers and the top of pile caps, embedding a steel pipe as a shear key at each location. The experimental results show that their load-bearing capacity is comparable to that of cast-in-place piers, with improved displacement ductility; compared to grout sleeve connected piers, both load-bearing capacity and displacement ductility were enhanced. Guan et al. [38] used locally precast UHPC specimens to reinforce the plastic hinge region of precast columns. The results show that the severely damaged area of the precast component deviated from the column foot connection area, reducing repair difficulty. The seismic performance was similar to that of cast-in-place specimens, with a slight enhancement in strength and stiffness of the precast specimens. Xu, Pan and Cai [39] through quasi-static tests, comparatively analyzed the mechanical properties of prefabricated bridge piers connected with ordinary grouting sleeves and those of improved piers with engineering viscous cement material added in the plastic hinge zone. The research results show that the improved piers perform better in terms of energy dissipation and damage tolerance. Wang et al. [40] focused on piers with grouting sleeves and adopted reinforcement schemes using carbon fiber composite materials and polyester resin combined with external energy dissipation devices to carry out shaking table tests. The test data shows that this reinforcement technology significantly reduces the horizontal displacement of the piers while improving their energy dissipation performance and ductility.

Currently, grout sleeve connection technology has been effectively applied in multiple bridge projects worldwide, including the Edison Road Bridge in Florida, USA, the I-85 Interchange Bridge in Georgia, the Keg Greek Highway in Iowa, the Jingxiong Intercity Railway Elevated Bridge, the Jia Min Elevated Bridge, the Chengpeng Urban Section Elevated Bridge in Chengdu, the Heng Shan East Road Overpass Bridge in Jilin City, and the Xiqu Fu Bridge in Shandong Province.



(**a**) (**b**)

Figure 2. Grout sleeve connection: (**a**) grout sleeve connection diagram, and (**b**) the Xiqu Fu Bridge of Shandong.

The grouting sleeve connection for prefabricated bridge piers offers advantages such as minimal on-site wet work, fast assembly speed, and mature technology. Under normal usage conditions, its mechanical performance is similar to that of traditional cast-in-place concrete bridge piers, providing certain economic benefits. However, this connection method causes the plastic hinge region of the bridge pier to shift from the base to the top of the sleeve area, necessitating special design considerations for the plastic hinge. The presence of assembly joint surfaces can result in significant horizontal displacement under seismic actions. Additionally, it faces challenges such as high requirements for construction precision, stringent static performance demands, the inability to inspect grouting quality, and limitations due to installation errors.

The future research directions for grouting sleeve connections should first focus on optimizing the performance of grouting materials. By developing grouting materials with higher strength, better flowability, and lower shrinkage, the stability and durability of the connection can be enhanced. Secondly, the improvement of construction techniques is equally important. Exploring more efficient and precise construction methods can reduce the amount of on-site work, thus improving construction efficiency and quality. Additionally, the development of advanced quality inspection technologies is essential. Utilizing non-destructive testing and other advanced techniques allows for real-time monitoring of the quality of grouting sleeve connections, ensuring that construction quality meets standard requirements. Furthermore, conducting in-depth studies on the structural performance of sleeve grouting connections to understand their stress characteristics and failure modes under different conditions will provide a scientific basis for design. Finally, reinforcing the plastic hinge with high-performance materials is an effective means to enhance ductility. By using high-strength materials or adding reinforcement measures at critical locations, the seismic resistance and deformation capacity of the structure can be improved.

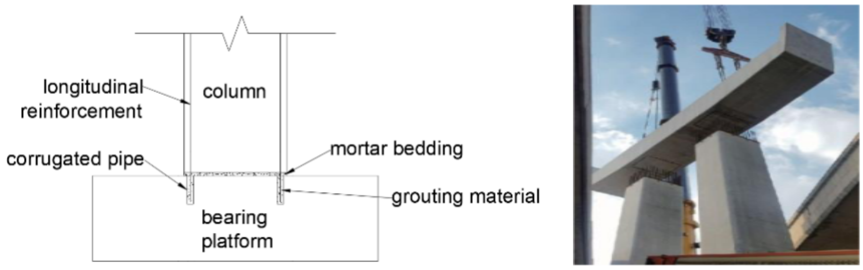
3.3. Corrugated Pipe Connection

The corrugated pipe connection utilizes a specially designed corrugated sleeve and grouting material to achieve rapid and reliable connection of longitudinal rebars in precast pier columns (**Figure 3**). This connection method involves inserting the longitudinal rebars to be connected into the corrugated sleeve, then filling the sleeve with grouting material. Once the grouting material hardens, a firm connection is formed between the longitudinal rebars and the corrugated sleeve. The connection relies not only on adhesive forces but also on the mechanical interlocking between the internal corrugations of the sleeve and the grouting material. Its calculation method is similar to that of the grouting sleeve connection.

