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REVIEW **Open Access**

Review of accelerated construction of bridge piers - methods and performance

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Abstract
Bridges are an essential part of every road and transportation system, and all countries must build bridges to improve their infrastructure. Accelerated bridge construction (ABC) is an innovative approach that has been noticed in recent years to facilitate and accelerate the process of building, repairing, or replacing bridges. This paper underscores the significance of ABC in bridge construction, focusing on its potential to offer speed, safety, and enhanced longevity for bridge pier. Through a comprehensive exploration of prefabricated elements and systems specific to bridge piers, insights into their applicability, advantages, and limitations are presented. A special section is dedicated to the investigation of pier connections under seismic loads. Furthermore, the review contrasts ABC with traditional construction methodologies, highlighting areas of excellence and potential improvement for ABC.

Keywords: Accelerated bridge construction, Bridge pier, Connections, Seismic performance, Advanced materials

1 Introduction

Bridges play an essential role in every road and transportation system, and bridge construction has been improved and developed significantly through the last decades. According to statistics from the Canadian government (Statistics Canada 2018), there are 51,717 bridges in Canada, including highway bridges, rural highway bridges, arterial bridges, collector bridges, local bridges, and footbridges. Figure 1 shows the total number of different types of publicly owned bridges in Canada.

According to the last Core Public Infrastructure Survey in Canada, more than 25% of local road and rural highway bridges are more than 50 years old, and 11% of all bridges in Canada are in poor or very poor condition, which means they need major rehabilitation or immediate replacement. As a result, there is a strong demand for the rehabilitation of worn-out bridges in Canada as well as building new ones (Statistics Canada 2018).

Hence, it is strongly required to improve bridge assets. However, reconstruction, rehabilitation, or repair of bridges and their components often result in traffic delays, incurring measurable costs in terms of time, wasted fuel, and emotional distress. To address these issues, transportation agencies are looking for Accelerated Bridge

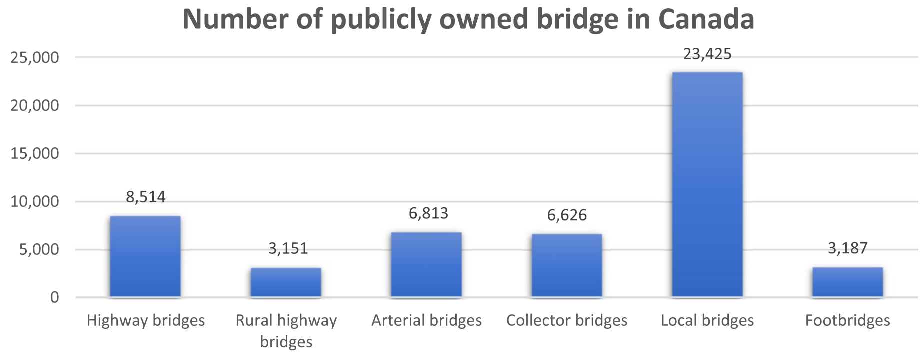


Fig. 1 Number of publicly owned bridges in Canada

Construction (ABC) methods that involve pre-fabricating the elements off-site and then assembling them on-site.

To date, ABC has been used in various bridge projects and with different strategies. Several approaches have been utilized in many countries, such as the United States, Japan, Taiwan, and European Nations, in interpreting and developing accelerated bridge construction, but among all nations, the United States has been a pioneer in this area. The National Cooperative Highway Research Program (NCHRP) and DOTs (Departments of Transportation) in the United States have concentrated on developing ABC and proposed several national workshops and reports on it. Moreover, significant efforts in the universities of the US have been made to enhance ABC technologies; for instance, the ABC Center at Florida International University (FIU-UTC), in collaboration with DOTs, the Federal Highway Administration (FHWA), and AASHTO, has been very active in this field through research, education, and technology transfer. Also, many successful projects have been done with ABC technologies in the short term.

Prefabrication of structural elements and the connection between them is the essence of ABC. The use of precast concrete for bridge piers offers potential time savings on-site and is a promising technology for ABC. In addition, the reduction of work on-site improves the safety of road users and workers while minimizing environmental impacts. This is why transport agencies are gradually adopting the ABC for many urban construction projects. Although there are various systems and prefabrication elements for bridge superstructures, only a few can be found for bridge substructures.

Current studies focus on analyzing the seismic behavior of prefabricated connections, evaluating their strength, ductility, and ability to dissipate seismic energy. Experimental tests, advanced numerical modeling, and laboratory analyses are carried out to better understand the substructure's behavior and put innovative solutions forward. Their ultimate goal is to achieve optimized seismic connections that meet ABC's requirements for safety, durability, and speed. Researchers and experts in the field are actively working on the development of design criteria suitable for the seismic connections of the prefabricated bridges used in the ABC. The objective is to define clear standards and guidelines that will enable them to obtain connections capable of withstanding seismic stresses while promoting the speed and efficiency of construction.

This paper will provide a review of the prefabricated elements and systems used in the ABC methods for different bridge pier columns. A particular focus will be made on pier connections and their performance in seismic zones.

The categorization of accelerated construction methods for bridge piers is informed not only by their inherent structural and functional attributes but also by their prominence in existing scholarly literature and engineering guidelines. This dual approach ensures our review is deeply rooted in technical validity while simultaneously resonating with prevalent industry trends and standards. By integrating these dimensions, the categorization offered here aims to provide a comprehensive and practically relevant perspective, aligning with both theoretical advancements and practical applications in the field of bridge engineering.

2 Objectives

In this paper, a detailed review is conducted on various types of connections in prefabricated bridge piers, focusing on their seismic performance, durability, and maintenance, as well as construction complexities. These connections are categorized based on both their structural and functional properties and their prevalence in scholarly literature and industry standards.

The overarching goal of this study is to provide a comprehensive overview that is insightful and practical for the field of bridge engineering, particularly focusing on prefabricated pier connections. This paper aspires to be a valuable resource, shedding light on the complexities and nuances of various connection types and their application in modern bridge construction. Offering this detailed examination aims to inform and guide both current and future practices in the industry, supporting the advancement and optimization of prefabricated bridge pier technologies.

The paper is organized into three distinct parts. The first section discusses the behavior of connections at the level of prefabricated piers. The second part presents the performance of the ABC methods for piers and the last part provides a critical view and recommendation for future research.

3 Pier connection systems

Repetition possibility and the opportunity to work on the ground level are two advantages of using prefabricated pier elements. The footings, columns, wall piers, and caps are the main elements related to pier systems. Footings and wall piers are made of reinforced concrete and the caps and columns can be made of steel or reinforced concrete. There are three types of connections related to the pier column system including the connection between the pier column to the pier cap, the connection of pier column segments, and the connection to the footing. When compared to building connections, bridge connections are exposed to much greater compressive stress and bending moment, necessitating more stringent restrictions on joint design and a successful seismic design should consider this matter a priority.

