Committee Report : JCI-TC183A

Technical Committee on Design Concept for Precast and Prestressed Concrete Structural Components including Connections

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Abstract

In structures utilizing the precast (PCa) concrete components, behavior of the connections which consequently exist between PCa members or between a PCa member and cast-in-place concrete is needed to consider adequately in the structural design. This committee has investigated domestic and international design codes and standards and summarized their design concepts. In addition, the evaluation equations and the application for the connections in PCa and non-prestressed reinforced concrete (PCaRC) members, PCa-prestressed concrete (PCaPC) members, and connected PCa members as seismic reinforcements were surveyed. Development of the structural components and new materials which are expected to be applied in the future practice were also discussed. Furthermore, examples of the application of PCa members in the buildings and bridges were investigated and conducted several case studies for a process of the application of PCa components and a trend in the practice of design and construction in Japan.

Keywords: Precast concrete construction, connections, PCaRC, PCaPC, performance assessment, new structural components and materials, design and construction examples, case study

1. Introduction

1.1 Background and Objectives

An application of precast (PCa) concrete components in the construction of the concrete structure is particularly focused on as an effective countermeasure for productivity improvement. In the design, when a structure using PCa components provides performance equivalent to that of

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a cast-in-place concrete structure, and the construction is realized, the designer can assume that the structure using PCa components is designed similarly to conventional monophonic concrete members. In this design concept, it is strongly required that behavior of the connections which consequently exist between PCa members or between PCa members and cast-in-place concrete is adequately considered in the structural design. For these reasons, the design of the connections is an important issue in the structural design using PCa components.

In conventional design procedures for PCa structural components, the structural performance is guaranteed based on the assumption that the structural member using PCa components is equivalent to that of cast-in-place concrete. However, for future development using a new structural system using PCa components, the connections for these structures should be identified, and the members integrated by the connections should be appropriately controlled up to their ultimate state. It is also necessary to control the post-tensioned connections by applying prestressing force, and sufficiently understand the characteristics of the connection up to the ultimate state. From the research background, JCI-TC-183A "Design Methods Technical Committee for Precast and Prestressed Concrete Structures with Connections" (Committee Chair: Dr. Tomohiro Miki (Kobe University)) was established in 2018 focusing particularly on the connections of PCa structural components. This committee conducted practical and multifaceted research and investigations working with academic researchers, designers, practitioners for maintenance of roads and railways, structural design, construction, and new materials developers.

The committee set the following four topics and goals as objectives of research. As for the detailed investigations, the working groups (WGs) were established regarding each research topic. **Table 1** summarizes the member list of the committee and WG related with.

1) WG1 (Codes and standards WG): Ascertaining the status on design codes and standards for PCa structures, gathering information on domestic and overseas design codes and standards for connecting PCa members (between PCa structures and cast-in-place concrete, and between PCa members), as well as their background research data
2) WG2 (Performance evaluation WG): Performance evaluation of connections in PCa structures, clarification of structural performance including connections, and investigation of research tendencies contributing to evaluation of structural integrity
3) WG3 (New structural developments and materials WG): Structures expected to be applied in the future in relation to PCa components, and new materials expected to be applied in the buildings

and civil engineering fields in the future

4) WG4 (Design and construction WG): Investigation of design and construction examples of structural members, structural system, and construction methods that include PCa connections aiming to understand the design and construction details of connections and identifying issues.

This paper outlines the activities of the committee in two years.

Table 1: Committee Composition and WG Member Assignments

			WG1	WG2	WG3	WG4
Committee Chair	Tomohiro Miki	Kobe University	○	○	○	○
Secretary	Yoshinobu Oshima	Nakano Corporation	WG chair	○		
〃	Makoto Maruta	Shizuoka Institute of Science and Technology	Deputy chief			
〃	Masanori Tani	Kyoto University		WG chair	○	
〃	Takashi Takeuchi	Kobe University	○	○		
〃	Hiroshi Sakata	KEN KEN Co,.Ltd.			WG chair	○
〃	Kazumasa Okubo	Kajima Corporation			Deputy chief	○
〃	Yuhiko Ichisawa	P.S.Mitsubishi Construction Co., Ltd.				WG chair
〃	Takeshi Oshiro	West Nippon Expressway Co., Ltd.	○			Deputy chief
Committee Members	Takashi Kitahara	Fuji P.S Corporation		○		
〃	Eiji Koda	Tokyo Rope International INC.			○	
〃	Takashi Kosaka	Hanshin Expressway Co., Ltd.		○		○
〃	Yasuaki Shimada	Oriental Shiraishi Corporation				○
〃	Kuniyoshi Sugimoto	Yokohama National University	○	○		
〃	Toshiya Tadokoro	Railway Technical Research Institute		○		
〃	Keisuke Fukuta	JR West Japan Consultants Company	○			
〃	Shinichi Hori	West Japan Railway Company (from June 2018)				○
〃	Tomoaki Maeda	West Japan Railway Company (up to June 2018)				
〃	Yoshiyuki Matsubara	Sumitomo Electric Industrie s, Ltd.			○	
〃	Hiroshi Murata	Taisei Corporation			○	○
Overseas corresponding member	Hyeong Jae Yoon	N.C.P. Inc.	○	○		