Regarding the seismic performance of corrugated pipe grout connections, Wilson [41] conducted scaled model tests, which showed that the grouted corrugated pipe connections exhibited good anchorage capacity and overall member performance. Matsumoto [42] added a 2.5-inch thick grout cushion layer and stirrups in their scaled experiments. The results indicated that the seismic performance of piers connected in this manner is comparable to that of cast-in-place piers. Chen [43] studied the mechanical properties of grouted corrugated pipes using biaxial tension tests. The results showed that as the diameter of the rebar and the anchorage length increased, the bond stress decreased, but the failure load increased. Fu et al. [44] studied the top-anchored grouted metal corrugated pipe connections for bridge piers, showing that the yield and ultimate loads of the top-anchored specimens were close to those of cast-in-place specimens, but their ductility was lower than that of cast-in-place specimens.

In terms of new materials and structures, Jia et al. [45] conducted quasi-static experiments on prefabricated bridge piers connected with metal corrugated pipes grouted with high-strength mortar. The results showed that their load-bearing capacity is comparable to that of cast-in-place piers, but their displacement ductility and energy dissipation capacity are slightly lower than those of cast-in-place piers. Jia et al. [46] embedded rubber pads at the bottom of the pier columns in the grouted corrugated pipe connections and conducted quasi-static tests. The results showed that they exhibited better energy dissipation capacity than cast-in-place members and reduced concrete damage at the bottom of the columns.

In practical engineering applications, corrugated pipe grout connection technology has been widely used in several bridge projects, including the Washington State Interstate 5 Bridge and Lake Belton Hubbard Bridge in the USA [47], the Laksi Interchange Bridge in Thailand, and the S6 and S7 Expressways in Shanghai.



(**a**) (**b**)

Figure 3. Corrugated pipe connection: (**a**) corrugated pipe grout connection diagram, and (**b**) Shanghai S7 highway bridge.

The corrugated pipe grout connection technology for prefabricated bridge piers has garnered attention due to its horizontal load-bearing capacity and hysteretic energy dissipation ability, which are comparable to cast-in-place columns. Additionally, it offers advantages such as relatively larger grout sleeve diameters, lower costs, and ease of construction. However, this technology faces challenges including susceptibility to joint cracking and reduced integrity, eccentricity errors in rebar placement, impact on rebar arrangement, and variability in anchorage effectiveness due to different types of grouting materials.

The future research direction for the corrugated pipe grouting connection method should focus on the material and size design of the corrugated pipe, which are crucial. By selecting appropriate materials and optimizing dimensions, the load-bearing capacity and durability of the corrugated pipe can be enhanced. Secondly, optimizing the performance of the grouting material is essential. Developing grouting materials with higher strength, better fluidity, and lower shrinkage can improve the stability and reliability of the connection. Additionally, incorporating prestressed tendons in the precast bridge piers connected by corrugated pipes is also an effective means to enhance the overall structural load-bearing capacity and durability. By introducing prestressed tendons, the seismic resistance and deformation capacity of the structure can be improved, enhancing its safety performance.