The connections of prefabricated bridges are generally located at critical points in the structure, such as the column-foundation or the column-pier cap joints, where plastic hinges are formed during strong earthquakes. However, conventional connection designs often exhibit common damages such as rebar buckling or fracture, joint opening, and even pull-out failures at bridge columns. Therefore, it is essential to pay close attention to connection design in moderate to high seismic zones.

To date, various systems have been used and developed for connecting columns to foundations, column caps, and other columns (in segmental piers). While some of these systems have been frequently used in various projects, others may have just been tested and approved in research and laboratory tests. These connections are discussed below.

3.1 Mechanical bar splice connections

Mechanical bar splices (bar couplers) can be used in the ABS approach to connect the column to the foundation, the column to the cap beam, and column segments in segmental piers. 3D view of the connection is illustrated in Fig. 2. Shear screw, headed bar, grouted sleeve, threaded, and bar-grip (swaged) are different types of couplers shown in Fig. 3 (Saiidi et al. 2020). Some details that the couplers can be used in a connection are presented in Fig. 4. Tight tolerances and transversal reinforcement suitable for the coupler size must be considered when using couplers. It is also worth mentioning that, if the number of couplers increases, the construction may be time-consuming. (Culmo et al. 2018).

Culmo et al. 2018 evaluated ABC systems in four measure parts, including testing and research, existing specification, implementation, and durability. In the case of precast column connections with mechanical connectors, there was no practical usage in terms of real bridges; however, the system has been used in significant research programs and there are provisions available in US codes (Culmo et al. 2018).

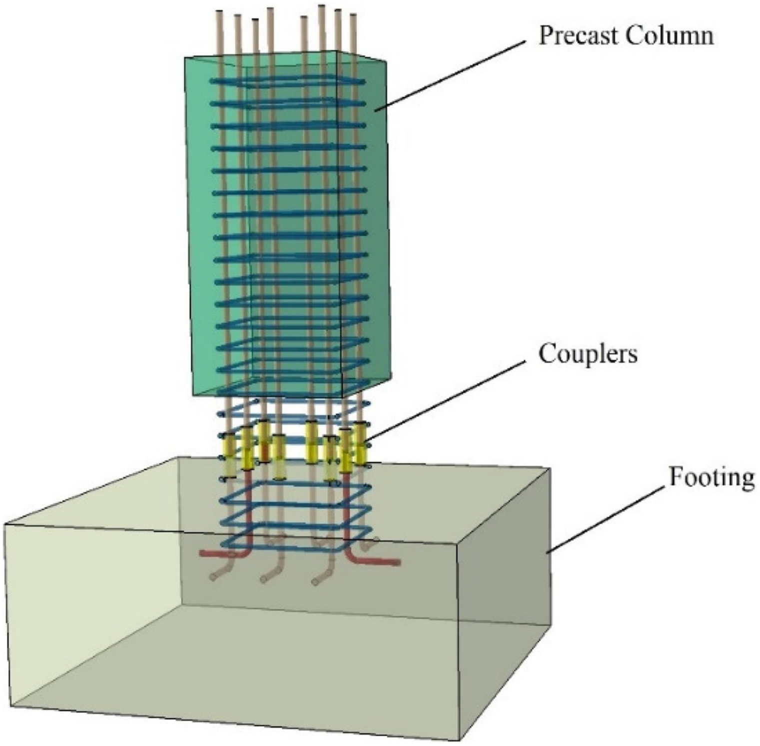
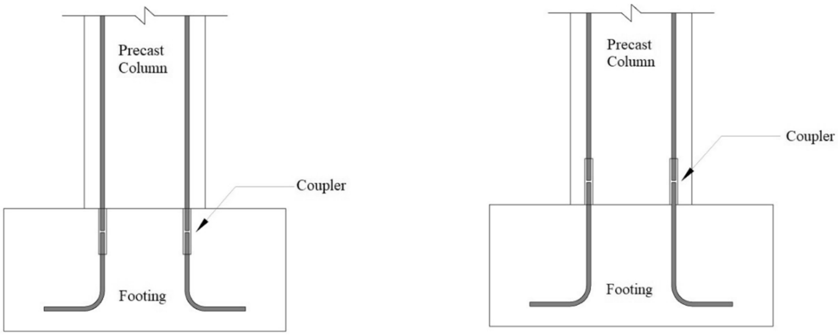


Fig. 2 Mechanical bar splice connection (© Munzer Hassan, ETS)

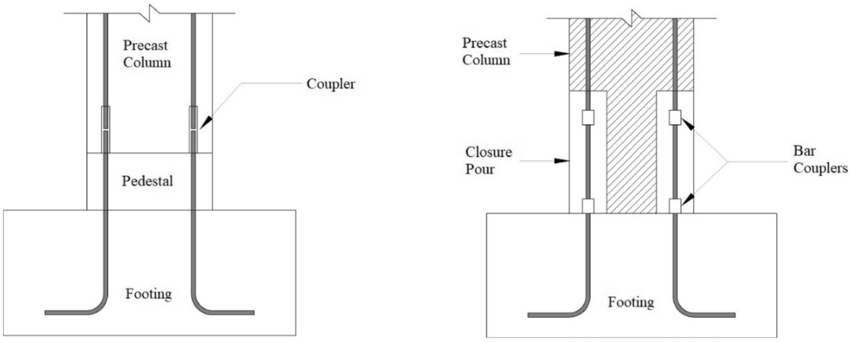
(a) Shear screw coupler (ancon.co.uk) **(b) Headed bar coupler** (hrc-usa.com) **(c) Grouted sleeve coupler** (splicesleeve.com)

(d) Threaded coupler (erico.com) **(e) Swaged coupler** (barsplice.com)

Fig. 3 Different types of couplers (Saiidi et al. 2020). **a** Couplers embedded in adjoining member. **b** Couplers in plastic hinges. **c** Shifted couplers. **d** Couplers at two levels



(a) Couplers embedded in adjoining member (b) Couplers in plastic hinges



(c) Shifted couplers (d) Couplers at two levels

Fig. 4 Some details for using couplers in a connection (Saiidi et al. 2020)

3.2 Grouted duct connections

In this type of connection, the column's longitudinal bars are extended out of the member and later inserted into ducts embedded in the column's adjacent member and they are filled with grout to complete the connection (Tazarv et al. 2021) (Fig. 5).

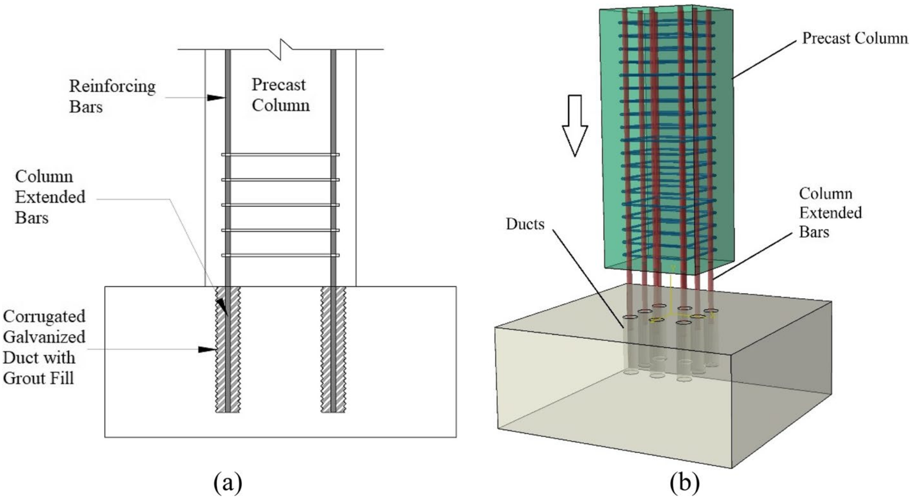


Fig. 5 Grouted duct connection: **a** Section (**b**) 3D view (© Munzer Hassan, ETS)

Cementitious non-shrink grouts are ideal for static and light dynamic loadings and are frequently used in many projects, (Culmo 2009).

