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State-of-the-art review of the seismic performance of precast segmental columns

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Abstract

Prefabricated construction is attracting increasing interest in recent years, since this construction method has various advantages as compared to the cast-in-situ construction method, such as less construction time, higher quality control and reduced environmental impact. As a typical type of prefabricated structures, precast segmental column (PSC) has been used as the substructure to accelerate the construction speed of bridges. This paper reviews the performances of the PSCs under seismic loadings. In particular, the seismic performances of the PSC itself under cyclic loading and real earthquake ground motions, the seismic behaviours of PSC-supported bridge structures, and the responses of precast rocking column (PRC)-supported bridges, are comprehensively reviewed and their pros and cons are discussed. For the completeness of the paper, the performances of the PSCs under multiple dynamic hazards, namely impact and blast loadings here are also briefly summarized at the end of this paper.

Keywords: Prefabricated construction, Precast segmental column, Seismic performance, Review

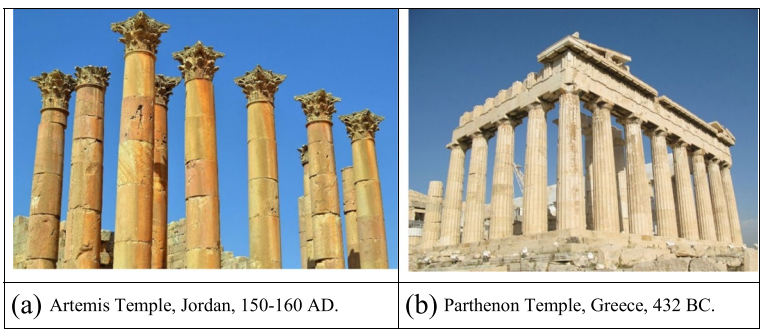
1 Introduction

In recent years, the prefabricated construction method is attracting more and more attentions in both the research and industry communities due to the numerous advantages of this method as compared to the traditional cast-in-place construction method. In the prefabricated construction, structural elements are normally cast in the precast factories, then these precast elements are shipped to the construction site, afterwards the workers assemble the precast elements together and finalise the construction. Since most of the construction works are done in the precast factories, the on-site work such as formwork preparation or scaffolding installation can be avoided. As such, the on-site construction time can be significantly reduced. This is especially important for the construction project in urban areas where traffic is heavy. Besides, the construction quality can be better controlled due to the more controllable environment in the prefabricated factories. This becomes more important when some new materials (such as the ultra-high-performance concrete (UHPC)) are used since the required curing conditions for these materials are generally stricter compared to the normal concrete, which can be better satisfied

in the prefabricated factories. In addition, the pollutions caused by the traditional construction such as dust pollution, water pollution and noise pollution can be significantly minimized by using prefabricated construction instead of cast-in-situ construction method.

Precast segmental column (PSC) is a typical type of prefabricated concrete structures. The adoption of PSC in structure construction could be dated back to the ancient times, many ancient structures that were built hundreds even thousands of years ago adopted this construction method. Figure 1 shows the applications of PSCs in ancient temple structures. As shown, in the Artemis temple that was built around 150-160 AD and the Parthenon Temple that was built around 432 BC, the stone segments were stacked one by one to form the column. Though connections between the segments were weak in these columns, these structures survived many major earthquakes in the history because they could rely on the self-weight of the column and super-structures to keep the integrity of the column. For the modern PSCs, posttensioned tendons are normally used in the column to clamp all the segments together to not only further integrate the prefabricated structural segments together but also provide restoring forces after deformation. Figure 2 shows the typical construction steps of the PSCs in bridge structures (Billington et al. 1997). According to reference (Shahawy 2003), one of the earliest projects that adopted modern PSCs in the construction was the Lavaca Bay Causeway, Texas, US in 1961. Ever since, the PSCs have been utilized in many construction projects around the world. Figure 3 shows some applications of the PSCs in practical projects.

Despite these applications, the knowledge on the seismic performance of prefabricated segmental columns is relatively limited. In order to promote the application of PSCs in areas with medium to high seismic intensities, it is necessary to study the seismic performance of PSCs. Intensive research works have been carried out by different researchers from various countries recently. A few related review papers have also been published (Zhang and Alam 2020; Zhong and Christopoulos 2021; Piras et al. 2022). This paper provides a further up to date state-of-the-art review on the seismic performances of PSCs and PSC-supported bridge structures. In particular, the cyclic performances of PSCs including the self-centring capacity, the damage mitigation methods and the energy dissipation devices, the dynamic behaviours of PSCs and PSC-supported bridge structures, the overturing behaviour of precast rocking



(a) Artemis Temple, Jordan, 150-160 AD. (b) Parthenon Temple, Greece, 432 BC.

Fig. 1 Ancient applications of PSCs

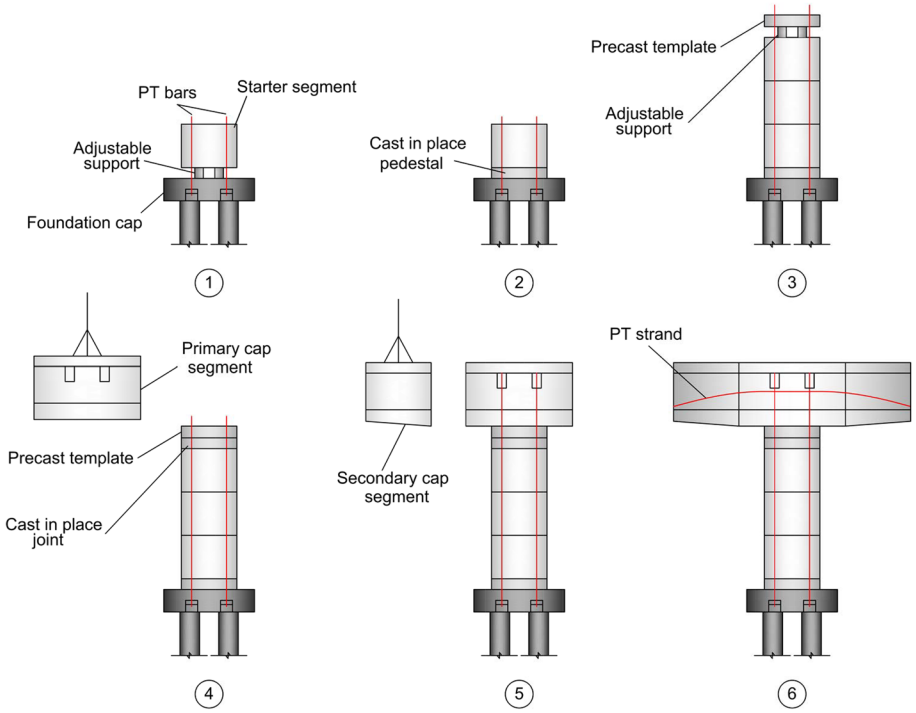


Fig. 2 Construction steps of the PSCs (Billington et al. 1997)

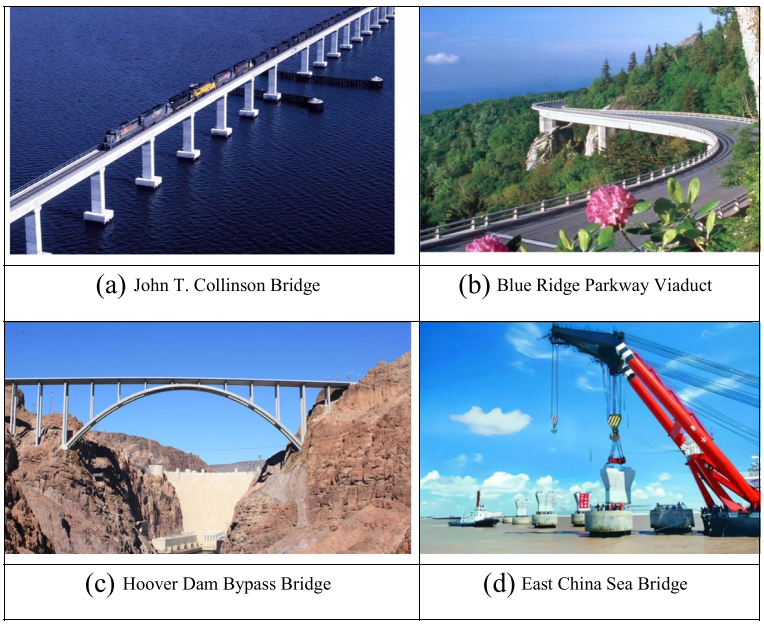


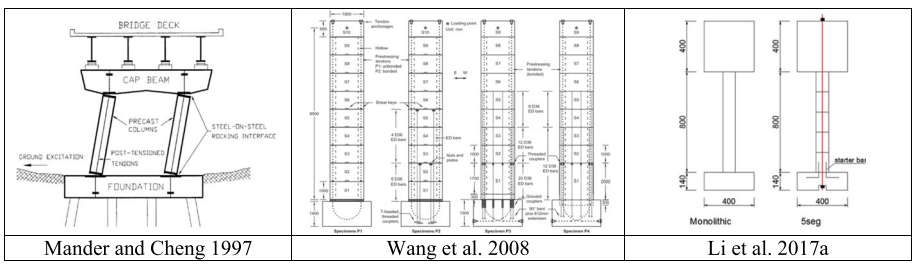
Fig. 3 Applications of PSCs

column (PRC)-supported bridges are comprehensively reviewed. For the completeness of the paper, the behaviours of PSC under the impact the blast loadings are also briefly summarized at the end of the paper.