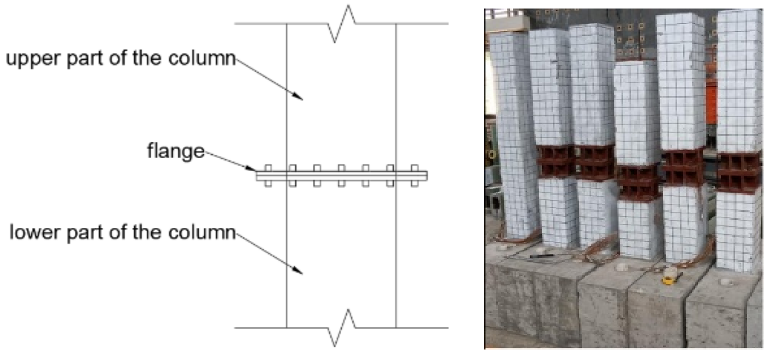
3.4. Bolt Flange Connection

Bolt flange connections are made by machining a flanged interface at the end of the column and then securely fastening the flange faces of two components together using bolts and nuts (**Figure 4**). When calculating the total effective cross-sectional area required for the bolts using the bolt load, the minimum bolt load needed under the pre-tightened condition is calculated by the following formula: $L_a = 3.14 D_G b y$, The minimum bolt load required under operating conditions is calculated by the following formula: $\sigma_\theta' = \frac{a^2b^2}{b^2-a^2}\frac{S_1-S_2}{r^2} + \frac{a^2S_1-b^2S}{b^2-a^2}$, Among them: $b$is the effective sealing width of the gasket; y is the specific pressure of the gasket; m is the gasket factor; p is the design internal pressure.

For the seismic performance of bolt flange connections, research by Zuo et al. [48] indicates that this connection reliably transmits internal forces. When the connection is located outside the plastic hinge region, the member's performance is the same as that of cast-in-place specimens; when it is within the plastic hinge region, there is a reduction in ductility. Hu, Hong and Pank [49] and Nzabonimpa, Hong and Kim [50] conducted experimental studies and numerical simulations on concrete columns with bolt flange connections. The study found that when the flange plate has sufficient stiffness and strength, its mechanical performance is essentially the same as that of cast-in-place columns.

In terms of new structural applications, Xiao [51] completed quasi-static tests on prefabricated steel reinforced concrete columns based on bolt flange connections. The study shows that they have good energy dissipation capacity, significantly affected by the shear span ratio. Specimens with smaller shear span ratios exhibit higher peak horizontal load-bearing capacity and fuller hysteresis loops but poorer ductility.

In practical engineering applications, bolt flange connections have been widely used in steel tube towers in the electric power and telecommunications industries [52, 53]. However, in the field of prefabricated bridges, despite their reliability in internal force transmission and construction efficiency, there are relatively few practical application cases.



(**a**) (**b**)

Figure 4. Bolt flange connection: (**a**) bolt flange connection diagram, and (**b**) bolt flange connection for pier columns.

The bolted flange connection technology for precast bridge piers offers advantages such as fast construction speed, convenience in construction, effective avoidance of wet operations at the construction site, and easy maintenance in later stages. It can effectively transfer horizontal forces and bending moments, enhance structural load-bearing capacity, and improve shear resistance. However, this connection method also reduces the ductility of the structure and has disadvantages such as difficulty in controlling precision and a large amount of on-site construction work.

In future research on bolted flange connections, attention should be focused on the precision of flange connections. By optimizing design and manufacturing processes, the need for on-site adjustments can be reduced, ensuring the tightness and stability of the connection. Secondly, using new materials to make flanges is also an effective way to improve their performance. For example, employing high-strength, corrosion-resistant alloy materials can enhance the load-bearing capacity and durability of the flanges. Additionally, utilizing automated equipment for flange alignment, installation, and welding can reduce manual operations, improving construction efficiency and precision.

3.5. Mortise-Tenon Connection

The mortise and tenon connection for bridge piers involves a protruding tenon at the top or bottom of the pier, which is embedded into the mortise slot of another component. Grout material is injected at the joint where the two components meet, achieving the connection between them (**Figure 5**).

Wang et al.[54] conducted quasi-static experiments on welded steel mortise and tenon connected assembly columns. The research shows that their load-bearing capacity is slightly lower than that of cast-in-place columns, but their ductility and energy dissipation are superior to those of cast-in-place columns. Wang, Shao and Yan[55] also conducted quasi-static experiments on mortise and tenon connected assembly columns. The study indicates that the connection did not fail during loading, and parameters such as ductility and load-bearing capacity were similar to those of cast-in-place columns, with seismic performance comparable to cast-in-place columns. Luo et al.[56] conducted quasi-static experiments on assembly columns with steel pipe concrete tenons. The research shows that their load-bearing capacity, stiffness, and seismic performance are not inferior to those of cast-in-place columns. Lin et al.[57] conducted quasi-static tests on mortise and tenon connected assembly columns with different design parameters. The study indicates that changes in groove depth and cast-in-place section height significantly affect the ductility coefficient and ultimate displacement of the piers.

