State-of-the-Art Review of Seismic-resistant Precast Bridge Columns

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ABSTRACT

Accelerated bridge constructions reduce on-site construction time and minimize the impact on transportations. Precast components have been extensively used in bridge superstructures and slowly transferred to substructures in low seismic regions. There have been significant research efforts on seismic-resistant precast bridge columns, however, the research results have not been transferred to industry to achieve their full potential. This review provides a summary of the research development and challenges for both researchers and practitioners. Three types of rocking columns are reviewed: emulative column, simple rocking column, and hybrid rocking column. Discussions on the application of new materials are presented as well. It is believed that hybrid rocking columns are the most prominent option comparing with the other two types. Upon a review of test results, it is suggested an effective stiffness ratio of 20% to 40% can be used for the design of precast rocking columns. To transfer research results to applications, more detailed design standards are to be developed for use by design professionals. A design standard that allows engineers to demonstrate strength and toughness of precast rocking column through analysis rather than experimental evidence would expand its applications in seismic regions.

Keywords: Precast column, post-tension, seismic design, accelerated bridge construction, hybrid rocking structure.

INTRODUCTION

Accelerated bridge construction (ABC) is playing increasingly important roles in modern transportation networks. ABC has been used in the U.S. [1], Canada [2], New Zealand [3] and many other countries [4]. The philosophy of accelerated construction is "get in, get out and stay out" [5], which aims at reducing construction time and costs. Although costs on small ABC projects may be higher than conventional construction at some stage [6], this is expected to be changed as more projects are built with ABC. The benefits of ABC also include improvements in safety, quality, durability, social costs and environmental impacts [7]. The use of precast columns is still relatively rare in high seismic regions. This is mainly due to the fact that seismic behavior is highly sensitive to the characteristics of the connections [8] of the earthquake-resisting systems. In seismic design, superstructures are designed elastically, however, substructures are typically designed to undertake plastic deformations, which require special seismic detailing. Among the 100 ABC projects recorded on ABC-UTC Project Database [9], 28 projects used precast pier components (e.g. columns and caps), 73 projects used precast abutments or walls, 74 projects used precast girders or deck panels.

When connections are properly detailed, precast concrete columns are excellent candidates for ABC in high seismic regions. This paper categorizes precast columns into three types based on their connections: emulative column, simple rocking column, and hybrid rocking column. Emulative columns are designed to achieve performance comparable to that of cast-in-place (CIP) monolithic elements [8, 10]. Simple rocking columns are designed to rock/rotate significantly in seismic events. The column and footing are cast separately without bonding in between but are connected using unbonded post-tensioned [PT] tendons. In such a system, rocking response releases the large moment demand to adjacent members. Hybrid rocking columns [11] are designed to achieve a balance between emulative and simple rocking column. The hybrid rocking column is reinforced with both unbonded PT tendon and continuous rebar, therefore, named as "hybrid". At the column-footing interface, the rebar, which is designed to yield under design earthquake, is typically unbonded to avoid strain concentration. Many researchers named the yielding rebar as energy dissipating (ED) bars [12]. The advantages of hybrid rocking columns are the improved energy dissipating capacity from ED bars, and relatively small residual displacement since the tendons are designed elastically. The three types of precast columns can be comprised of a single precast element or multiple segments. In situations where there is transportation or pre-fabrication constrain for large columns, segmental constructions can be the solution. However, it is normally preferred to use as fewer segments as possible to accelerate on-site construction. Segmental PT columns in the forms of simple rocking and hybrid rocking are illustrated in Figure 1 and Figure 2.