2 Cyclic performance of PSCs

2.1 Self-centring capacity

The residual displacement is one of the most important indices for evaluating the seismic performance of bridge columns. Large residual displacement will make it difficult or impossible to repair the columns after a seismic event. It was reported that during the 1995 Hyogo-ken Nanbu (Kobe) earthquake, around 100 bridge piers were demolished due to the large residual drift (more than 1.75%) after the earthquake, even some of them showed no apparent damage (Kawashima et al. 1998). Therefore, reducing the residual displacement is important and should be taken into consideration in the design of columns. One of the most appealing characteristics of PSC is its self-centring capability, i.e., the ability to reduce the residual displacement of the structure after the earthquake. In 1997, Mander and Cheng installed unbonded tendons in PRCs (see Fig. 4), and it was found the column had very small residual displacement due to the rocking behaviour and the restoring force provided by the posttensioned tendon and the gravity load (Mander and Cheng 1997). In 2004, Billington and Yoon carried out experimental studies on the precast columns with unbonded posttensioned tendon and ductile fiber-reinforced cement-based composite (Billington and Yoon 2004). It was found that column with unbonded tendon reached 9% drift ratio with minimal residual drift. In 2006, Chou and Chen investigated the cyclic performance of PSCs with concrete-filled tube (CFT) segments and unbonded tendons (Chou and Chen 2006). The columns showed small strength degradation and residual displacement at a maximum drift of 6%. Palermo and Marriott carried out experiments to investigate the cyclic performance of the seismic resistant bridge columns which included unbonded posttensioned tendons and internal mild steel energy dissipation bars (Palermo et al. 2007). The test results demonstrated that the seismic resistant column had negligible residual displacement and minor damage. A parameter 'λ' dubbed 'moment ratio', which was defined as the ratio for the moment provided by the posttensioned tendon and the extra axial load to the moment provided by the energy dissipation (ED) bars, was introduced. It was concluded that, to achieve a satisfactory self-centring ability, the value of 'λ' should be kept larger than 1. Wang et al. tested four large-scale PSCs with a height around 10 m (Wang et al. 2008). A U-loop duct was formed in the foundation for the tendon to avoid the installation of anchorage system underneath the foundation. In the test, unbonded tendon was used in one specimen and the column showed minimal residual displacement. Ou et al. carried out large scale tests on PSCs with different amount of ED bars and different levels of posttensioning force in the tendons (Ou et al. 2009). It was found that the column



Mander and Cheng 1997	Wang et al. 2008	Li et al. 2017a

Fig. 4 Design concept of PSCs

without ED bars had minimal residual displacement. With the increase of the ED bar ratio, the residual displacement also increased. A parameter, 'λ_{ED},' which represented the ratio of the lateral strength provided by the ED bars to the total lateral strength of the column was introduced. From the test results, it was found that when the values of λ_{ED} were between 28% and 35%, the specimens showed flag-shape hysteretic curves with large amount of energy dissipation and minimal residual displacement, but the column with λ_{ED} of 50% had much larger residual drift (about 3% under 5% applied drift) as compared to the other specimens. Thus, it was recommended that λ_{ED} should not exceed 35% to ensure a good self-centring ability of the PSCs. As shown in Fig. 5, Li et al. compared the cyclic performances of a monolithic column and PSCs with different designs (Li et al. 2017a). All the PSCs had unboned tendons. It was found that the monolithic column had large residual displacement due to the plastic deformation of the steel bars and the concrete damage while all the PSCs showed minimal residual displacement due to the restoring force provided by the unboned tendon.

According to the above review, it can be found that the unbonded tendon could provide the PSCs with very good self-centring ability. Besides the unbonded tendons, some researcher adopted bonded tendons. In 2008, Shim et al. (2008) conducted experimental studies on the PSCs with bonded threaded prestressing bars. According to the test results, the columns showed recentering behaviour, but the residual displacements were large. Bu et al. (2015) also used bonded posttensioned bars in some of the tested specimens. Large posttensioning force loss was found during the tests and the columns with bonded posttensioned bars experienced about 3% residual drift when the applied drift reached 6%. Wang et al. (2008) tested four PSCs under cyclic loading. Among the four specimens, three of them had bonded posttensioned tendons. Large residual drifts were found from the hysteretic curves. Wang et al. (2014) tested a series of PSCs with different designs, two of them had bonded tendons and the other two had unboned tendons. It was found that the use of bonded tendons increased the lateral strength and the energy dissipation of the column, but it also increased the residual displacement. Li et al. (2017b) investigated the effect of bonding conditions of the tendon through numerical simulations, it was found that the column with bonded tendon had higher strength but lower ductility and it experienced larger residual displacement due to the stress concentration in the bonded tendon, which caused yielding of the tendon and loss of posttensioned force.

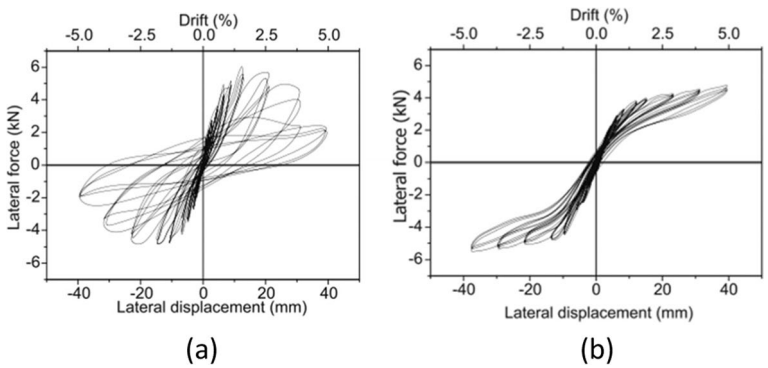
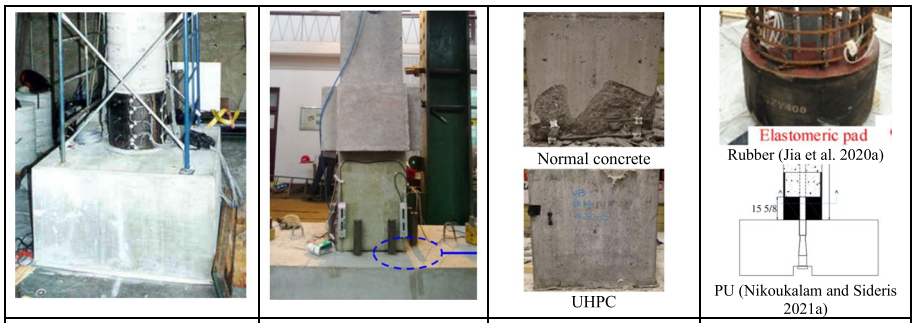


Fig. 5 Typical hysteretic curves of monolithic column (**a**); and PSC (**b**) (Li et al. 2017a)

From the experimental tests and numerical simulations that have been reviewed above, it can be summarized that for the PSCs, using unbonded posttensioned tendon can effectively minimize the residual displacement of the column, which can significantly facilitate the post-quake retrofitting activities. Using bonded tendons results in stress concentration and prestressing loss in the tendon, causing larger residual displacement. Therefore, to achieve a seismic resistant column system with minimal residual drift, it is recommended to use unbonded tendons in the PSCs instead of bonded tendons. On the other hand, it should be noted that the unbonded tendon is deemed more vulnerable to corrosion damage than bonded tendons due to the exposure to air and moisture during its service life (Castel et al. 2011; Podolny Jr 1992). Techniques such as using greased and sheathed strands (also known as mono-strand tendon) have been proposed to mitigate the corrosion damage of the unbonded tendon (Podolny Jr 1992). FRP tendon were also adopted and investigated to replace the steel tendon considering its good corrosion resistance (Wang et al. 2015; Guo et al. 2015). Using FRP tendons can certainly mitigate the corrosion damage of tendons and can also potentially increase the deformation restoring capacity because of the relatively high strength of FRP than steel so that the responses are likely remain in elastic range. However, normal FRP materials such as GFRP and BFRP have low modulus as compared to steel tendon. Therefore, the column response amplitude during earthquake excitation could be larger than that with steel tendons. Moreover, FRP fails brittlely when its capacity is reached, column with FRP posttensioned tendons may experience brittle damage. Therefore, carefully analyses are needed to evaluate the respective advantages and disadvantage of using FRP or steel tendons in the design. It should be noted that recently high modulus, i.e., modulus comparable to steel, carbon fibres have been invented, which nevertheless is still very costly for use in construction. However, considering the lifecycle maintenance cost and durability of the segmental column, the use of the new high-strength, high-modulus and corrosion resistant FRP tendons could be a viable choice in construction of prefabricated segmental columns.