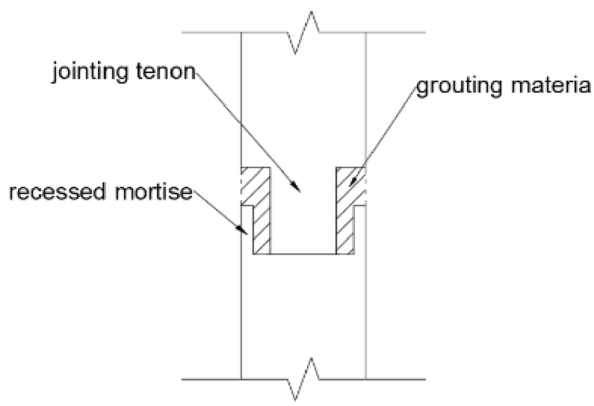


Figure 5. Mortise-tenon connection.

The mortise and tenon connection has played a significant role in traditional Chinese wooden structure architecture. Today, this connection method is also being adapted for use in modern engineering, and it is currently in the research stage in the field of prefabricated assembly bridge construction [58].

The mortise and tenon connection technology of prefabricated bridge piers offers the advantages of simple and efficient construction, minimal on-site wet work, and guaranteed quality of on-site operations. It exhibits ductility and energy dissipation similar to cast-in-place columns and has good seismic performance. However, its load-bearing capacity is slightly lower than that of cast-in-place columns. As the axial compression ratio increases, the peak strength of the prefabricated column improves, but the rate of strength degradation and stiffness degeneration accelerates, leading to poorer energy dissipation, deformation capacity, and ductility.

Future research on mortise and tenon connections for prefabricated bridges should focus on the application of high-performance new materials. By using materials with higher strength, better durability, and improved seismic performance, the overall structural performance can be enhanced. Additionally, optimizing connection techniques is essential, including key technologies such as rebar embedding in the base and grouting at the joint surfaces to ensure the quality and reliability of the connections. Moreover, improving the connection system to enhance the overall seismic capacity of the structure is an important research direction.

4. Economic Performance Analysis of Prefabricated Assembly Pier Column Connection Technology

In the field of modern bridge engineering, the connection technology for prefabricated pier columns is increasingly being emphasized as a key factor in ensuring structural safety and functionality. Current research and development efforts are primarily focused on enhancing the overall performance of structures through innovative connection methods and the application of high-performance materials. Engineers have conducted in-depth studies on aspects such as the design of connection nodes, seismic design theory, material performance theory, and construction process simulations.

Although these technologies have made significant progress in improving structural performance, their economic viability is often not given sufficient attention, which is one of the important factors affecting their application and promotion in practical engineering. Economic performance involves not only initial material and construction costs but also long-term maintenance expenses and lifecycle cost-benefit analysis. Therefore, to more comprehensively evaluate the practicality and economy of various connection methods, it is necessary to systematically analyze and compare these aspects. **Table 1** provides an initial qualitative comparison of the economic performance of several commonly used connection methods.

Table 1. Economic performance analysis table for prefabricated assembly pier column connection technology.

Connection Methods	Construction Costs	Material Costs	Maintenance Costs	Potential Long-Term Economic Benefits
Socket connection	Moderate, with a large amount of on-site casting	Moderate, requiring specific filling materials	Low to moderate	High, with strong adaptability
Grout sleeve connection	Moderate, with high technical requirements	Relatively high, requiring specially made grout sleeve	Moderate	High, with good overall structural integrity
Corrugated pipe connection	Moderate, with strict construction precision requirements	Relatively high, requiring specially made corrugated pipe	Moderate	Moderate to high, improving seismic performance and load-bearing capacity
Bolt flange connection	Relatively high, with low construction convenience	Relatively high, requiring specially made flange plates	Moderate	Moderate to high, reliably transferring internal forces and enhancing load-bearing capacity
Mortise-tenon connection	Lower, with a small amount of on-site work	Moderate, requiring specific filling materials	Low to moderate	High, traditional connection methods may bring cultural and economic value