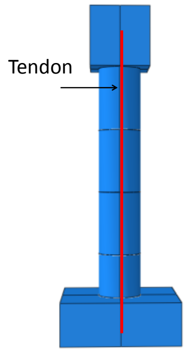

Figure 1. Simple rocking

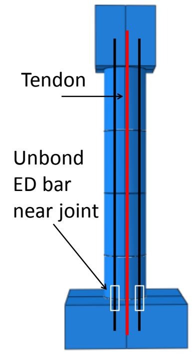

Figure 2. Hybrid rocking

EMULATIVE COLUMN

Emulative columns are designed to perform essentially like monolithic CIP concrete columns. A number of emulative connections suitable for ABC were evaluated by Marsh [13]. The connections are typically in the form of grouted, socket and coupled connections [14-17]. PT tendons may or may not be used in emulative columns. Emulative connections can be further divided into ductile and strong connections. Structures with ductile connections are expected to yield in the connection regions. Structures with strong connections are expected to yield outside the connection regions. In the design of emulative connections, special attention should be given to the development length of reinforcement, ductility and strain concentrations, such that the connections perform as intended. Figure 3 and Figure 4 illustrate typical grout-fill and socket connections. Two emulative segmental columns were tested by Mashal, White [18]. One of the columns had a square section with grouted connections. Another specimen had a circular section with socket connections. It was concluded that although both connections showed slightly pinched hysteresis loops, the energy dissipation was satisfactory and met the expectation of emulative connections. Coupled ductile and strong connections are shown in Figures 5a and 5b. For coupled connections, the couplers may be placed either in the column portion or footing portion [19, 20]. Most of the design codes do not permit using couplers in plastic hinge regions with an exception of Utah Deportment of Transportation [19]. Saiidi, Tazarv [21] suggested that prohibition of coupler in plastic hinge regions should be relaxed based on their study of five types of coupler: shear screw, headed bar, grouted sleeve, threaded and swaged. The coupled connections can also be used when smart materials such as shape memory alloy are used in plastic hinge regions and mild steel used elsewhere [22, 23]. Application of precast column is not limited to shallow foundations, it can also be used in deep foundations [24]. Tran et al. [25] tested the deep foundation splice shown in Figure 6 under quasi-static loads. It was concluded that if adequate transverse steel is provided in the splice zone, the plastic hinge would form in the column. Recommendations for transverse steel design were provided by the authors. In the connection regions, ultra-high performance concrete (UHPC) is frequently used due to its high strength and bonding behavor. Tazarv and Saiidi [26], Shafieifar et al. [27], Ameli et al. [28] and Parks et al. [29] investigated UHPC and grouted splice sleeves in achieving emulative behaviors.

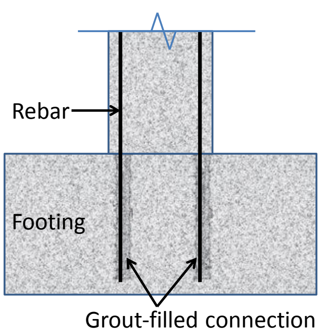

Figure 3. Grout-filled connection

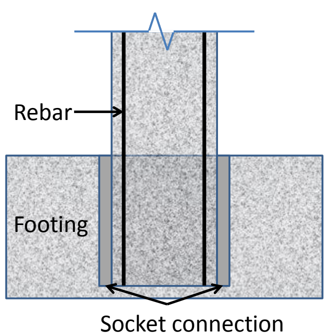

Figure 4. Socket connection

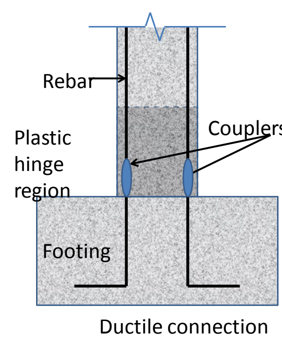

Figure 5a. Ductile coupler connection

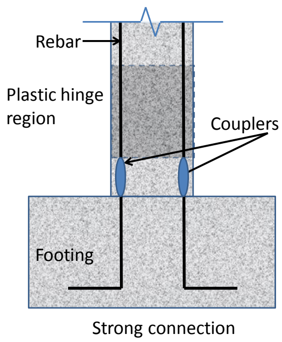

Figure 5b. Strong coupler connection

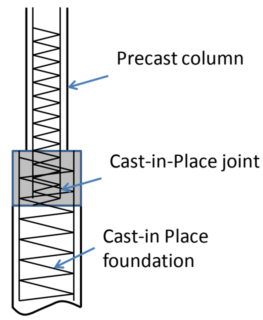

Figure 6. Deep foundation connection

The research and design code on emulative structures are relatively established. A number of large scale research projects have taken place. For instance, some of the large research projects are the testing of a five-story precast concrete building (PRES project) in the U.S. [30], testing of two full-scale building structures in Japan [31] and testing on a full-scale 3-storey precast concrete building (SAFECAST Project) in Europe [32]. Design guidelines on emulative connections are well documented in references such as PCI Design Handbook [33] and ACI-318 [34]. The design philosophy of emulative columns is similar with traditional monolithic columns.