2.2 Damage mitigation

Under seismic loadings, openings could develop at the joints between the segments of the PSCs especially between the segments at the bottom ends. The concrete near the joints could experience excessive compressive stress when the joints open, which can cause concrete crushing and spalling damages. According to previous experimental studies on the PSCs, the damage that observed in the specimens concentrated at the joints where large openings developed and it was mainly the concrete crushing damage (Wang et al. 2008; Ou et al. 2009). To mitigate such damage, as shown in Fig. 6, different methods have been proposed and investigated, including using steel jacket, FRP wrap or jacket to confine the concrete, using high performance concrete materials such as UHPC and engineered cementitious composite (ECC), and using rubber or polyurethane (PU) in the segments. Related studies are summarized and the pros and cons of each strengthening techniques are discussed in this section.



(a) Steel jacket (Hewes and Priestley 2002)	(b) FRP jacket (Guo et al. 2015)	(c) UHPC/ECC (Yang and Okumus 2017)	(d) Rubber/PU

Fig. 6 Damage mitigation methods for PSCs

2.2.1 Steel jacket

Hewes and Priestley (2002), in 2001, carried out tests on PSCs under cyclic loadings. In the design, to mitigate the concrete crushing damage owing to segment rocking, the bottom segment was confined with steel jacket to mitigate the concrete damage at the toes of the segment. From the test results, the jacket effectively minimized the damage of the bottom segment. However, concrete spalling damage shifted above and occurred in the upper segment without steel jacket. To address this problem, Chou and Chen (2006) proposed concrete-filled tube (CFT) segmental columns, in which all the segments were confined with steel jacket. The CFT segmental columns showed minimal damages in the segments and reached 6% drift ratio without obvious strength degradation. The residual displacement was also small as the damage was minimal, which further resulted in the small prestressing force loss. However, the use of steel tube increases the material and construction cost, as well as the maintenance cost because of corrosion problem, especially when such structures are used in the coastal area. In 2015, Guerrini et al. (2015) tested dual-shell hollow core precast columns under cyclic loading. Two steel shells served as the formwork as well as the jackets to confine the concrete. The results demonstrated that the column could underwent large drift ratio (10%) with minimal damage. Amini et al. (2017) proposed using steel tube to confine the bottom segment and add lead plates between the joints. The test results showed that with these two designs, the damage level of the segments could be reduced. Thonstad et al. (2017) adopted steel confining shoe in the precast posttensioned column and it was found the concrete spalling was avoided. Mashal and Palermo (2019) tested a bridge bent with low-damage seismic designs. The top and bottom ends of the precast columns were armed with steel jackets. The contact interfaces between the columns and the footing or the cap beam were also armed with steel plates. According to the test results, no apparent damage was found in the column, footing, and cap beam of the bent. In contrast, the traditional cast-in-situ specimen experienced concrete crushing and steel bars yielding and buckling damages during the test. The low damage design methods have been applied in a real bridge named as 'Wigram-Magdala Link Bridge' in New Zealand. In 2021, Shen et al. (2021) tested precast CFT columns under cyclic loading. The columns achieved 6.8% drift without significant decrease of loading capacity, and only minimal damage was found in the

column except some crushing damage of the mortar bed between the column and the footing. In 2021, Reggiani Manzo and Vassiliou (2021) tested PRCs under cyclic loading. In the design, the ends of the column were protected by steel jackets. Unboned tendon was used to provide the restoring force. One end of the tendon was fixed in the footing, the other end of the tendon was anchored in the cap beam with springs underneath the anchor. The use of the spring reduced the post yield stiffness and also the design moment of the system, which made it like a seismic isolation method, i.e., at the expense of large drift response, it reduced the design force of the system. The column with steel jacket underwent very large drift ratio (30%) without any damage. In 2022, Dangol and Pantelides (2022) tested a posttensioned bent with buckling restrained brace (BRB). The ends of the precast columns were confined with steel collars. The column showed minimal damage due to the use of steel collars and the BRB contributed most of the energy dissipation of the bent. A similar design was proposed by Dong et al. (2022) very recently. In which, a self-centring braced double-column rocking bent (SBRB) consisting of a double-column rocking bent and a traditional or self-centring dissipation braces were developed to enhance the seismic resilience of the bridge bent. It was found that the SBRB was featured by prominent seismic performance including high lateral stiffness and strength, stable energy dissipation ability and good self-centring capability.

2.2.2 FRP jacket

Different types of FRP jackets were also adopted to confine the concrete. ElGawady et al. (2010) tested PSCs with glass fibre reinforced polymer (GFRP) tubes under cyclic loading and compared their performances with a reference monolithic column. It was found that the columns with GFRP tube confinement could undergo a drift ratio of 15% without strength degradation, and only minor damage was found in the specimens after the tests. Similarly, ElGawady and Sha'lan tested a bridge bent with concrete-filled GFRP tube segments (ElGawady and Sha'lan 2010). Guo et al. (2015) tested a precast concrete column with the bottom of the column encased in a GFRP jacket. It was concluded that the GFRP jacket was useful to protect the toes of the core concrete from crushing. Li et al. (2019a) adopted basalt fibre reinforced polymer (BFRP) wrap to confine the precast segments and the test results showed that minimal concrete crushing damage was found and the column had no strength degradation at 6% drift ratio. In 2020, Zhang et al. (2020a) repaired the damaged PSC with carbon fibre reinforced polymer (CFRP) wraps and carried out cyclic tests on the repaired specimen. It was found that the CFRP wrap could restore or improve the performance of the PSCs. Considering the corrosion resistance ability of FRP jacket, it could be a good alternative to the steel jacket to protect the concrete in the PSCs.

2.2.3 UHPC and ECC

Billington and Yoon (2004) applied ductile fiber-reinforced cement-based composite (DRFCC) in the potential plastic hinge region of PSC. It was found that columns with DRFCC had more distributed and fine cracks as compared to the column with normal concrete, and spalling damage did not occur to the DRFCC material. Tazarv and Saiid Saiidi (2015) applied ECC in the precast columns. The damage of the column with ECC was found significantly reduced as compared to the cast-in-place column. Ichikawa et al.

(2016) used UHPC segments in the potential plastic hinge region. No spalling or crushing was observed in the UHPC segments. Varela and Saiidi (2016a) proposed a resilient deconstructible column that consisted of two parts, one was the deconstructible plastic hinge and the other was the upper column. The upper column was designed to be elastic during the test. ECC was used for the deconstructible plastic hinge and the damage was minimal in this part till the end of the test. Yang and Okumus (2017) tested PSCs with the bottom segments made of normal strength concrete or UHPC. For the UHPC segment, two cases were considered, i.e., with and without steel reinforcement respectively. The test results showed that concrete crushing developed to 40% of the bottom segment height for the column with normal strength concrete, while only minor edge concrete crushing propagated to 4% of the bottom segment height for the column with UHPC. Moreover, the reinforcement was found having negligible effect on the UHPC segments. Wang et al. (2018a, b) tested PSCs with ultra-high-performance fiber-reinforced concrete (UHPFRC) segments. It was found only minor spalling was developed at the cover concrete. Shafieifar et al. (2018) proposed a connection for precast footing or cap beam-column connection, in which a splice region was designed and UHPC was used to cast the splice region after the assembling of the column. The designs could achieve a rapid construction with relatively large tolerance for construction. According to the test results, the post cast UHPC region had minor damage and most of the damage was found in regions with normal strength concrete. The columns behaved like a monolithic column. Zhang et al. (2019) proposed PSCs with solid or hollow UHPFRC bottom segments. It was concluded that the damage that observed in the column with normal strength concrete was significantly reduced due to the use of UHPFRC segments.