The layout and tolerances are crucial for grouted duct connections, and to achieve greater tolerance, a smaller quantity of large bars can be used (Pang et al. 2010). The position of column reinforcement and the associated ducts must be determined using common working layout lines and points (Caltrans 2021). The repair is simpler in a column-footing connection with the ducts in the column than for a cast-in-place or socket system since the rigidity of the ducts causes the damage to be concentrated in the grout pad beneath the column (Belleri and Riva 2012).

In the NCHRP project 102 – 12 (Culmo et al. 2018), grouted duct connectors were evaluated as a commonly used technology in bridge construction. Many tests and studies have been done on the column-to-cap and column-to-footing assemblies, and the design provisions were fully developed for the system. Moreover, this system has been used many times with significant exposure in the case of durability.

3.3 Pocket and socket connections

The pocket connection (Fig. 6), which is commonly used for column-cap beam connections, is similar to the grouted duct connection. Here a large void receives all the longitudinal reinforcement instead of using a separate duct for each longitudinal bar.

In the socket connection (Fig. 7), the column is received by the foundation without any form of interlocking reinforcement between the components. To strengthen bond resistance, the precast columns' linked section has a rough surface. Two methods can be used to link sockets: The first is to prefabricate the column and cast the foundation in place around it after column leveling and bracing. In the second method, both the column and the foundation are precast (Galvis and Correal 2017).

One major benefit of pocket connections is the generous allowance for error in construction that is made possible inside the pocket itself. However, there is often a lot of connecting material, and reinforcing details in the footing is difficult. For elements with socket connections, transporting and handling precast pieces is easier due to the lack of

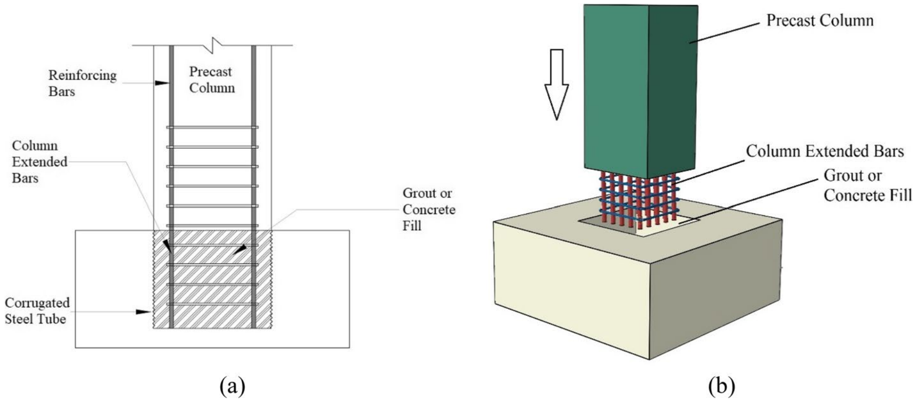


Fig. 6 Pocket connection: **a** Section (**b**) 3D view (© Munzer Hassan, ETS)

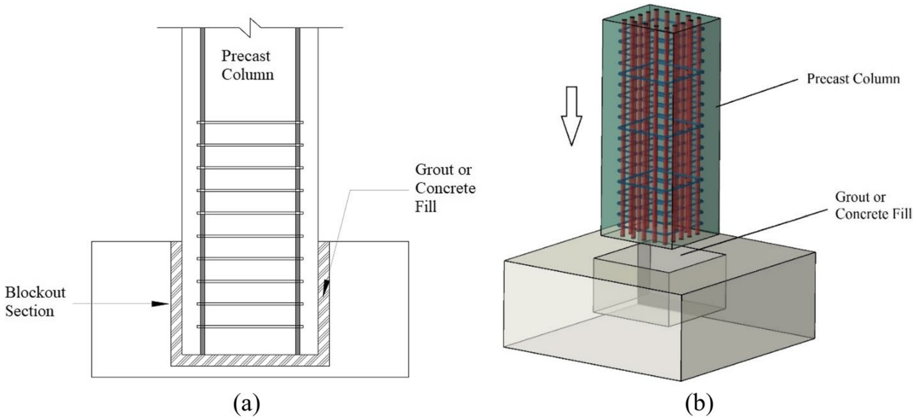


Fig. 7 Socket connection: **a** Section **b** 3D view (© Munzer Hassan, ETS)

crossing reinforcement between them. Yet, the same complexities with foundation reinforcement that were raised about the pocket connection also apply to this one (Galvis and Correal 2017).

Another disadvantage of such connections is that all of them rely on wet materials to connect elements that need enough time for curing and this matter leads to delays in the construction of the next components of the bridge such as the superstructure. Moreover, curing of cementitious materials should be done in certain temperatures which is impossible in very low degrees in winter except with specific equipment.

The evaluation of Culmo et al. shows that column-to-pier cap connections were investigated in more than three research projects, and design and construction provisions for the connection are fully developed in US codes. The connection has been implemented in two successful projects with limited exposure until the evaluation date (Culmo et al. 2018).

The assessment of the socket connection conducted by Culmo et al. demonstrates that it has been examined in many research programs, exceeding a count of three. Furthermore, standards for the system's design and construction can be found in US codes such as FHWA-HIF 13-037-A. (Marsh et al. 2013). The durability of the system has been acknowledged to be at least on par with that of a CIP connection, and it has demonstrated effective implementation in many practical bridge projects (Culmo et al. 2018).

3.4 Pipe-pin connections

Pins facilitate relative rotation and mitigate moment transmission between structural components. Consequently, structures that include flexible connections need fewer structural and foundation components in comparison to those with rigid connections (Mehraein and Saiidi 2019). A pipe-pin connection (Fig. 8) uses a column-anchored steel pipe and an adjoining steel can. A slight space between the steel pipe and the can allows the extended section to freely spin inside the can and prevents double curvature bending. This connection transfers compressive axial load through bearing and shear through contact of the protruded pipe and the neighboring member's steel can or friction force at the interface (Saiidi et al. 2020). The connection is close to a true pin, thus temporary supports are needed until the bent cap diaphragms are cast and hardened to attach the superstructure (Caltrans 2021).