SIMPLE ROCKING COLUMN

Simple rocking columns can be categorized to two types, which are unrestrained simple rocking column and restrained simple rocking column. This paper refers free standing column (with only vertical support) as unrestrained simple rocking column (Figure 7). Columns with PT tendons (but without ED bar) are referred as restrained simple rocking column (Figure 8). Unrestrained rocking columns were first studied by Housner [35], who proved that blocks with larger geometry were more stable. In AASHTO [36], rocking foundations are defined in the category of Permissible Earthquake-Resisting Elements that require owner's approval. A set of design criteria is described in the appendix of AASHTO [36]. Unrestrained rocking columns have many distinct characteristics that cannot be represented by Single-Degree-of-Freedom (SDOF) structures, as demonstrated by Makris and Konstantinidis [37]. For unrestrained rocking columns, the restoring force is from gravity, rather than bending stiffness. The stiffness of an unrestrained rocking column is negative when rocking is initiated, whereas for a SDOF, the stiffness is positive. The dynamic behaviour of unrestrained rocking column is determined by the geometry and gravity acceleration. For flexible rocking columns, the rocking response is coupled with flexural deformations. Vassiliou et al. [38] studied rocking responses of deformable columns and suggested that the stability of large cantilever columns would not be reduced by deformability.

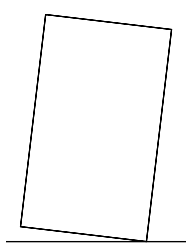

Figure 7. Unrestrained rocking column

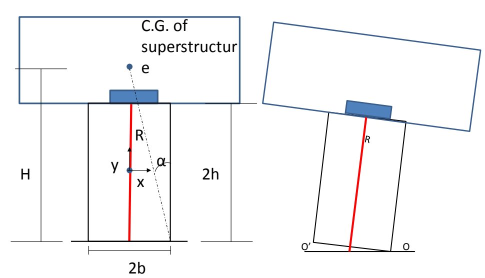

Figure 8. Restrained rocking column

To make unrestrained rocking columns more stable, vertical tendons anchored to foundation can be used to form restrained rocking response. The formulations of restrained rocking responses were studied by a number of researcher [39-41]. PT force delays the initiation of rocking. During rocking response, the PT force also provides re-centering force. Makris and Vassiliou [42] demonstrated that the use of vertical tendons can change the stiffness of rocking column from negative to positive. However, the effectiveness of tendons reduces as the geometry of column becomes larger. This is because rotational inertia is proportional to the square of the column size, which would provide most of the re-centering force for large columns.

Mander and Cheng [43] performed theoretical and experimental studies of simple rocking columns. The authors suggested limiting axial load ratio to 10% (including gravity and prestressing effects) to delay damages. Shaking table tests of simple rocking frame with two columns was conducted by Cheng [44]. It was reported that up to at least 5% rotation, there was little damage or residual deformation. Hewes and Priestley [45] tested four segmental concrete column and each of the columns was tested twice. In the first set of tests, cyclic loads were applied to specimen with a low PT prestress. Then, the specimens were repaired and tested again with higher PT prestress. It was found that thicker steel jackets helped reduce damage. Specimens with thin jackets showed higher energy dissipation, which might be contributed by concrete crushing in thin jackets. The authors suggested that the axial load ratio should be limited to 20%. Finite element models of the test specimen were developed by Dawood et al. [46] and Zhang and Alam [47]. Hollow rectangular segmental columns in shaking table tests were carried out by Yamashita and Sanders [48]. Shaking table test of segmental columns were also tested by [49]. Sideris et al. [50-51] performed shaking table tests and quasi-static cyclic testing of segmental column with sliding-rocking (HSR) joints. In the tests, both sliding and rocking at the joints were allowed. It was observed that the rocking dominant joints provided better re-centering capacity than sliding dominant joints. It was also found that near-fault motions resulted in larger deformations compared with far-field motions [52].

The disadvantages of using simple rocking columns are the relative low energy dissipation associated with high displacement demand, less reliable shear transfer mechanism and less redundancy compared with monolithic columns. The low energy dissipation is due to the flag-shaped hysteretic behaviour since the structure essentially remains elastic. In such situations, oscillations may continue after earthquakes causing low-cycle fatigue effects [53]. The excessive displacement demand may significantly damage bridge joints, adjacent structures as well as non-structural components. In terms of shear transfer relying on friction, it is not reliable when frame action significantly reduces compression at exterior columns, it is also less reliable when vertical acceleration causes uplifts. In ACI-318 [34], it states that connections that rely solely on friction caused by gravity shall not be permitted. It may be a challenge to meet current code requirements using simple rocking columns for new structures.