2.2.4 Rubber or PU

Jia et al. (2020a) in 2020 investigated the seismic performance of precast columns with built in rubber pads. The columns with rubber pads experienced minor damage in the concrete, but obvious torsional deformation was found due to the low torsional stiffness of the rubber pads. In 2021, Nikoukalam and Sideris (2021a, b) tested PSCs with the bottom segment enhanced by polyurethane (PU). In the test, the concrete of the bottom segment was partially or totally replaced by PU. It was found the column with PU demonstrated better damage resistant performance. When the drift ratio reached 8.2%, there was no major damage in the column. However, it should be noted that the primary function of column is to carry vertical loads, replacing concrete at the bottom segment by rubber could significantly reduce the vertical load-carrying capacity of the column owing to the low compressive strength of rubber and PU.

2.3 Energy dissipation

In the early-stage tests on PSCs, for example, in references (Mander and Cheng 1997; Billington and Yoon 2004; Chou and Chen 2006; Hewes and Priestley 2002), only post-tensioned tendons were used to clamp all the segments. The columns showed good self-centring ability, but the energy dissipation capacity of the columns was limited. During a real earthquake, more energy therefore could be transferred to the superstructure compared to the traditional monolithic columns-supported bridge, which in turn may result in the larger superstructural responses. Therefore, different ED devices have

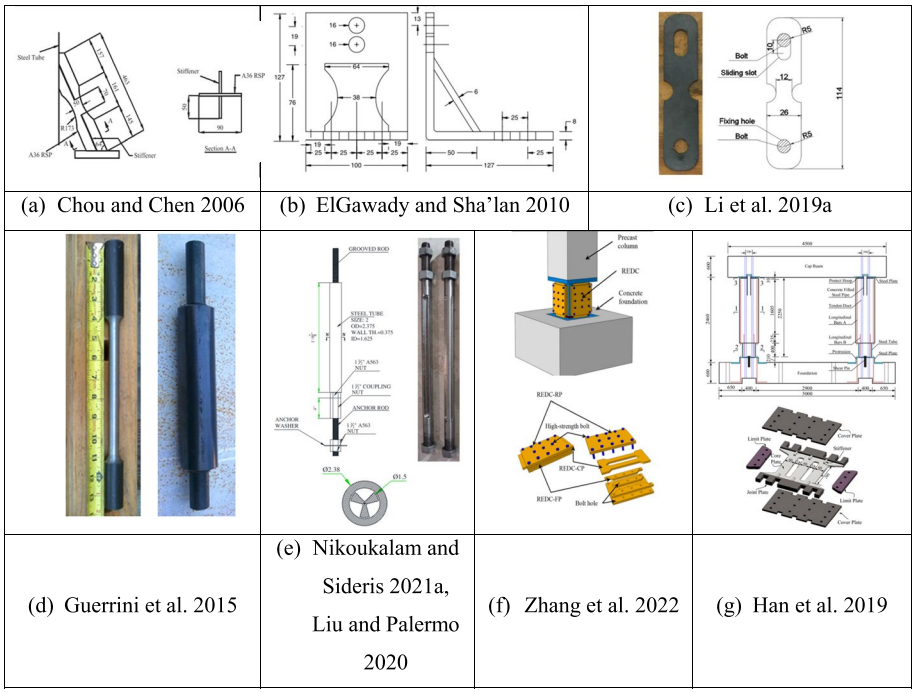
been proposed to increase the energy dissipation capacity of the PSCs and to reduce the superstructural responses. The ED devices can be generally categorized into internal ED bars and external ED devices. Besides, a new hybrid rocking-sliding column system was recently proposed to improve the ED ability of the PSCs.

2.3.1 Internal ED bars

Palermo et al. (2007) tested precast columns with internal ED bars and unbonded tendons. The precast columns showed stable hysteretic behaviour to large drift ratios. Ou et al. (2009) tested four PSCs under cyclic loading. Different amount of internal ED bars was used in the columns. The ED bars were unbonded near the joint between the bottom segment and the footing to avoid stress concentration. It was found that the equivalent viscous damping ratio of the columns with ED bars ranged from 16% to 22%, while the value for the column without ED bars was 6% at the drift ratio of 5%. The ED bars were effective to increase the ED capacity of the PSCs. Ou et al. (2010) further investigated the PSCs with high performance ED bars. The high-performance ED bars had larger strength, higher ductility and better corrosion resistance as compared to the normal steel bars. The results demonstrated that the column with high performance ED bars have similar drift capacity and energy dissipation as that of the column with normal ED bars, but unbonding of ED bars was required for the normal steel ED bars while it was not necessary for the high-performance ED bars. Eliminating the unbonding step could save labour work and improve the corrosion resistance of the ED bars. Cai et al. (2018) adopted hybrid normal strength and high strength steel as the ED bars. It was found the energy dissipation of the column with hybrid ED bars was comparable to that of the column with normal strength steel bars. The use of high strength steel could increase the post yield stiffness and reduce the residual displacement, which could potentially reduce the maximum seismic response of the PSC. Bu et al. (2015) tested PSCs with and without ED bars and compared their performances with a monolithic column. The equivalent viscous damping ratios of the column with and without ED bars reached 9.7% and 4.9% at 6% drift ratio, respectively. Similar studies on PSCs with internal ED bars were conducted by other researchers around the world, such as Davis et al. (2017), Shim et al. (2017), Cha et al. (2018), Nikbakht and Rashid (2018), Nikbakht et al. (2015), Zhuo et al. (2019), Tong et al. (2019), Wang et al. (2018b), Jia et al. (2020b) and Shen et al. (2021). Similar conclusions were obtained, namely, it could increase the energy dissipation capacity of the PSC. It should be noted that in general the use of ED bars increases the energy absorption capacity but also increases the residual deformation because of the plastic deformation of the ED bars. Therefore, as discussed above, a careful analysis is needed to determine the choices of ED bars to achieve the best overall performances of the segmental columns.

2.3.2 External ED

Though the internal ED bars were proved to be effective to improve the ED ability of the PSCs from the above review, it should be noted that they were difficult to replace if they were damaged after strong earthquakes. To address this problem, different external ED devices have been proposed. Steel plate was a commonly used one. For example, as shown in Fig. 7a, Chou and Chen (2006) proposed external



(a) Chou and Chen 2006 | (b) ElGawady and Sha'lan 2010 | (c) Li et al. 2019a

(d) Guerrini et al. 2015 | (e) Nikoukalam and Sideris 2021a, Liu and Palermo 2020 | (f) Zhang et al. 2022 | (g) Han et al. 2019

Fig. 7 External ED devices

ED devices made of steel plate and stiffeners. It was found the column with and without external ED devices had 9% and 6% equivalent viscous damping ratios, respectively, demonstrating the effectiveness of using the ED device to increase the ED capacity of the PSCs. Similar external ED devices were also used by ElGawady and Sha'lan (2010) as shown in Fig. 7b. It should be noted that, generally speaking, the residual displacement of PSC could be increased when ED devices are added due to the possible buckling of the devices. Li et al. (2019a) proposed using tension-only external ED plates to improve the ED capacity of the PSCs (Fig. 7c). Compared to the other ED devices, this tension-only ED plate could avoid the buckling problem of the device, leading to the smaller residual displacement. Another type of external ED device was made by machined steel bar. In some of the studies (Zhang et al. 2021a; Moustafa and ElGawady 2018; Thapa and Pantelides 2021), the machined steel bars were installed to the PSCs directly with tension only design, while in some other studies (Guo et al. 2015; Guerrini et al. 2015; Marriott et al. 2009, 2011), as shown in Fig. 7d, the machined steel bars were encased in steel tubes to avoid global buckling, acting like a small BRB. In the latter design, epoxy was commonly used to fill the gap between the steel bar and the steel tube. To avoid the grouting step, in references (Mashal and Palermo 2019; Nikoukalam and Sideris 2021a, b; Liu and Palermo 2020), the inner steel bars were machined with grooves without reducing the diameter of the machined portion as shown in Fig. 7e. Zhang et al. (2022), designed replaceable energy dissipation connectors for the precast column. As shown in Fig. 7f, the core plate (REDC-CP) could deform and dissipate energy when the column was subjected to cyclic loading, the restraint plates and filling plates (REDC-RP, REDC-FP) made the core plate buckling resistant, forming a buckling resistant and replaceable

external ED system. Similar design (Fig. 7g) was also adopted in a precast self-centering double-column rocking piers (Han et al. 2019). The bridge bent with such innovative design showed excellent self-centering ability and energy dissipation capacity.