3.5 Re-centering systems

After significant displacements, re-centering techniques are utilized to return bridge columns to their vertical position. These systems can apply nonlinear geometry to materials with linear elastic properties or employ nonlinear elastic materials such as Shape Memory Alloy (SMA) reinforcing bars (Culmo et al. 2018).

Rocking column systems including a post-tension tendon in the middle of the section of piers can be used to connect segmental prefabricated columns. The tendons should be protected from corrosion and one of the potential corrosion prevention

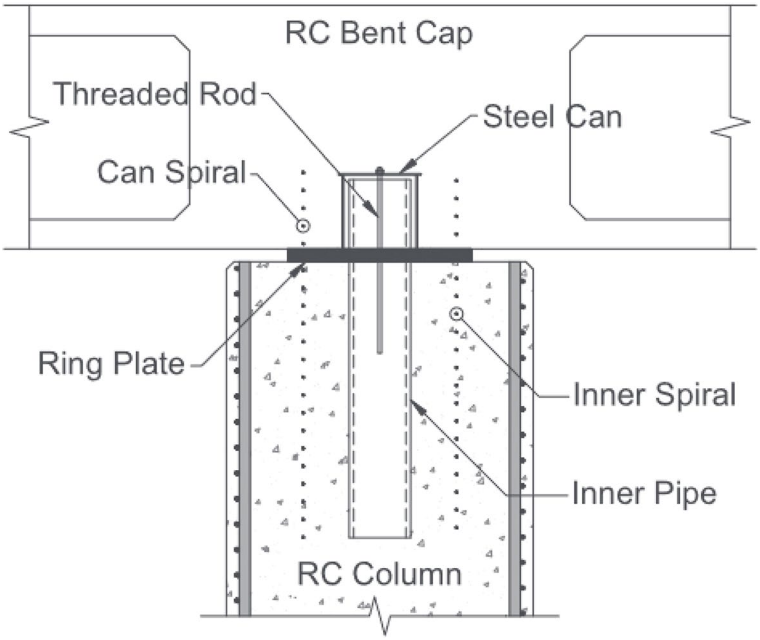


Fig. 8 Pipe-Pin Connection (Tazarv et al. 2021)

techniques is to grout the tendon into an internal duct that may freely slide inside an external duct that is attached to the surrounding concrete (Culmo et al. 2018).

3.6 Connections with advanced materials

Various advanced materials have been investigated and tested by researchers to develop and enhance the properties of the connection of prefabricated pier elements. Some of these novel materials are discussed in this section.

3.6.1 Ultra-high-performance concrete (UHPC)

In the context of using materials in the accelerated construction of bridges, the UHPC plays a crucial role. This method consists of pouring UHPC to fill the void between the prefabricated column and the footing (Fig. 9). It makes it possible to meet the requirements of speed and efficiency of the process. However, it should be noted that estimating the capacities of an anchorage zone in UHPC can be complex due to the lack of appropriate standards in this area. ROSINI (2018) highlighted this difficulty and the need for an accurate methodology to assess the performance of anchor zones in UHPC. In the absence of standardized tests, extensive research is needed to better understand the capabilities and behaviors of this critical zone in UHPC structures.

A successful example of using UHPC is the Hodder Avenue Underpass in Ontario, which is the first structure in North America to incorporate precast UHPC pier cap and pier column shells along with high-performance precast concrete box girders, parapet walls, and approach slabs (Li et al. 2014).

In November 2018, a comprehensive examination was conducted on a set of 20 bridges in the state of New York. These bridges were specifically chosen due to their utilization of field-cast ultra-high-performance concrete (UHPC) connections, and the bridges that were evaluated did not exhibit any signs of deterioration related to using UHPC (Seibert et al. 2019).

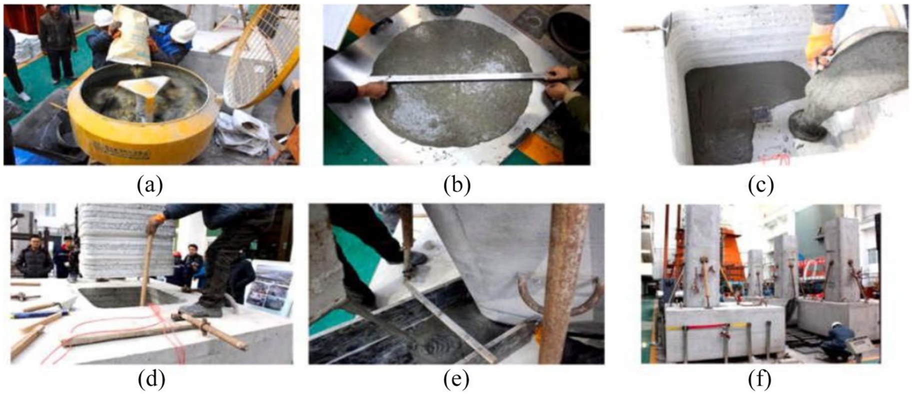


Fig. 9 Connection filled with UHPC: **a** mixture of UHPC; **b** sag test; **c** sinking the cushion into the pocket; **d** positioning of the column in the pocket of the sole; **e** casting of the void between the column and the footing; **f** completed specimens (Zhang et al. 2021a)

3.6.2 Engineered cementitious composite (ECC)

The engineered cementitious composite (ECC) is a type of concrete that has been reinforced with fibers, and it is anticipated to demonstrate limited structural deterioration when subjected to repeated loading conditions (Saiidi et al. 2017).

3.6.3 Reinforcing superelastic shape memory alloy (SE SMA)

A practical substitute for reinforcing steel bars is reinforcing bars made from superelastic shape memory alloy (SE SMA). SMA-reinforced members are guaranteed to return to their original places after yielding because of the low residual stresses experienced during cyclic actions (Saiidi et al. 2017).

3.6.4 Glass fibre reinforced polymer (GFRP) bars

Glass fibre reinforced polymer (GFRP) bars are employed as a corrosion-resistant reinforcing material in settings characterized by high aggressiveness, where conventional steel reinforcement undergoes deterioration due to corrosion. Glass Fiber Reinforced Polymer (GFRP) has been found to effectively mitigate maintenance expenses while simultaneously enhancing the structural integrity, durability, and longevity of various constructions (Hassanli et al. 2021).

3.6.5 Carbon fiber reinforced polymer (CFRP)

According to (Yu et al. 2006), the utilization of CFRP jackets has several benefits such as their lightweight nature, superior strength, high stiffness-to-weight ratios, corrosion resistance, and notably, their simplicity of installation. The aforementioned benefits render these materials well-suited for the retrofitting of bridge columns as well as providing confinement and boosting shear strength in prefabricated pier connections (Motaref et al. 2014).

3.7 Innovative connections

In recent years, many researchers have proposed novel connections and systems for ABC and examined them through laboratory tests and software modeling. While some of these technologies aimed to enhance previous connection details by using new materials or energy-dissipating devices in the connections, others tried to introduce new connections that were totally different from common existing ones.