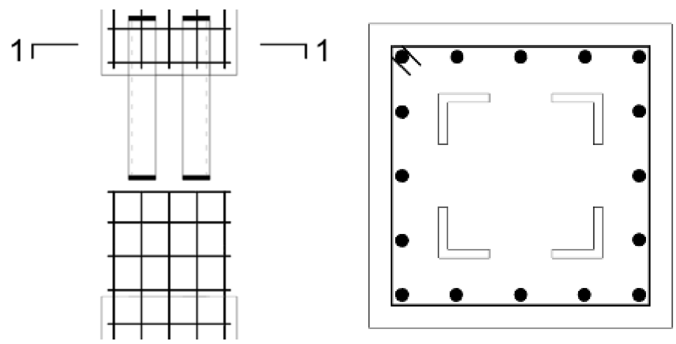
5. The Separated Steel Connection Technology and the Multi-Chamber Steel Tube Concrete Connection Technology

This article systematically summarizes the process characteristics and mechanical properties of technologies such as socket-type connections, grouted sleeve connections, and corrugated pipe grouting connections. Compared with cast-in-place structures, these connection methods all have obvious advantages. However, in practical applications, they face problems such as large on-site workload, high construction precision requirements, imperfect quality inspection methods, and more construction costs. Therefore, there is an urgent

requirement for a prefabricated elevated bridge pier column that can solve the above problems existing in current prefabricated bridge piers. To achieve this goal, two new types of connection methods are proposed.

5.1. The Separated Steel Connection Technology

The separated steel connection involves embedding two or more shaped steel members at the top (or bottom) of one part of the pier column, with a rebar cage reserved at the bottom (or top) of the other part. To enhance the overall mechanical performance and connection strength, both ends of the shaped steel have end plates, and studs are arranged on the flanges. The design value of shear bearing capacity for a single shear connector: $N_v^c = 0.43A_s\sqrt{E_c f_c} \leq 0.7A_s f_u$, E_c is the elastic modulus of concrete; A_s is the cross-sectional area of the shank of the cylindrical head welded nail; f_c is the design value of the ultimate tensile strength of the cylindrical head welded nail. During on-site lifting, as long as the positions are aligned, rapid assembly construction can be achieved (**Figure 6**). After inspection to ensure the connection is qualified, concrete can be poured at the joint area. The bonding force between steel and concrete ensures the load transmission from one part to the other part of the bridge pier.

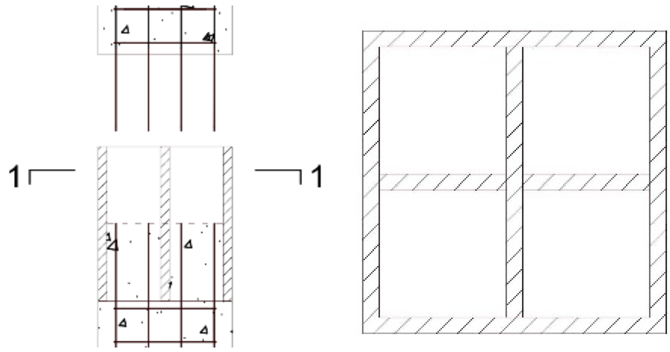


(**a**) (**b**)

Figure 6. Separated steel connection technology: (**a**) Separated steel connection, and (**b**) Cross-sectional view.

5.2. The Multi-Chamber Steel Tube Concrete Connection Technology

The multi-chamber steel tube concrete connection is achieved by embedding one steel tube with multi-cavity at the top (or bottom) of one part of the pier, with longitudinal reinforcement reserved at the bottom (or top) of the other part of the pier, and studs arranged on the inside of the steel tube. The splicing method is similar to that of separated steel type connections (**Figure 7**). After inspection to ensure the connection is qualified, concrete is poured into the connection joint from reserved holes. The bonding force between the multi-cavity steel tube and concrete ensures the load transmission from one part to the other part of the bridge pier.



(**a**) (**b**)

Figure 7. Multi-chamber steel tube concrete connection technology: (**a**) multi-chamber steel tube concrete connection, and (**b**) cross-sectional view.

5.3. The Superiority of the New Connection Method

The two new connection technologies proposed for the existing problems not only possess the general advantages of prefabricated bridge piers but also have the following benefits:

1. Simple connection, easy control of precision, and detectable: Easier to control position and precision during installation, making it convenient for workers to operate. Compared to other connection methods, it can better ensure on-site construction quality.
2. Economical: Since the new technology uses conventional steel and concrete, the cost is very close to that of cast-in-place components, and the overall cost is significantly lower than other connection technologies.
3. More reasonable force distribution: Depending on the stress state at the connection location, the cross-sectional shape of the steel connector can be flexibly selected to optimize performance. For instance, in areas subjected to high shear forces, the web section should be enhanced; facing high bending moments, the flange size needs to be increased; when axial force dominates, the entire steel connector's cross-section should be enlarged; and for high torsional forces, the steel connector should be placed as close to the outer edge of the section as possible.
4. Clearer load transfer path: In the structure, the first segment of the pier column transfers the load through rebar and concrete to the separated steel connector (or multi-cavity steel tube concrete), which then passes the load to the rebar of the next segment of the pier column, ultimately transferring the load to the entire pier column via the rebar. This transfer mechanism ensures effective distribution and stable transmission of loads within the structure.