2.3.3 Rocking-sliding column system

Except for the ED devices reviewed above, another hybrid sliding-rocking PSC was proposed in (Sideris et al. 2014a; Salehi et al. 2017, 2021a; Valigura et al. 2020) to improve the energy dissipation ability of the column. In their design, sliding was allowed at the interfaces between the joints. The internal unbonded tendon were used to provide the column with restoring force and special design was made for the joints. As shown in Fig. 8, the bottom joint between the footing and the base segment was designed to be rocking-domain and the other joints between the segments were designed to be slip-domain. For the slip-domain joints, a thin layer of silicone material was used to achieve a small surface contact friction coefficient, which made the surfaces able to slide under lateral loading. The test results demonstrated that sliding at the joints contributed to most of the responses when the drift ratio was small (3%), and the equivalent viscous damping ratio was about 30%. For larger drift ratios (3-10%), rocking dominated the response of the column and the equivalent viscous damping ratio was about 17% at 10% drift ratio. Overall, it was found that the sliding between the segments significantly contributed to the energy dissipation of the column. Further study was carried out to investigate the seismic performance of the sliding-rocking columns under torsional and biaxial loading (Salehi et al. 2021b).

3 Shake table tests on PSCs

For the papers reviewed in the above section, cyclic load was applied to the PSCs. In order to investigate the real seismic performance of PSCs, shake table tests have been carried out to better understand their dynamic responses under seismic excitations. In 2009, Yamashita and Sanders (2009) conducted shake table tests on a 1/4

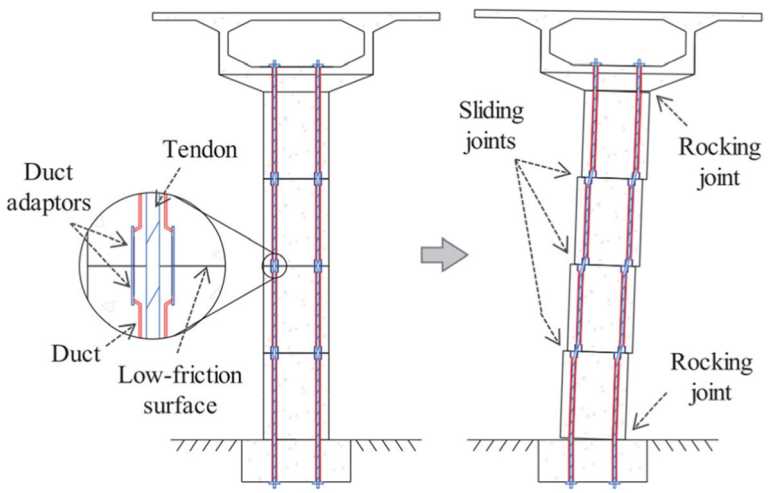
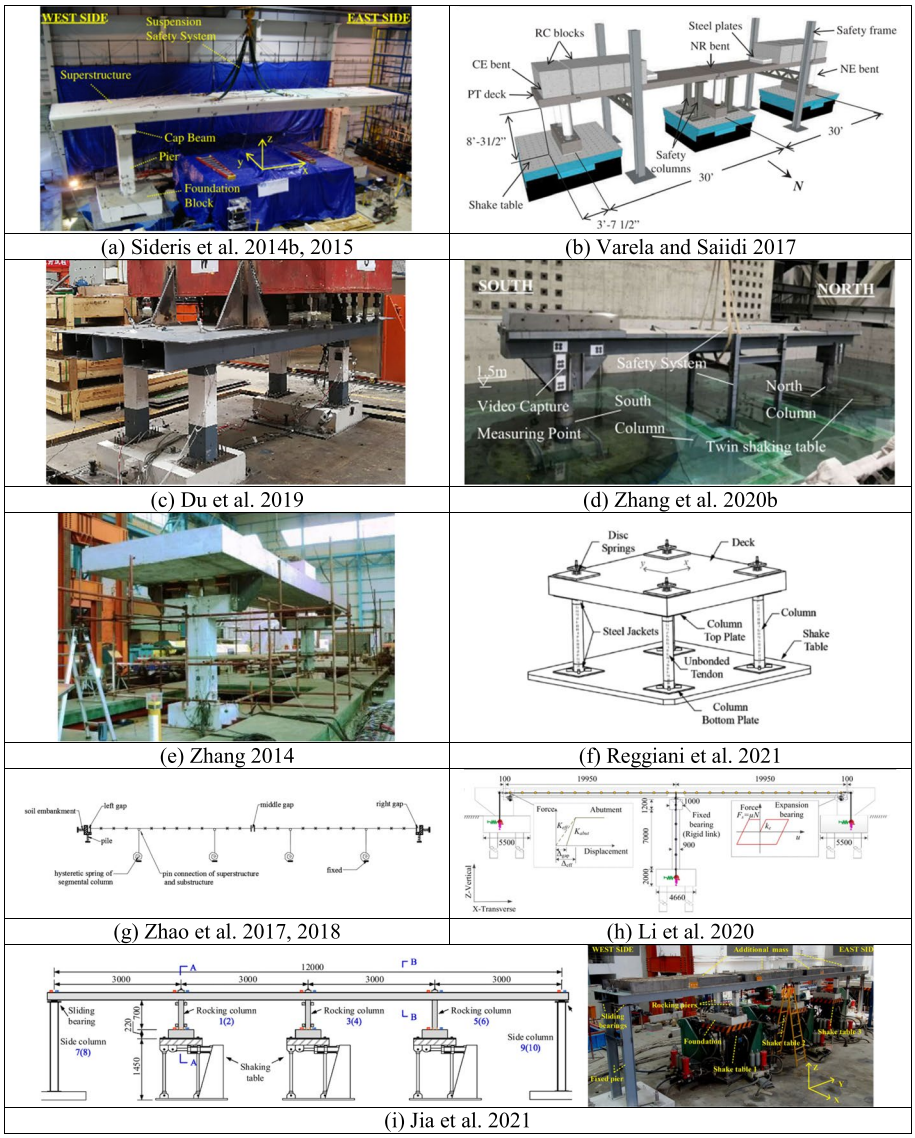


Fig. 8 Concept of sliding-rocking PSC (Salehi et al. 2021b)

scale PSC model on the shake table. The column had the geometry dimensions of 1016 mm × 457 mm × 2082 mm (length × width × height). The column was subjected to a series of excitations with increasing PGAs. It showed minor damage at the base segment after all the tests, which could be easily repaired. Due to the existence of the post-tensioned unbonded tendon, the column had very small residual displacement. Motaref et al. (2010, 2013) carried out shake table tests on a series of PSCs with the bottom segments made of concrete, rubber, FRP wrap, and ECC. It was found that the tendon provided continuity for the segments and reduced the residual displacement of the column. The rubber pad minimized the damage of the column and improved the energy dissipation of the column. Both the FRP wrap and ECC could minimize the damage of the concrete and improve the ductility of the column. Varela and Saiidi (2016a, b) tested PSCs with replaceable plastic hinge segments. The replaceable plastic hinges were made of rubber and NiTi SMA or ECC and copper–aluminium–manganese SMA. The columns were subjected to near-fault earthquake motions. No apparent damage was found in the columns and the residual displacement was less than 0.5% when the maximum drift reached 7%. Moustafa and ElGawady (2018, 2020) carried out shake table tests on double skin FRP-concrete-steel PSCs. Near fault excitations were used in the tests. It was found the RC column experienced severe damage and had 1.5% residual drift after the tests while the PSCs had minimal damage due to the confinement of the FRP and the residual drift was only 0.08%. Li et al. (2019b) tested a monolithic and a PSC column on shake tables under biaxial excitations. It was found that: (1) with the increased ground motion level, a lot of tensile cracks were found distributing along the monolithic column, while the precast segmental column suffered minor concrete crushing mainly at the joint between the footing and the bottom segment. (2) the variations of the fundamental period of the segmental column were much less as compared to the monolithic column, which indicates that the segmental column experienced less damages under the same levels of earthquake excitations because there was no tensile damage to concrete segments. (3) at the same ground motion level, the lateral drift responses of the precast segmental column were similar to those of the monolithic column when the PGAs were small. With the increase of the ground motion level, the precast segmental column had larger drift responses due to the joint openings. (4) significant twisting was found in the segmental column under bidirectional earthquake excitations, which could be attributed to the insufficient friction between the segments to resist the torsional moment induced by the bidirectional earthquake inputs. Therefore, shear keys between the segments were proposed and investigated through numerical simulations.