For example, (Zhang et al. 2021b) presented an embedded concrete-filled steel tube (CFST) precast column-to-cap beam socket connection. the precast column and cap beam were integrated by ultrahigh-performance concrete (UHPC) grouting and the socket hole was formed by a steel pile. Shear bars were also welded around the CFST (Fig. 10). The prefabrication and assembly of the integrated CFST RC-to-cap beam socket connection is a straightforward process. The UHPC used in this connection exhibits excellent fluidity and bonding strength while the high construction tolerance ensures the reliability and efficiency of the joint regions (Zhang et al. 2021b).

The method is not frequently used in areas of moderate or high seismicity due to the lack of information on their seismic performance. Researchers have therefore conducted experimental and numerical studies to study the seismic performance

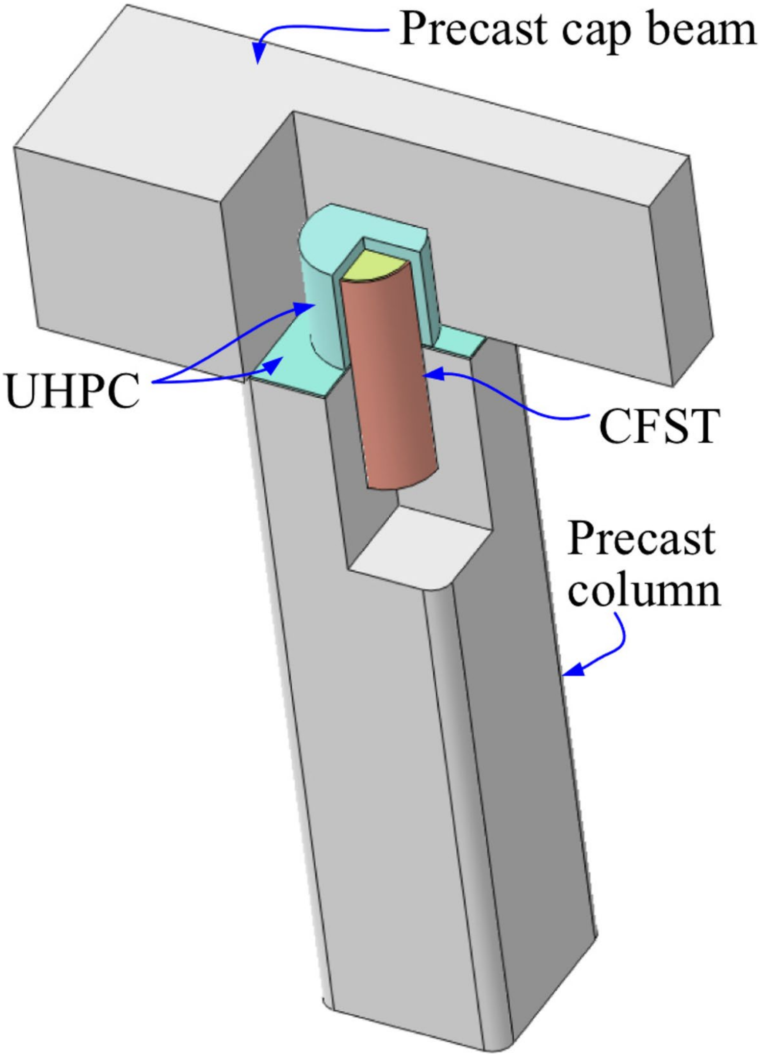


Fig. 10 CFST socket connection (Zhang et al. 2021b)

of precast columns with injected sleeve connections in areas of moderate or high seismicity.

4 Performance

In a seismic event, all prefabricated elements and their connections must endure the highest force demand as well as cyclic effects. Seismic forces in a prefabricated Bridge are similar to a non-prefabricated one, which means reinforcing steel in footings, plastic hinge zones, column confinement, and connections between the superstructure and substructure needs to satisfy provisions of design codes (Culmo 2009).

Connections at precast concrete substructures are generally made at the bent cap-column and column-foundation interfaces, to facilitate fabrication and transportation. However, in seismic regions with moderate or high activity, designing connections that can withstand inelastic cyclic deformations while being easily constructible is the main challenge for ABC.

Researchers and transportation departments have introduced many connection details for low seismic regions. However, only a few can be found for high seismic areas, so enhancing the behavior of the prefabricated elements under severe seismic loads and proponing reliable connection details in such regions are still hotspots for research.

4.1 Mechanical bar splice connections

The position of the connection, such as in the column or footing/cap beam, is expected to have an impact on its performance, specifically in terms of its ductility capability. The orientation of the coupler is also expected to have an influence on the performance of the connection. The positioning of the coupler within the footing/cap beam results in increased ductility capability, but at the expense of heightened column damage, when compared to its location within the column (Culmo et al. 2018). Despite the widespread usage of bar couplers in reinforced concrete (RC) construction, their application in plastic hinges of ductile components in bridges and buildings is subject to limitations or outright prohibitions in U.S, codes (Saiidi et al. 2020).

In laboratory tests involving cyclic loading, the preferred choices for column-to-footing assemblies in plastic hinge zones are typically headed rebar coupler (HC) and grouted sleeve coupler (GC) splices. The performance of shear screw couplers has been seen to be compromised due to stress concentrations and premature bar breakage occurring under the screws, resulting in lower strength and deformation capacity. Further investigation is required to effectively assess the seismic behavior of alternative mechanical connections situated inside or in close proximity to the plastic hinge area of columns (Culmo et al. 2018).

(Ameli et al. 2015) performed tests on four half-scale specimens, three of which were composed of precast concrete elements connected with injected sleeves while the fourth was made of cast-in-place concrete. According to these experimental findings, the precast subassemblies showed comparable strengths but less displacement capacity than the control CIP specimens. An improvement in seismic response was witnessed when the connectors' placement was altered or when dowel bars close to the connector were debonded. Similar studies were conducted by (Ding et al. 2022), (Xu et al. 2022), and (Yang et al. 2022), who performed shake table tests and simulations on prefabricated columns with injected sleeve connections.

4.2 Grouted duct connections

The utilization of grouted ducts may be observed in two distinct areas: the capacity-protected region (Pang et al. 2008), and the plastic hinge zone (Belleri and Riva 2012). When employed inside the plastic hinge region, the inclusion of ducts serves to impede the occurrence of bar buckling, potentially resulting in a greater ductility capacity compared to an equivalent cast-in-place system. The ductility capacity is also affected by the occurrence of local debonding in the bar close to the duct (Culmo et al. 2018).

Although research to date has proved sufficient moment transfer of the connection, it is not recommended for high seismic areas that require plastic hinging of the connection (Culmo 2009). To promote the use of grouted duct ABC column connections in high seismic areas, a refined design equation based on all available test data, and building standards was determined by (Tazarv et al. 2021).

GD connections have been successfully integrated into many bridge projects located in the states of Texas, South Carolina, Washington, and California (Saiidi et al. 2020).