HYBRID ROCKING COLUMN

Hybrid rocking columns are characterized with both unbounded tendons and continuous energy dissipating bars (ED bars) as shown in Figure 2. The opening of the joint and energy dissipation are controlled using ED bars. The amount of ED bars should be adequate to provide energy dissipating capacity, at the same time, the strength of ED bars should be smaller than tendons such that the columns show self-centering behavior. Although current design codes do not contain design guidelines for hybrid rocking column, ACI-318 [34] permits novel columns if testing results meet ACI-374 [53] criteria. ACI-374 [53] specifies the detailed testing procedures for structures not fully satisfying the prescriptive requirements of ACI-318 [34]. The main criteria for cyclic loading up to 3.5% drift are: a) strength degradation shall be within 25%; b) relative energy dissipation ratio shall not be less than 1/8; c) secant stiffness from drift of -3.5% to 3.5% shall not be less than 5% initial stiffness. It should be noted that even structures designed as per ACI-318 [34] may not meet the requirement of ACI-374 [53], the latter has more stringent requirements. Hybrid connection design for buildings are defined in ACI-550.3 [54], which specifies design requirement for special frames with beams post-tensioned to columns. In this structural system, rocking occurs at beam-column joints. ED bars are used at the joints and are unbonded to avoid strain concentration. This hybrid connection is shown in Figure 9.

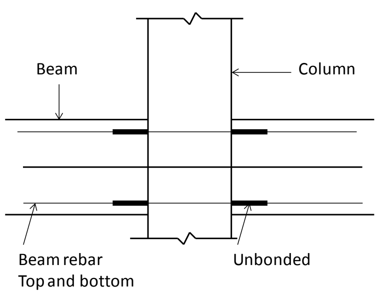

Figure 9. PT moment frame

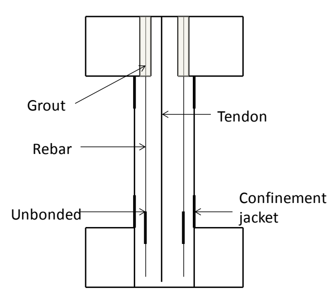

Figure 10. Pre-tensioned hybrid rocking column

Researchers have performed a large number of experimental studies and analytical studies on hybrid rocking columns. The supplemental energy dissipation of hybrid rocking column was achieved using internal mild steel bars or external replicable devices [55]. Hybrid rocking columns under cyclic loadings were tested by Cohagen et al. [56], Ou [57], Wang et al. [58], and Larkin et al. [59] and other researchers. In these experiments, the axial load ratios range from 6% to 25%. The ED bar ratios (ED bar area divided by concrete gross section area) range from 0 to 1.4% and the tendon area ratios (tendon area divided by concrete gross section area) range from 0.15% to 1%. The locations of tendons may be at the center of cross sections or around the parameter. A number of possible details are shown in Figure 10 to Figure 13 [55, 60-62]. Figure 10 and Figure 11 show hybrid column using pre-tensioned and post-tensioned tendons. Figure 12 shows a column with external mild steel ED bar, which can be replaced after earthquake events. Figure 13 shows a segmental construction with shear keys in between segments.