4 Bridge with PSC piers

Most previous studies focused on the seismic performance of single PSCs. Very limited studies investigated the responses of full bridge system supported by PSCs, and these studies are summarized in this section. Sideris et al. (2014b, 2015) proposed a hybrid sliding-rocking segmental bridge system in 2014 and investigated its seismic performance through shake table tests (Fig. 9a). The test results demonstrated that the joint sliding caused some concrete spalling damage at the joints and it dissipated a lot of energy during the tests. Varela and Saiidi (2017) carried out shake table tests on a large-scale (1/4 scale) bridge system with replaceable plastic hinges made of low-damage



(a) Sideris et al. 2014b, 2015 (b) Varela and Saiidi 2017

(c) Du et al. 2019 (d) Zhang et al. 2020b

(e) Zhang 2014 (f) Reggiani et al. 2021

(g) Zhao et al. 2017, 2018 (h) Li et al. 2020

(i) Jia et al. 2021

Fig. 9 Previous studies on the seismic responses of PSCs-supported bridge systems

materials (Fig. 9b). It was found that all the nonlinear behaviours were concentrated in the replaceable plastic hinges and the other components such as the cap beam, the column and the footing remained elastic. Du et al. (2019) carried out shake table tests on a single span freestanding rocking bridge system (Fig. 9c). The top and bottom parts of the columns were strengthened by steel boxes with a thickness of 5 mm. The column experienced minimal damage and negligible residual displacement after multiple excitations. Zhang et al. (2020b) carried out underwater shaking-table tests on a quarter-scaled single-span bridge with segmental concrete-filled steel tube columns (Fig. 9d). The bridge was subjected to natural and artificially simulated ground motions with different amplitudes. The seismic performances of the bridge with and without water were compared. The presence of water was found to reduce the acceleration response of the superstructure. Zhang (2014) carried out both cyclic tests on PSCs and shake table

tests on a bridge system with PSCs (Fig. 9e). Steel fibre reinforced self-consolidating concrete (SFRSCC) was used to construct the segments. It was found that the bridge system with SFRSCC segmental column had limited damage and almost negligible residual displacement under earthquake excitations. Reggiani et al. (2021) carried out shake table tests on a resilient bridge system with precast columns (Fig. 9f). Springs were used underneath the anchorage system of the tendon anchor. The springs increased the flexibility of the system. Only minimal damage was observed even at the drift ratio of 20%. Zhao et al. (2017) investigated the seismic responses of two-span bridge systems with PSCs and monolithic columns through numerical simulations, and poundings between different components of the bridges were taken into consideration in the simulations (Fig. 9g). It was found that pounding could reduce the bridge peak responses and residual displacement especially for the traditional monolithic bridge. Moreover, when the gap size is small, bridge with monolithic columns experiences more number of poundings. When plastic deformation occurs, the bridge with segmental columns suffers more number of poundings. The influence of spatially varying ground motions was further investigated by Zhao et al. (2018). It was found that the understanding of the influences of spatially varying ground motions on the traditional monolithic bridges can be applied to the segmental column-supported bridge structure. Mantawy et al. (2019) developed a new numerical modelling strategy to model the debonded reinforcement in PSCs in Opensees by incorporating a fatigue material with the reinforcement steel model. The strategy showed excellent agreement with the measured responses. Li et al. (2020) simulated a two-span bridge system with conventional monolithic RC column and PSC column with UHPC segments under earthquake motions (Fig. 9h). It was found the residual drift of the bridge with PSC column decreased about 80% and the peak drift demand increased about 17%. Li et al. (2022) carried out numerical studies on the seismic responses of PSCs-supported bridge structures subjected to near-fault ground motions. It was concluded that the influence of permanent ground displacement on the PSCs-supported bridge is not evident but it could significantly influence the traditional monolithic columns-supported bridge. It was also found that, for the monolithic columns-supported bridge, the largest structural response occurs when resonance occurs. For the segmental columns-supported bridge, generally speaking, the longer pulse results in larger structural responses. Very recently, Jia et al. (2021) tested a bridge system with rocking columns on a shake table array (Fig. 9i). It was found that the proposed bridge system with rocking columns had excellent seismic performance. It experienced limited damage and residual displacement. Also, the bridge with rocking columns had stable dynamic characteristics.

5 Overturning behaviours

Another aspect related to PSC is its overturning behaviours. The corresponding researches were mainly focused on the rocking column, i.e., only one segment was considered. Very systematic research works have been carried out in this area. Due to the page limit, this paper does not aim to provide a comprehensive review on this area, but just briefly summarizes the history of the relevant researches. Interested readers can refer to some review papers, e.g. the one presented by Makris (2014a), for more details.

The analytical study on the seismic response of slender, freestanding columns was presented by Milne (1885) as early as in 1885. However, it was Housner (1963) who found the foundation for this research area. After that, very systematic studies have been performed by different researchers especially by Makris and his co-workers. In the early ages, the freestanding single column was considered. Two overturning modes (i.e., overturning with and without impact) for a free-standing block under cycloidal pulses was identified based on the analytical analyses, and the safe region of the block was determined by solving the minimum overturning acceleration spectrum (Zhang and Makris 2001; Makris and Zhang 2001; Makris and Vassiliou 2012). As discussed above, prestressed tendons are normally included in the PSC/rocking column. Vassiliou and Makris (2015) investigated the influence of the stiffness and prestressing force of prestressing tendon on the rocking response of a slender column, and it was found that the vertical tendons were effective in suppressing the response of small columns subjected to long-period excitations. As discussed in Section 2, the energy dissipation capacity of PSC/rocking column is minimum. Moreover, as demonstrated in the previous studies (e.g. (Zhang and Makris 2001; Makris and Zhang 2001; Makris and Vassiliou 2012)), it has insufficient rocking stability. To overcome this problem, ED devices have been added to the free-standing column, and Housner's classical model has been developed to take the ED devices into consideration (e.g. (Dimitrakopoulos and DeJong 2012a)). Later on, the superstructure was added to the solitary column, and rocking frame was considered. Analyses (e.g. (Makris and Vassiliou 2013; Makris 2014b)) revealed that the dynamic rocking response of a rocking frame can be identical to the rocking response of a solitary free-standing column with the same slenderness but larger size. It was also concluded that the heavier is the freely supported cap beam, the more stable is the rocking frame. Similar to the solitary rocking column, prestressed tendons and/or ED devices have also been added to rocking frames, and the roles of tendons and dampers in improving structural stability were validated (e.g. in (Makris and Vassiliou 2015; Dimitrakopoulos and Giouvanidis 2015)). Recently, some novel vibration control devices such as inerters have been added to resist the rocking responses of both the rigid and flexible rocking structures (Thiers-Moggia and Málaga-Chuquitaype 2019, 2020). It was found that inerter is an effective technology to improve the stability of flexible rocking structure. It is worth noting that most of the above studies are based on the dimensional analysis, in which the responses are related to the orientations of the involved physical quantities. In order to obtain more universal results, dimensionless analysis has also been developed (e.g. (Dimitrakopoulos and DeJong 2012b)). It was found that when the parameters of the system (the rocking structure) and input are expressed in the appropriate dimensionless-orientationless groups, the rocking response of the structure becomes perfectly self-similar for slender blocks and practically self-similar for non-slender blocks (Dimitrakopoulos and DeJong 2012b).

6 Future development

Though many studies have been carried out to investigate the seismic performance of the PSCs as reviewed above, more studies are still necessary. The following aspects may deserve further investigations in future studies.

6.1 New materials and construction details

6.1.1 New materials

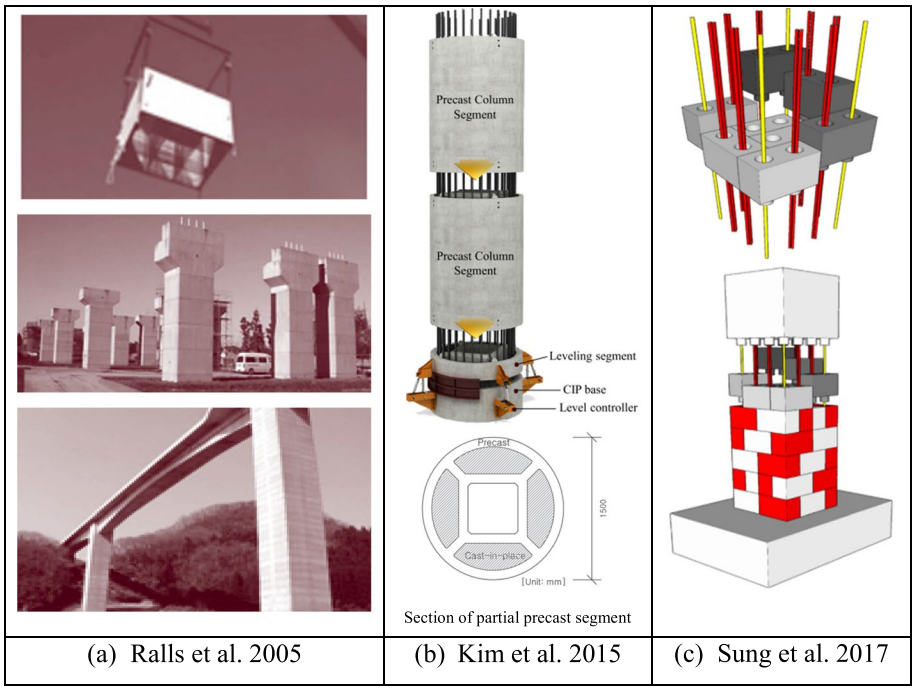
Since the PSCs have multiple joints, corrosion of the reinforcement, ED bars and unbonded tendon remains a concern when they are used in coastal areas with aggressive environment. FRP bars and tendons can potentially replace the steel rebars and tendons in the PSCs. Stainless bars may also be another choice to replace the normal steel rebars. Recently, Jia et al. (2022) investigated the PSCs with GFRP and stainless bars as the continuous longitudinal reinforcement. Guo et al. (2015) adopted BFRP tendon instead of steel tendon in the PSCs. It was found that the BFRP tendon could meet the requirements of PSCs in providing the column with restoring force. Slight slip was found between the glue and BFRP tendon in the anchorage system of the tendon. Therefore, ensuring a reliable anchorage for the FRP tendon is critical for its applications in the PSCs. However, the PSCs with FRP tendon under seismic excitations have been rarely investigated, and more investigations are needed.