4.3 Pocket and socket connections

There is still ongoing research to investigate the seismic performance of pocket and socket connections. Restrepo et al. examined cap pocket full ductility (CPFD) specimens for the column to cap beam connection in bridges. The result showed that the performance aim of the design was met by the Cap Pocket Full Ductility (CPFD) specimen, which displayed significant plastic hinging of the column, low joint distress, and essentially elastic behavior of the bent cap for an extended period of drift without appreciable strength loss (Restrepo et al. 2011). There are also considerations for the seismic design of pocket and socket connections based on investigations done in DOTs recommended by AASHTO Guide Specification for ABC (Culmo et al. 2018).

The depth of embedment of the column into the footing is a crucial factor influencing the structural performance of a socket connection, particularly when subjected to lateral and gravity stresses. According to the current state of literature, there is a widely acknowledged consensus that the plastic moment capacity of a column may be effectively achieved when the embedment depth exceeds 1.0 times the diameter of the column (Culmo et al. 2018).

In a case study, Khaleghi et al. utilized two types of connections in a precast pier system. The connection between the pier column and the cast-in-place footing was a socket connection, but where the column was embedded in the footing, the surface was roughened and the circular section was changed to an octagonal shape. The pier cap connection was provided by vertical bars projecting from the column that were grouted into ducts, using the largest bars possible. Pull-out tests illustrated that anchorage of the large bars could be provided at a depth less than the minimum requirements of the AASHTO LRFD (AASHTO 2007) code. In addition, cyclic tests demonstrated the sufficient strength and ductility of the connection (Khaleghi et al. 2012).

Two instances of pocket connection installation in the column to pier cap connections for non-seismic locations are the Squaw Creek Bridge in Iowa and the Escambia Bay Bridge in Florida (Wright 2010). The utilization of pockets constructed with corrugated steel pipes proved to be effective in the abutments of the Boone County Bridge in Iowa (Wipf et al. 2009) and the Madison County Bridge in Iowa (Phares et al. 2009). However, it is worth noting that neither of the implementations included any seismic detailing. One instance of socket connections being utilized in the context of column-to-spread footing can be observed in the construction of the US 12 bridge over Interstate 5 in Grand Mound, Washington (Culmo et al. 2018).

4.4 Pipe-Pin connections

The primary purpose of the top pipe-pin connection under earthquake stress is to function as a bi-directional flexural hinge, facilitating the transmission of shear and axial loads exclusively (Saiidi et al. 2020).

In research done by (Mehrsoroush et al. 2017), the seismic performance of precast pier systems consisting of pocket and pipe-pin connections was studied. On a shaking table, the pier model was subjected to increasing amplitudes of the Sylmar converter station ground motion record. Promising results were achieved with the suggested pocket connections, pipe pin, and rebar hinge, even at high drift ratios. The precast cap beam was also elastic and undamaged during the whole testing process.

The utilization of top pipe pin connections has been observed in many bridge columns, such as the approach ramps of the San Francisco-Oakland Bay Bridge replacement project (Fig. 11). Nevertheless, the notion of base pipe-pin connections is a novel concept that has to be implemented in practical applications (Saiidi et al. 2020).

4.5 Re-centering systems

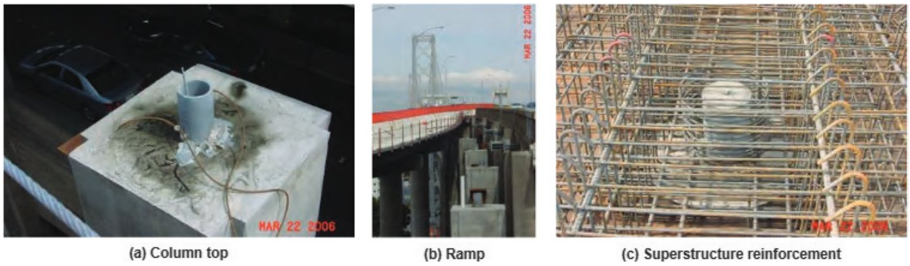
One of the best ways to limit damage in the pier is to provide enough dissipation capacity in the connection, creating a sort of jointed ductile connection system (Palermo and Mashal 2012). An efficient and viable solution is to allow the rocking motion between structural members (Priestley et al. 1999). The idea is commonly used in post-tensioned precast segmented column systems in low seismicity areas for bridge substructures. However, in areas of high seismicity, this system has a low energy dissipation capacity, which has led to studies aimed at remedying this problem.

Comparing two different precast pier systems in seismic regions was conducted by Hieber et al. (Hieber et al. 2005). One was a reinforced concrete system, in which the precast concrete components were connected by mild steel deformed bars. The second was a hybrid system, which created connections by combining mild steel deformed bars and unbonded post-tensioning. According to the findings of the parametric analysis, the systems had the potential for high seismic performance.

The seismic behavior of different substructure systems using post-tensioned bars has been the main subject of several studies. Ou et al. investigated the seismic performance of segmental precast unbonded post-tensioned bridge columns with hollow sections, (Ou et al. 2007) using a finite element model.

In experimental research by Shim et al., the seismic response of piers with a circular solid section was investigated. The specimens consisted of prestressed bars and steel tubes, and stud connectors were welded on the embedded steel pipes to allow anchoring of the pier segment to the footing. Quasi-static tests were conducted to evaluate the cyclic response of the precast bridge piers, and the results showed that the axial prestress that was applied enabled the restoration of the deformation under slight lateral displacements, causing only negligible harm (Shim et al. 2008).

Hung et al. (2017) studied the seismic performance of another type of connection for precast columns in segments called semi-rigid or hybrid connections. This connection



(a) Column top (b) Ramp (c) Superstructure reinforcement

Fig. 11 Implementation of pipe-pin connection (Saiidi et al. 2020) uses bonded bar reinforcement connected by bar couplers and shear keys, which prevents large axial prestress forces. In another study, Shim et al. (Shim et al. 2017) suggested a combination of continuous mild reinforcing bars and prestressed tendons to enhance the seismic performance as well as the economy of post-tensioned precast bridge piers.

Dissipative Controlled Rocking (DCR) consists of dissipative linkages (reinforcing bars or mechanical dissipative devices) placed at the rocking section which activates when an earthquake occurs, restoring or self-centering capacity plus dissipation. Some studies (Ou et al. 2007); (Priestley and Calvi 2002); (Yen and Aref 2010) demonstrated that DCR technology can drastically limit the damage in the pier, limiting the dissipation capacity in one or more critical rocking regions (Palermo and Mashal 2012).

In Canada, building each pier leg of New Samuel De Champlain Bridge was executed using precast segmental techniques (Nader 2020).

4.6 Connections with advanced materials

The effect of using different materials is another hotspot in investigations about the seismic performance of precast systems in bridges. The research conducted by Tazarv and Saiidi in 2014 Considered the development of new ABC connectors for bridge columns employing unique details and cutting-edge materials as its major goal. Ultra-high-performance concrete (UHPC), Nickel-Titanium shape memory alloy (NiTi SMA), and engineered cementitious composite (ECC) were the new materials, and two types of mechanical bar splices, grouted coupler, and headed bar coupler systems were used in the connections. SMA and ECC were incorporated in the plastic hinge of one of the UHPC-filled-duct columns to improve the overall seismic performance of the column and post-earthquake serviceability (Tazarv and Saiidi 2014).