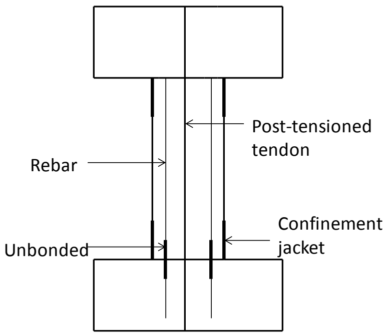

Figure 11. Post-tensioned hybrid rocking column

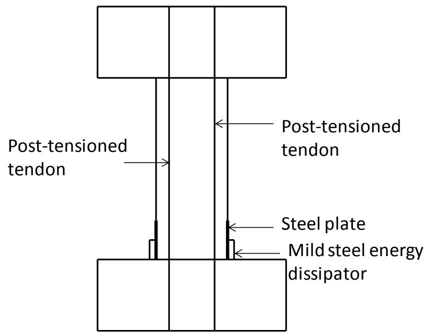

Figure 12. Hybrid rocking column with external ED bar

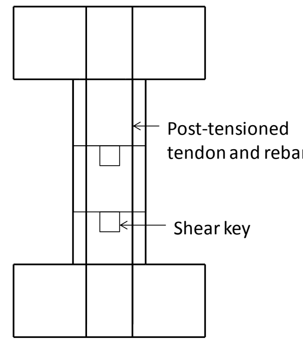

Figure 13. Hybrid rocking column with shear key

The effects of ED bar ratios were investigated by a number of researchers. Ou et al. [63] tested seven large-scale segmental rectangular concrete columns with ED bar ratios of 0%, 0.5%, and 1%. With the increase in energy dissipation capacity, the residual displacement increased. Three of the seven specimens were tested under pseudo-dynamic loading and then followed by cyclic loading to investigate residual strength. Specimens showed decreased stiffness, strength and energy dissipation capacity and even smaller residual drifts. It was explained that the decrease of residual drift may be caused by crushing of the concrete cover. Therefore, residual drift cannot be the only criteria for the seismic performance of rocking columns. It can be misleading when the residual displacement is very small while column residual strength is significantly decreased. Cohagen et al. [56] tested two unbounded PT columns with different ED bar ratios. It was found that the column with PT force show damage earlier than the column without PT force. The damage was mostly due to higher axial compression. White and Palermo [14] compared the performance of one emulative with two hybrid rocking columns. The two hybrid rocking columns were detailed using couplers and socket connections. After the first round of test, the columns were repaired and tested the second time. The authors indicated that the repair methodology requires further improvement to avoid ED bars pullout in subsequent earthquakes. Thonstad et al. [61] conducted multi-shaking table test of a two-span bridge with pre-tensioned hybrid rocking column. It was found that residual drift was within 0.2% when the maximum drift achieved 221% of design motion. The damage was limited to longitudinal rebar fracture and bulging of the column confining tube at 6% drift.

Design suggestions have been proposed by researchers in various perspectives. In terms of damage states, Kwan and Billington [64] proposed two-level design criteria for hybrid rocking column. For the functional level displacement, it was a) displacement at yielding of unbonded PT; b) displacement leading to 1% residual drift; c) 0.7 times survival-level displacement. It was suggested that the yield strain is 0.007 for PT bars and 0.01 for PT strands. The proposed criterion for life safety is the displacement at which the capacity decreases by 10% comparing with the peak capacity. In a subsequent study, Kwan and Billington [65] simplified finite element models of the column to SDOF models. At the same time the authors noted that this approach only covered the fundamental mode shape and different hysteretic under varying axial loading was not considered. The authors concluded that a force reduction factor R of 3 for single column and a reduction factor R of 5 for multicolumn bent would provide high safety margin. Regarding ED bar designs, Ou et al. [66] suggested that ED bar contribution to the column strength should be within 35% of overall strength to limit the residual drift to 1%. The design, modeling, and experimental response of PT column was discussed in Palermo et al. [67]. The displacement based design approach was presented in Ou et al. [12]. Saiidi et al. [60] proposed AASHTO guidelines for design and construction FRP-confined hybrid rocking columns. It was suggested that the AASHTO [68] equation for analytical plastic hinge length of monolithic columns still applies. For columns with more than 1% ED bar ratio, the damping was taken as 5%, which was consistent with monolithic column design [68, 69]. When the ED bar ratio was less than 1%, Saiidi et al. [60] suggested reducing damping to 3.2% since a flag-shaped hysteretic behavior is expected.

CONCLUSIONS

This study categorizes precast columns to three types: emulative column, simple rocking column and hybrid rocking column.

Numerous tests have been done on segmental and continuous PT columns and design suggestions were made by researchers. In most of these tests, strands and large diameter bars were used as PT. Attempts were made using SMA and FRP as PT materials. Supplemental energy dissipating was achieved either using external ED devices or internal ED bars, with alternative materials such as SMA. PT rocking columns are subjected to higher compression comparing with traditional columns due to the rocking impact as well as PT forces. To improve the ductility and to limit compression damage, advanced materials were considered replacing normal weight concrete at the plastic hinge regions, such as ultra-high performance concrete, engineered cementitious composites, and fibre-reinforced concrete. In addition, steel and FRP jackets were also used to provide better confinement thus improve ductility. Based on the testing, researchers suggested limiting total axial load within 10% to 20%.

Upon a review of test results, for columns with ED bar ratios range from 0 to 1.4% and tendon area ratios range from 0.15% to 1%, the effective stiffness to gross section stiffness ratio range from 20% to 40%. Both the lower and upper bound stiffness may need to be checked in designs. It should be noted that as long as the crushed concrete does not hinder the re-entering force of the tendon, the residual displacement would be small, which does not necessarily mean the column is undamaged. Therefore, residual displacement is only one of the criteria for evaluation purpose.

To fully transfer research results to applications, detailed design standards are to be developed for use by design professional. Although hybrid PT columns may be used if meeting acceptance criteria in ACI-374 (2014) based on physical testing, this would require much effort from practitioners. A design standard that allows engineers to demonstrate strength and toughness of rocking column through analysis rather than experimental evidences would expand its applications in seismic regions. In addition, efficient and reliable methods are to be developed for the repair of various supplemental energy dissipating systems.

ACKNOWLEDGMENTS

The financial contributions of the Canadian Precast Prestressed Concrete Institute Graduate Scholarship and The Natural Sciences and Engineering Research Council (NSERC) of Canada through Discovery Grant were critical to conduct this study and are gratefully acknowledged.

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