1.2 Definition of Connection

"Connection" in the PCa structures covered by this committee was not merely limited to portion such as the joint surface of different members and the joint surface between the similar structural members, but rather "area (domain)" required for the connections, such as between PCa and PCa or between PCa and cast-in-place concrete. Example of a connection is shown in **Fig. 1**.

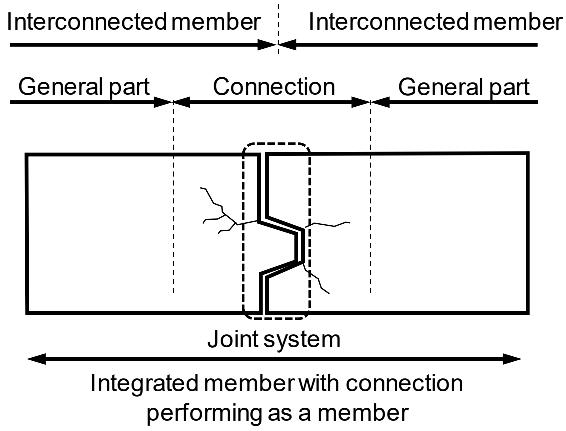


Fig. 1: Example of Connection Region Proposed by this Research Committee

Since there are various manners to consider connections in structural design and construction, no unified evaluation method has been established for the connections in PCa structures. The connection in design can be classified in three different points of view, respectively, as listed in **Table 2**: 1) how to control the member with connection according to the objective structures, acting forces, and resistance mechanism, 2) the performance of members with connections and the modeling of resistance mechanisms at connection surfaces, and 3) concrete condition at joining surfaces and the types of joint system, etc. These are summarized in the next chapter.

Table 2: Concepts of Connections

Design concepts	・Equivalent to integrated structure →Designed to perform as if it is conventional RC structure and PC structure ・Non-equivalent to integrated structure →Design as specific PCa structure considering the effect of connection (modified and applied to design of RC structure and PC structure)
Model of member, performance and resistance mechanism	・Same structural member (axial direction) ・Different structural members (orthogonal direction) ・Structural members joined in cross-section, such as half PCa and PCa synthetic structures
Condition of the joint surface	・Direct connection of PCa members (wet, dry, mechanical, etc.) ・Connection using cast-in-situ concrete

2. Codes and Standards for Precast Connections

Provision and design cases in the domestic design codes and standards were collected regarding the connection of PCa members (between PCa structures and cast-in-place concrete, and between PCa members), as well as research related with the PCa connections. Base on the comparison of codes and standards, the concepts of target members and connection designs are clarified and their features are presented. The codes and manuals in the United States are summarized in **Fig. 2**.

Through the research, it was clarified that, in the building area, when the joints of PCa members are reinforced concrete (RC) structures, the design methods of RC structures can be applied by designing and constructing the connections such to perform as if they are cast-in-place concrete structures. As for the case of PCa structures, the method of estimating the frictional force due to prestressing has also been specified.

On the contrary, in the civil engineering area, in the case of non-prestressed RC structures, a performance equivalent to a cast-in-place concrete structure is guaranteed by satisfying the provisions on the reinforcing bar joints. As for the PCa structures, the connection should not lead to a sudden fracture, although the mechanical effect of connection is not explicitly considered in design.

The difference between building and civil engineering areas may be attributed to the difference in the concepts of safety assurance for the entire structural system. For example, in architectural structures, several connections of skeleton members with a large degree of redundancy and plastic design, and while in civil engineering (bridge) structures, connection of beams and floor slabs is a popular which may provide a small degree of redundancy.