According to (Shafieifar et al. 2018) the use of UHPFRC in the cap beam prevented plasticization in the cap beam area, thus providing capacity protection and moving damage away from the cap beam. Specimens exhibited ductile behavior, with plastic hinge formation at the desired location. The high workability of the UHPFRC and the high tolerance of the bars in the proposed detail facilitated and accelerated construction on site.

Comparative research in 2022 by Govahi, Salkhordeh, and Mirtaheri examined the cyclic performance of segmental post-tensioned bridge columns (SPCs) equipped with four different mitigation strategies, including high-strength rebars (SPCHS), base seat angles (SPCSA), lead base isolation (SPCI), and FRP tubes (SPCFRP). They were modeled in ABAQUS software and tested under cyclic load with strain control up to 5.5%. As is shown in Fig. 12, the results demonstrated that the model with base seat angles revealed the maximum amount of dissipated hysteretic energy (Govahi et al. 2022).

4.7 Innovative connections

Some researchers have tried to use, examine, and evaluate composite sections in the prefabricated pier systems in various ways such as using steel jackets or concrete-filled steel profiles. The seismic performance of prefabricated single-segment steel jacket piers connected by grouting sleeves was the main subject of a study by Deng, Jia, and Liang in 2021. The potential plastic hinge area at the bottom of the pier was wrapped with a steel jacket. The seismic performance of bridge piers can be enhanced by installing a steel

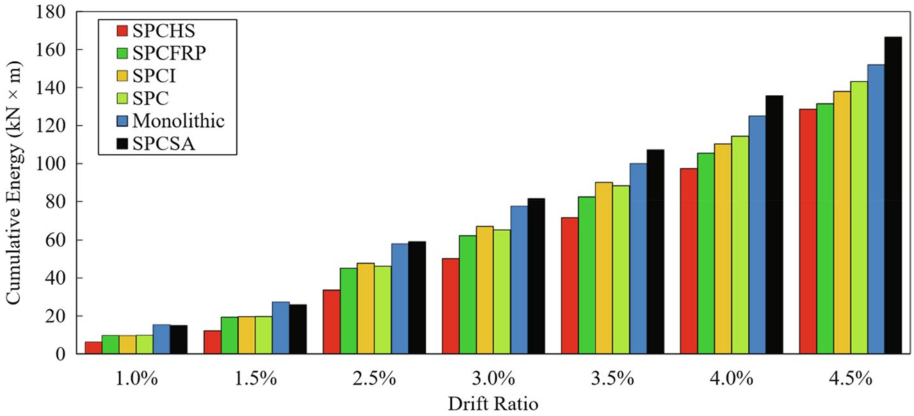


Fig. 12 Cumulative energy in the specimens (Govahi et al. 2022)

jacket, according to the increased stiffness, improved ductility, reduced acceleration displacement, and reduced strain response of the pier with a steel jacket (Deng et al. 2021).

In some studies, researchers have used concrete-filled steel tubes along with other connection technologies to provide better structural performance. As an instance, in 2021, Zhang et al. introduced an embedded concrete-filled steel tube (CFST) precast column-to-cap beam socket connection. The precast column and cap beam were integrated by ultra-high-performance concrete (UHPC) grouting. In addition, the socket hole was formed by a steel pipe, and shear bars were welded around the CFST. Outcomes of the laboratory tests illustrated that, due to the socket formed by the steel pipe, the energy dissipation ability of the connection increased, and greater lateral restraint to the embedded CFST was observed (Zhang et al. 2021b).

Fu et al. made a finite element model of a prefabricated steel tube-confined concrete circular pier by ABAQUS software. The cyclic load was applied to the model while the thickness and strength of the enveloping steel tube varied to evaluate the influence of these design parameters on the seismic performance of the PSTC circular pier. Flexural capacity, yield load, yield displacement, and initial tangential stiffness were all shown to rise with increasing steel tube thickness, but ductility was found to decrease (Fu et al. 2022).

In another research in 2022, Zhu, Ma, and Tan designed two innovative dry connections for concrete-encased concrete-filled steel tube (CECFST) columns. Column shoes were used to join the outer RC pieces together at their longitudinal reinforcement. The steel tubes of the CFST were joined together internally by relying on the bond strength between lapped or anchored bars and the concrete core (Zhu et al. 2022).

In 2022, Liu et al. studied the side shear strength and load-transfer mechanism of corrugated steel tube socket connection (CSSC) for column-foundation connections. According to the test results, the axial bearing capacity and ductility values of the CSSC specimens were much higher than those of the CIP specimen (Liu et al. 2022).

In 2021, Lu et al. invented a column base connection with anchor bolts and replaceable steel fuses for buildings. The system contained buckling restraints to prevent buckling, padding blocks as lateral support for the steel, and a concrete-filled steel tubular (CFST) core (Fig. 13). In the laboratory tests, after the first stage of testing was completed, steel

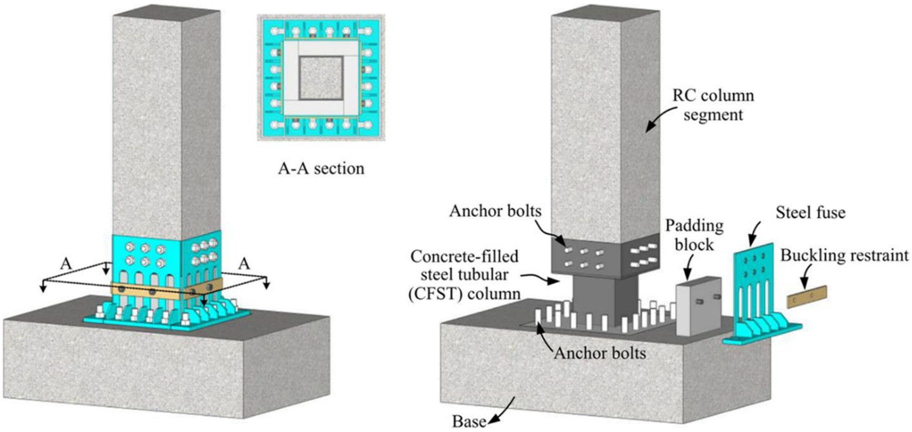


Fig. 13 Precast column base connection (Lu et al. 2021)

Table 1 Some of the bridge projects around the world and the accelerated construction methods Employed in them

Project	Year Completed	Location	Accelerated Construction Methods Employed
US 12 bridge over Interstate I-5	2011	Washington, US	Column-to-spread footing socket connection
Chang-Shou Bridge	1987	Nan-Tou, Taiwan	Precast segmental columns
New Samuel De Champlain Bridge	2019	Montréal, Canada	Precast segmental columns
Edison Bridge Replacement	1993	Florida, US	Mechanical bar coupler
Lake Belton New Bridge	2002	Texas, US	Grouted duct column connection
San Francisco-Oakland Bay Bridge replacement	2013	California, US	Pipe-pin connection
Squaw Creek Bridge	2008	Iowa, US	Pocket connection in the column to pier cap connections
Escambia Bay Bridge	2007	Florida, US	Pocket connection in the column to pier cap connections
Boone County Bridge	2006	Iowa, US	Pocket connection with corrugated steel pipes
Madison County Bridge	2007	Iowa, US	Pocket connection with corrugated steel pipes
Otomigawa Bridge	-	Ayabe, Japan	High-performance concrete panels for columns

fuses and padding blocks were replaced and tested again. The replaceable column-base connections exhibited stable hysteretic behavior since the plastic deformation was concentrated on replaceable steel fuses and padding blocks. (Lu et al. 2021).