6. Comprehensive Performance Analysis

With the rapid development of the economy and the continuous advancement of urbanization, the construction of transportation infrastructure has also developed rapidly. Prefabricated assembly bridges, with their advantages of being environmentally friendly, efficient, and having a wide range of applications, are increasingly widely used in engineering projects. These bridges can not only significantly reduce energy consumption and emissions during the construction process but also improve construction efficiency and ensure the consistency and reliability of the project quality.

When selecting a construction connection method, it is essential to comprehensively consider "time," "cost," "operational capability," and "usage conditions." Among these, "time" relates to construction efficiency, including on-site workload and assembly speed; "cost" encompasses the overall expenses of materials, construction, and maintenance; "operational capability" focuses on the convenience of construction, precision control, and the difficulty of quality inspection; while "usage conditions" refer to the suitability of the connection method under specific environmental or engineering conditions. **Table 2** provides a preliminary qualitative comparison of the comprehensive performance of the aforementioned connection methods.

Table 2. Comprehensive performance analysis table of prefabricated assembly pier column connection technology.

Connection Methods	Time	Cost	Operational Capability	Usage Conditions
Socket connection	Moderate	Moderate	Relatively high	Extensive applicability, especially for bridges that require high bearing capacity and good energy dissipation performance.
Grout sleeve connection	Moderate	Relatively high	Moderate	Applicable to bridges that require high construction accuracy and good overall structural integrity, but not suitable for high-intensity regions.
Corrugated pipe connection	Moderate	Relatively high	Moderate	Suitable for bridges that require quick construction, but attention should be paid to the problems of joint cracking and rebar eccentricity error.
Bolt flange connection	Relatively high	Relatively high	Moderate	Applicable to steel tube towers in the electric power and communication industries, but seldom used in the field of prefabricated bridges.
Mortise-tenon connection	Lower	Moderate	Relatively high	Currently, it is mostly used in the research stage and has a slightly lower bearing capacity than cast-in-place columns.
Separated steel connection	Lower	Lower	Relatively high	Applicable to bridges that require efficient, economical, and convenient construction, and the comprehensive cost is significantly lower than other connection technologies.
Multi-chamber steel tube concrete connection	Lower	Lower	Relatively high	

7. Conclusions and Prospects

To adapt to the requirements of the nation's new quality productivity and overcome the shortcomings of existing technologies, the future development and research of prefabricated pier column connection technology should innovate in terms of new materials, new devices, cost reduction and efficiency enhancement, and carbon sequestration and environmental protection. The specific details are as follows:

Innovation in connection methods: Combining engineering needs and environmental conditions, further study new connection methods and combinations of multiple connection methods, aiming for more convenient connections, higher construction efficiency, detectable quality, better durability, and lower costs.

Application of new materials and devices: Further study the application of high-strength steel or high-strength concrete made from solid waste materials in the segment connection of prefabricated pier columns. Additionally, the use of external energy dissipation devices or shape memory alloys (SMA) smart reset devices can improve the energy dissipation capacity of pier columns, which should also be thoroughly researched.

Research on multi-hazard coupled mechanical performance: Current research mainly focuses on the seismic capacity and mechanical performance of connection methods. However, the environment and stress state of bridge piers are very complex, so further research on the mechanical performance under multi-hazard coupled actions is necessary.

Intelligent monitoring: The segment connection position of prefabricated pier columns has a natural post-construction pouring belt. The durability of this position directly affects the overall performance of the pier column. Therefore, long-term health monitoring of the pier column connection nodes should be conducted. Using intelligent sensing technology and data analysis platforms to monitor the connection nodes in real time to assess their health status and provide early warnings of potential problems, achieving intelligent maintenance and management.

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Data Availability Statement

Data will be available on request from the author.

Conflicts of Interest

The authors declare no conflict of interest.

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