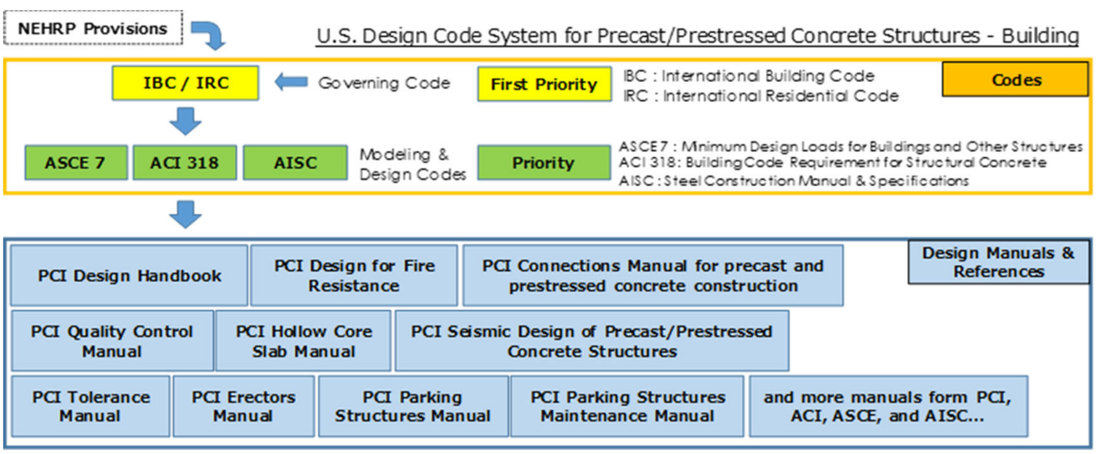
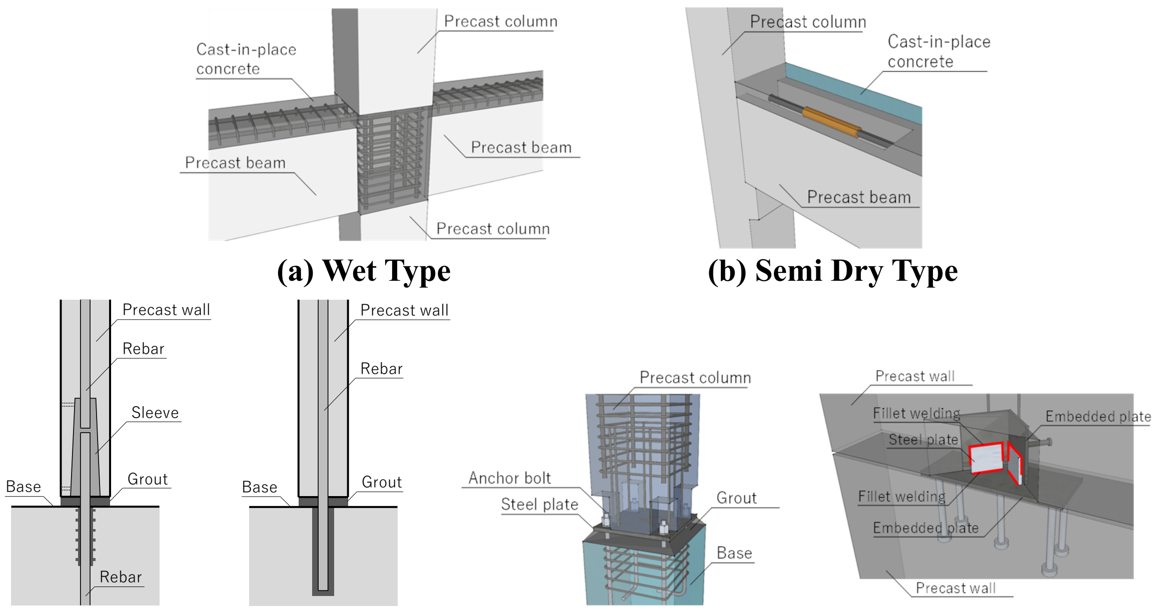


Fig. 2: Design Standards and Manuals for Precast Structures in the United States

In the practice and research in the United States, the connection methods in PCa structures are roughly divided into two types: “emulative” and "jointed" connections. The emulative connection is usually designed to achieve the same performance as an RC structure. In contrast, the jointed connection intentionally produces a nonlinear rotation of the structure through rocking controlled in the surface of the connection. Standards in the United States have been established to realize each concept. **Figure 3** shows the examples of the various splice and connection types used in the United States, and these examples generally are referred to as PCa system include PCaPC, which is a pretensioned system.