Table 1 shows some of the bridge projects around the world that ABC technologies were used in the bridge substructure.

5 Critical view and recommendation for future research

In this paper, research on various accelerated bridge construction methods for pier has been meticulously compiled. A precise comparison of different pier connection systems is challenging due to the limited real-world project experiences and the diversity of existing systems and tests. However, it is endeavored to provide a comprehensive overview of various connection types. This comprehensive overview is instrumental for guiding future research and advancing these technologies, highlighting areas for development and refining construction methods. This approach plays a significant role in navigating the challenges of bridge construction, paving the way for innovative solutions in the field. A summarized list of these connections is presented, highlighting their general advantages and disadvantages:

1. Mechanical Bar Splice Connections: They offer moderate seismic performance and are quick to install, making them suitable for projects with tight timelines. While cost-effective upfront, they may require more maintenance in seismic-prone areas.
2. Grouted Duct Connections: Known for excellent seismic resilience, these connections are complex and slower to install, leading to higher initial costs. However, their robust seismic performance often results in lower long-term maintenance needs.
3. Pocket and Socket Connections: Suitable for moderate seismic activity, these connections are quick and easy to construct, making them cost-effective. However, in high seismic zones, they might need more frequent maintenance.
4. Pipe-Pin Connections: They provide good seismic resilience and are relatively quick to construct. Their cost-effectiveness and maintenance needs can vary depending on the design and materials used.
5. Re-Centering Systems: These systems are highly effective in seismic events, often reducing long-term maintenance costs. However, their complexity can lead to slower installation and higher initial costs.
6. Connections with Advanced Materials (UHPC, ECC, etc.): These connections leverage high-performance materials for superior durability and seismic resilience. While they significantly reduce long-term maintenance, their initial cost and installation complexity can be higher. They are particularly advantageous in demanding seismic environments.
7. Innovative Connections: These often involve new design concepts or methodologies, offering unique solutions to construction challenges. They excel in adaptability and efficiency but can be complex and costly. Their seismic performance varies based on the innovation implemented.

Based on the materials used, these connections can be categorized as dry and wet connections (Zhu et al. 2022). Wet connections account for the vast majority of bridge substructure technologies produced to date, and some of them are discussed here. Connections that need grouting or using wet materials on the site are not suitable in very cold weather. Moreover, the high number of rebars that need to be connected in the systems makes the erecting and adjusting of the elements too difficult.

An inherent drawback in existing bridge prefabricated pier connections is the potential for vulnerabilities related to long-term durability and maintenance. Over time, exposure to environmental variables, such as severe weather conditions, corrosive substances, and cyclic loading can lead to the deterioration of connection elements. The deterioration of the bridge could threaten its overall structural integrity, necessitating regular inspections and repair interventions. Researchers and practitioners should investigate cutting-edge corrosion-resistant materials and coatings to solve the durability issues related to prefabricated pier connections. By using materials that are more resistant to environmental deterioration, connections' service lives may be greatly increased and maintenance needs can be decreased.

Future research on ABC for bridge pier connections should focus on the development of new materials, particularly for seismic resistance and durability. It's crucial to assess the environmental and economic sustainability of these methods. Research should also aim at creating more resilient designs specifically for high seismic areas and developing flexible, adaptive connection designs. Composite modular systems are one of the best technologies that can be developed and enhanced in the future to address current drawbacks and limitation of presented connections. Incorporating advanced monitoring technologies for long-term maintenance and focusing on training for specialized construction techniques are vital. Lastly, establishing updated regulatory standards and guidelines specific to ABC in bridge pier connections will be key to advancing this field.

The techniques covered in this review will have a significant impact on how bridges are built in the future. In addition to cutting project schedules, expedited construction methods provide a number of benefits, including fewer traffic interruptions and increased general safety. Using prefabricated and modular components allows for more accuracy in building, which might result in constructions of a better caliber. Furthermore, the increased focus on sustainability in civil engineering projects is consistent with the economical use of resources and less ecological footprint linked to expedited construction.

6 Conclusion

In this paper, different prefabricated elements of bridge pier systems for ABC utilization are discussed. Since the connection details between these elements are the most crucial matter in a successful seismic design, the connections and their seismic performance have been considered the main subject of the current study. Various aspects of this matter are discussed by reviewing recent investigations around the world.

Up until this point, most of the technologies that have been utilized in real projects for ABC in bridge pier systems do not support high seismic and hazard demands in bridges. To address this issue, many researchers have proposed novel connections and systems for ABC and examined them through laboratory tests and software modeling to study their seismic performance by measuring the ductility and monitoring the formation of plastic hinges. While some of these technologies aimed to enhance previous connection details by using new materials or energy-dissipating devices in the connections, others tried to introduce new connections that were totally different from common existing connections.

The use of cutting-edge materials in precast pier connections has changed the field of bridge-building procedures. The utilization of ultra-high-performance concrete in diverse applications demonstrates its capacity to establish durable and long-lasting connection systems. Furthermore, the implementation of novel materials such as shape memory alloys exemplifies the transition of the industry towards connection systems that are more flexible and durable. The amalgamation of findings from many research projects provides substantial evidence supporting the notion that the integration of advanced materials inside prefabricated pier connections may significantly augment the durability, strength, and flexibility of these crucial structural elements.

The utilization of composite sections, namely steel jackets and concrete-filled steel profiles, has demonstrated notable progress in enhancing seismic resistance. The combination of these components, as shown by several studies, leads to significant enhancements in stiffness, ductility, and overall response when subjected to seismic stress.

Although many efforts, such as reports, manuals, and innovative research, have been made to date, accelerated bridge construction is still a hotspot for future investigations. The common proposed substructure connections in ABC manuals may not satisfy the demands and needs of new projects, especially in places with high traffic congestion or harsh environments. One topic that is available to enhance and do more research on is designing and testing novel prefabricated connection details for high seismic zones and unique environmental conditions. These connections should have enough resistance and ductility to resist seismic events as well as adequate resistance to chemical and physical attacks from the surrounding environment.

In addition, given the growing worldwide focus on sustainability, it is imperative that forthcoming research and applications in prefabricated pier systems place paramount importance on environmental friendliness while also upholding structural integrity.

Authors' contributions

Conceptualization, M.K. and M.H.; methodology, M.K. and M.H.; writing original draft preparation, M.K.; writing review and editing, M.H.; supervision, M.H. All authors have read and agreed to the published version of the manuscript.

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Declarations

Competing interests

The authors declare no conflict of interest.

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