Due to the innate mechanical advantages, SMA could provide both restoring force and energy dissipation capacity for the PSCs. Applying SMA in PSCs is attracting more interests in structure engineering recently (Zareie et al. 2020). Tazarv and Saiid Saiidi (2015) adopted NiTi SMA bars in the plastic hinge region of the precast columns. It was found the SMA bars significantly reduced the residual displacement compared with that of the monolithic column. Varela and Saiidi adopted copper–aluminium–manganese SMA (Varela and Saiidi 2016a) and NiTi SMA (Varela and Saiidi 2016b) in the plastic hinges of the precast columns. Baker et al. (2018) applied SMA bars in a real life bridge column for the first time.

For the concrete material, as reviewed in the previous sections, UHPC and ECC have been used in the PSCs (Tazarv and Saiidi 2015). The cost for these materials is however high compared to the normal concrete. Combining these materials with normal strength concrete in the PSCs can potentially improve the performance of the column while maintaining the cost acceptable. Environmentally friendly material such as geopolymer concrete (GPC) can be also applied in the PSCs to form a seismic resilient, environmentally sustainable while economic-effective structure type. For example, Hao et al. (2020) adopted GPC to construct the segments and BFRP as prestressed tendon, and tested them on the shake tables. It was found that the column with GPC and BFRP had comparable performance as the PSC with ordinary concrete and steel reinforcement. Hassanli et al. (2017) adopted crumb rubber concrete in the PSCs. It was observed that with the strengthening of FRP wrap, the column with crumb rubber concrete showed stable hysteretic performance and good ductility. The negative effect of rubber particles on the concrete was less obvious in the structural level.

6.1.2 New construction methods

Apart from the advanced new materials, new construction methods have also been proposed. As shown in Fig. 10a, Sumitomo Mitsui Construction Company in Japan used precast segmental panels as the formwork for the post-cast core concrete to shorten the construction time of bridge piers (Ralls et al. 2005). Kim et al. (2015) proposed a partial PSC with cast-in-place (CIP) base. As shown in Fig. 10b, the base of the column was CIP while the upper part of the column was constructed by the partial precast hollow



(a) Ralls et al. 2005 (b) Kim et al. 2015 (c) Sung et al. 2017

Fig. 10 New PSC construction methods

circular segment. According to the cyclic test results, the column showed good ductility and energy dissipation capability. Sung et al. (2017) proposed a PSC constructed with modular segments (as shown in Fig. 10c). This block-stacking concept included multiple segments which were interconnectable. Such design kept the segments small, which made it more convenient and easier for transportation and erection. The concept was examined by carrying out cyclic tests on two specimens with RC shear keys or steel-bar shear keys between the segments. The test results demonstrated that both types of the column showed stable ductility and low residual deformation.

6.1.3 Connections between the precast elements

In the precast column, different methods have been proposed to connect the prefabricated elements. In general, they can be categorized into two major design concepts, the "emulative connection" and the "non-emulative connection". For the emulative connection method, the concept is to design the precast column with similar performance as the traditional cast-in-place monolithic column. The emulative connection has various types of construction details, including the post-cast wet joint connection, grout-filled connection and socket connection. Figure 11 shows different types of the connections. As shown in Fig. 11a, the wet joint connection needs on site preparation, concrete pouring and curing during the assembling process, which weakens one of the most important advantages of the precast construction, i.e., time saving. Therefore, the grout-filled connection was proposed to addresses this shortcoming. As shown in Fig. 11b, corrugated duct or grout splice sleeve were used in the grout-filled connection. Socket connection is another type of emulative connection. As shown in Fig. 11c, the column is installed in a reserved socket in the

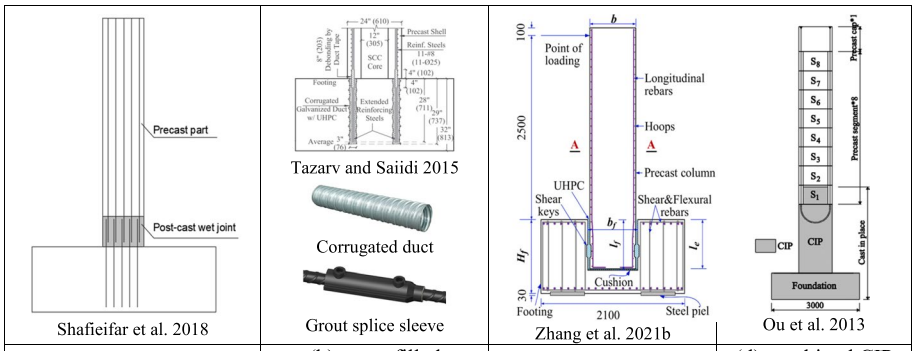


Fig. 11 Different types of the connections

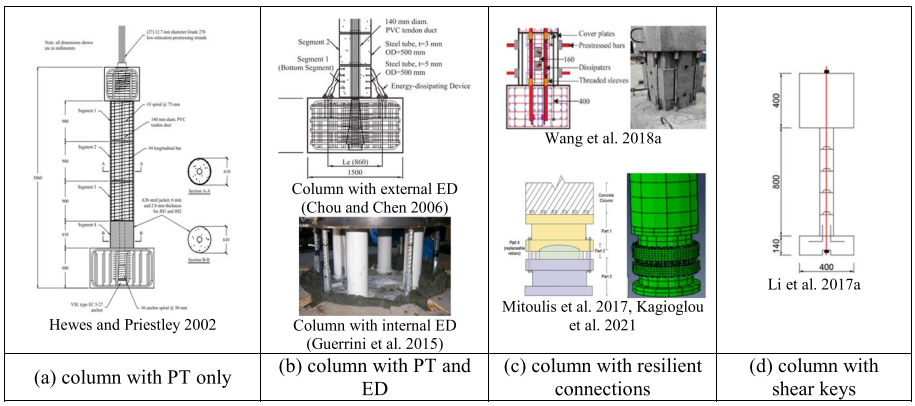


Fig. 12 Different types of non-emulative connections

footing and high-performance grout is used to fill the gap between the column and the socket (Zhang et al. 2021b). According to the previous studies, the columns with the properly designed emulative connections could achieve similar hysteretic responses as monolithic column (Popa et al. 2015). Ou et al. also combined the precast segments with the cast-in-place parts to form a emulative connection (Ou et al. 2013). In their design, as shown in Fig. 11d, the lower part of the column was cast together with the footing and the upper segments were clamped together with the cast-in-place region by U-loop post-tensioned strands. The motivations of such designs were to emulate the seismic behaviour of a traditional monolithic column and take the advantages of precast structures.