(a) Wet Type **(b) Semi Dry Type**

(c) Dry: Spliced **(d) Dry: Sleeved** **(e) Dry: Bolted** **(f) Dry: Welded**

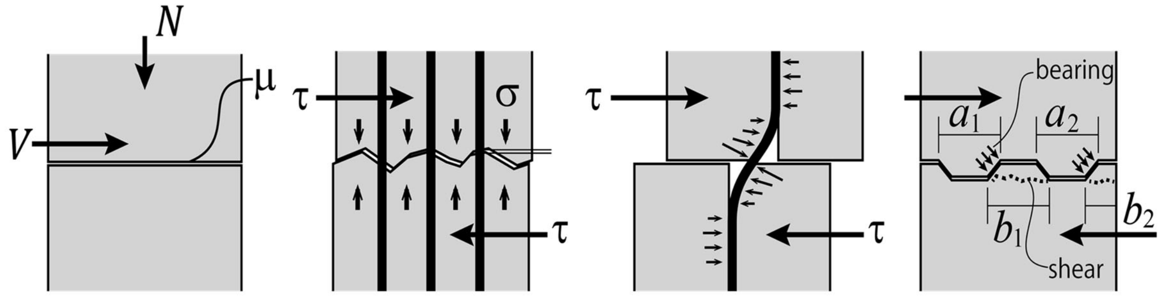
Fig. 3: Examples of Various Splice and Connection Types Used in the United States

3. Resisting Mechanisms and Evaluation Equations on PCa Connections

3.1 Concepts of Performance-Based Design for Connections

Regarding the structural performance evaluation of PCaRC and PCaPC members with connections and seismic strengthening in which PCa members are integrated by prestressing, the basic concept and evaluation equations of stress transfer mechanisms (**Fig. 4**) at connections were explained. In addition, an example of seismic performance evaluation of structures with joints using PCa members in the United States was presented.

From the investigations, it was found that the principal design concepts for performance evaluation of connections were common in the architectural and civil engineering areas. If the



(a) Friction (b) Shear friction (c) Dowel action (d) Shear key

Fig. 4: Resolution of Stress Transfer in Connection Elements

stiffness and bearing capacity of connections are considered to be similar with those of cast-in-place structures, their performance can be evaluated as a monolithic structure. On the other hand, if the stiffness or capacity is considered to be different, their performance can be evaluated by modeling the behavior of the connections appropriately.

In the architectural area in Japan, it is very common to emulate PCa members as equivalent to cast-in-place members. In this design concept, it is assumed that a shear resistance mechanism at the joint interface and ensuring shear capacity against the shear forces acting on the joint based on the guidelines of the Architectural Institute of Japan (AIJ) and other academic societies. On the other hand, in the civil engineering area, since there are many types of members to be manufactured by PCa, and verification of fatigue durability is also strongly required, and structural types and verification items are limited , and evaluation techniques for emulating cast-in-place are relatively maintained. This enables the use of general design tools, such as the certificated structural calculation programs commonly used in the structural calculation of ordinary cast-in-place RC buildings, for PCa construction.

For PCaPC structures in which the PCa members are assembled by post-tensioning, the performance of members can be evaluated considering the effect of the absence of ordinary reinforcement at the connection. The modified evaluation methods of cast-in-place PC structures with ordinary reinforcement are usually applied to PCaPC structures.

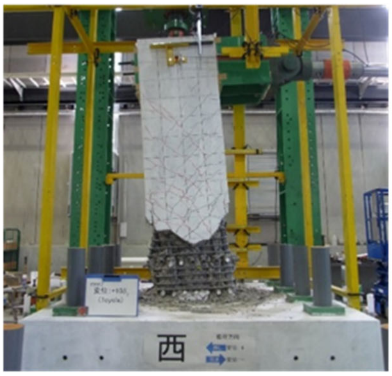
In the civil engineering area, several performance evaluation methods are shown in the provision of the standards and guidelines. However, since the PCa members are applied to various types of structure and have wide variety of verification items, the performance is usually verified based on the limited data obtained by an appropriate model of the connections which are supported by the results of individual verification in the experiments. In the architectural area, the performance verification based on the individual experimental and analytical research is often implemented to develop new construction methods mainly aiming at a construction rationalization to obtain the performance certification of a third-party organization. The developed construction methods can be applied to the actual buildings as they are considered to satisfy the technical standards of laws and regulations by the performance certification.