For the non-emulative connection, the precast column is normally cast separately with the footing and the column is allowed to rock against the footing. The precast segments are normally connected to the footing with post-tensioned tendons. Figure 12 shows the designs of the non-emulative connections. In the early stage, no ED bars were used in the column (Hewes and Priestley 2002) and it was found the column had limited energy dissipation capacity (Fig. 12a). Internal ED bars or external ED devices were then proposed to increase the energy dissipation capacity of the precast columns (Fig. 12b). Recently, to mitigate the damage of the bridge pier

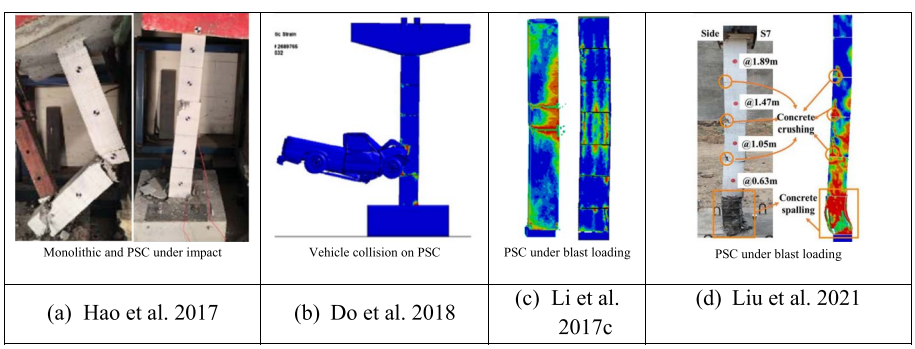
and also improve the post-earthquake retrofitting ability, earthquake resilient designs were proposed in the precast columns with non-emulative connection. As shown in the upper figures in Fig. 12c, a connection with internal ED bars and cover plates was developed by Wang et al. (2018a). Both the ED bars and cover plate can be replaced after being damaged during a strong earthquake. However, during the test, the cover plates fractured due to the buckling of the internal ED bars, which need further optimizations. The bottom figures in Fig. 12c show another design to achieve earthquake resilience that was proposed by Mitoulis and Rodriguez Rodriguez (2017) and Kagioglou et al. (2021). In the design, a novel hinge was placed between the footing and the column. The damage of the column under earthquake loadings was mainly concentrated at the hinge, specifically, the rebars that can be replaced easily. For the shear resistance of the precast columns, it is commonly believed that the friction between the precast segments is enough to resist the lateral loading under seismic loading, however, based on the cyclic tests and shake table tests carried out by the authors of this paper, shear slip and residual twisting could occur in the column without shear keys. Therefore, as shown in Fig. 12d shear keys between the segments were proposed and investigated (Li et al. 2017a).

6.2 Behaviours under other extreme loadings

During the service life of the precast bridges, they may suffer not only earthquake loading, but also other extreme loadings such as impact loading (e.g., caused by vehicle collision) and blast loading (e.g. caused by terrorist attack). Though many studies have been carried out to investigate its seismic performance as reviewed above, studies on their performances under other dynamic loadings are limited. This section briefly reviews the performances of PSCs under the impact and blast loadings. More comprehensive research works in these areas are necessary. Moreover, all these studies considered one dynamic loading only (i.e., either earthquake loading, or impact loading or blast load), no study investigates the resilience of PSCs-supported bridges subjected to multi-hazards. More studies in this area are also needed.

6.2.1 Under impact loading

Hao et al. (2017), Zhang et al. (2016a, b, 2018a, b) and Zhang and Hao (2019a, b) carried out a number of impact tests on PSCs with different designs (as shown in Fig. 13a). These were the first systematic studies on the impact performance of PSCs.



(a) Hao et al. 2017 | (b) Do et al. 2018 | (c) Li et al. 2017c | (d) Liu et al. 2021

Fig. 13 PSCs subjected to extreme loadings

A monolithic column was also tested as the reference. For the PSCs, different designs, including the number of segments, the use of concrete shear keys between the segments, the shape of the shear keys and strengthening with BFRP wrap, were considered in the experimental studies. In general, it was found that the segmental column was flexible than the monolithic column (Zhang et al. 2016a). Openings could develop between the joints when the column was subjected to high level impact. Due to the posttensioned tendon used in the PSCs, the PSCs had smaller residual displacement as compared to the monolithic column (Zhang et al. 2016a). Less damage was found in the PSCs as compared to the monolithic column (Zhang et al. 2016a). Concrete shear keys were effective and critical to improve the shear resistance of the PSCs under impact loading, but large size shear keys could cause stress concentration thus more concrete damage (Zhang et al. 2016b). Such stress concentration could be mitigated by using domed shape shear keys instead of the trapezoidal shape shear keys (Zhang et al. 2018b). The effect of impact locations was also investigated, it was concluded that the impact locations affected the damage modes and response of the PSCs. Flexural bending, bending-shear, shear dominated failure modes were observed when the columns were impacted at the mid-span, at the joint between the two bottom segments, and impacted on the bottom segment, respectively (Zhang and Hao 2019a). Based on the impact tests, Do et al. (2018) carried out numerical studies on the PSCs under impact loading. The effects of segment number, prestressing level and the concrete strength were investigated. Steel tube confinement was proposed by Do et al. (2019a) to mitigate the damage of the PSCs under impact loading. As the shear force could cause tendon fracture, multiple steel shear keys were proposed at the two bottommost joints, which were found effective in reducing the shear force in the tendon. It should be mentioned that according to the shake table test results and numerical simulations from Li et al. (2019b), residual twisting could occur to the PSC under biaxial earthquake excitations and could be mitigated by multiple steel shear keys. Therefore, to improve the shear resistance between the segments and to avoid stress concentration, multiple steel shear keys are recommended in the design of PSCs. The performance of the PSCs subjected to truck impacts was investigated by Do et al. (2019b) (Fig. 13b) and Wu et al. (2021). It was found that the damage of the monolithic column was more severe than that of the PSCs. The damage of the PSCs concentrated more in the segments where the vehicle directly impacted, while more distributed damage occurred to the monolithic column. The use of ED bars and CFRP wrapping to strengthen the PSCs under impact loading was investigated by Xue et al. (2021). It was found adding ED bars and using CFRP to wrap the segments could improve the impact performance of PSCs when the impact location was on the segment while the strengthening methods became less effective when the joint was impacted.

6.2.2 Under blast loading

Li et al. (2017c) carried out numerical studies on the PSCs under blast loading (Fig. 13c). The PSCs with/without shear keys and ED bars were simulated and investigated. The influences of the prestressing level, number of segments on the dynamic performance were also studied. It was found that spalling damage occurred to the concrete of the monolithic column, while less damage was found in the PSCs due to

the fact that joint opening, slippage and rotations of segments could absorb the blast energy. Liu et al. (2021) conducted field tests on PSCs under blast loading Fig. 13d. It was observed that the PSCs had localized failure in the segments where the explosion directly faced. In comparison, more distributed cracks along the column were found in the monolithic column.

7 Summary

The precast segmental column (PSC), as a typical type of prefabricated structural component, can overcome the shortcomings of traditional cast-in-place monolithic columns such as the excessive concrete damage and steel reinforcement yielding and buckling in the plastic hinge regions and thus large residual displacement. Moreover, it can save the construction time, improve the construction quality and reduce the environmental impact. PSCs therefore become more and more popular. This paper comprehensively reviews the seismic performances of PSCs and PSCs-supported bridge structures. The overturning behaviours and the behaviours of PSCs subjected to the impact and blast loadings have also been briefly summarized. The possible future developments are also discussed. The following conclusions can be obtained:

(1) PSCs have very good self-centring ability due to the adoption of prestressed tendon. Compared to the bonded tendon, unbonded posttensioned tendon is recommended. To address the possible corrosion problem of unbonded tendon, FRP tendon can be used as an alternative to the steel tendons, but further studies are needed.
(2) The toes (especially the bottom toes) of the segments in the PSCs normally experience large compressive stress due to the joint opening, which causes concrete crushing and spalling damage under seismic loadings. The use of steel jacket, FRP jacket, UHPC and ECC, and rubber or PU can effectively minimize the damage of the segments.
(3) Energy dissipation capacity of the PSCs can be improved by adding internal or external ED devices. The external ED devices are recommended as they can be easily replaced after damage. Internal SMA bars are also helpful in increasing the ED ability of the PSCs. New structural system with sliding joints has been proved to be effective in increasing the ED capacity of the PSCs.
(4) Shake table tests on the PSCs and studies on the PSCs-supported whole bridge structure are relatively limited. More researches are needed to comprehensively understand the real dynamic behaviour of PSCs and PSCs-supported bridge structures.
(5) Advanced new materials have been used in the PSCs to improve their seismic performance. New construction methods were also proposed to achieve specific purpose. Combined use of new materials and construction methods can possibly form earthquake resilient and environmentally friendly PSCs.
(6) The overturning behaviours of solitary freestanding rocking columns, rocking columns with prestressed tendons and ED devices, and rocking frames have been comprehensively investigated. The rocking isolation can be an effective seismic protection strategy.

(7) Studies on the PSCs under other extreme loadings such as impact and blast are relatively limited. It was generally found that the PSCs experienced less damage and the damage was more localized as compared to the monolithic column under impact and blast loadings. To better understand the performance of the PSCs under these extreme loadings, more studies should be carried out.

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Declarations

Competing interests
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