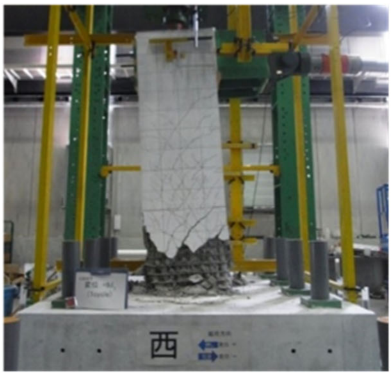
3.2 Required Performance and Evaluation of Connections

In the architectural area, seismic design method of cast-in-place concrete structure has been applied to PCaRC structures in which sufficient stiffness and capacity for the shear and bending acting on the joint are ensured. Shear forces acting on the joint are resisted by friction, shear friction, dowels, shear keys, and bending moment is resisted by using mechanical splices with sufficient strength and stiffness to ensure performance equivalent to that of cast-in-place connections. On the other hand, in the case of PCaPC structures, post-tensioning is usually applied to the connections. In this connection, the opening at the connections is allowed. For the evaluation of flexural cracking capacity and ultimate shear capacity, it is necessary to consider the effect of the existence of connection. The shear force at the connection interface is resisted by the friction in principle.

In the civil engineering area, especially for the PCa segment girders of highway bridges, the shear force acting on the joint key due to torsional moments is designed such as not to exceed a limit value. The shear transfer capacity at the connection is conventionally the sum of the shear capacity of shear key and the friction capacity. In the Specifications for Highway Bridges revised in 2017, the effect of prestressing is considered to calculate the former capacity. Furthermore, regarding PCa floor slabs of road bridges, durability under the fatigue loading is confirmed by a moving wheel loading test, while the loop joints is designed to satisfy the required lap length for the purpose that connections can be considered as monolithic RC sections.

Regarding design methods of connections for moment frame viaducts in the railway structures, since there is no unified design methods and verification methods, the performance verification is alternated by confirming structural performance and fatigue durability through experimental loading tests for specimens simulating the PCa structures to which the PCa construction is applied as demonstrated in **Photo 1**.





(a) At end of No. 1 **(b) At end of No. 2** **(c) At end of No. 3.**

Photo 1: Static-Cyclic Loading Tests on PCa Members with Connections

4. New Structural Components and Materials to be Applied in Near Future

A literature survey was conducted on new structural components and materials which are expected to be applied in the areas of architectural and civil engineering in the near future. Here, the recent literatures on PCaPC construction with connections were collected from papers of the Architectural Institute of Japan (AIJ), the JCI, and the Japan Prestressed Concrete Institute (JPCI). In the architectural area, an investigation of both the R&D stage and practical examples was performed while in the civil engineering area, the R&D examples which have not been actually applied were selected. In the field of architecture, the structural members and structural types were classified as wall members, beam members, column-beam joints, connection surfaces/connections, wall panel systems, prestressing connections, seismic retrofits. In the civil engineering area, the structural type was classified as underground structures, hollow towers/tanks, PCaPC floor systems. Moreover, new materials related to reinforcements and various types of concrete were investigated.

The committee identified several proposals in the architectural area have payed attention on the structural performance of members such as walls and beams. In addition, several studies were focused on rationalization of construction and improvement of structural performance by using unbonded PC structural components and ultra-high strength fiber-reinforced concrete. In the civil engineering area, there were multiple faces of R&D tendencies, such as an improvement of the durability of structures by applying prestressing force to connections and highly durable materials in the severe environment. Regarding new materials, tendencies in the development and application of new materials corresponding to various needs such as high strength and high durability have been identified.

5. Case Studies on Examples in Practice of Design and Construction for Members and Structures with Connections

5.1 Concepts of Investigation on Design and Construction Examples

The committee implemented an investigation of design and construction cases which include members and/or structural components having connections between PCa members, or between PCa members and other members. The purpose of research is to ascertain the design and construction contents and identifying issues related with the PCa connections. The investigation was conducted in both architectural and civil engineering areas regarding the reasons for the development and application of PCa members and structures including connections, and specific contents of the design and construction. Keywords of the investigation was precast, prestressed, assembled by post-tensioning, connections, and joints in the practice cases.

For design and construction cases in the architectural engineering area, a total of 14 cases were classified according to building use (residential buildings, stadiums, mixed-use buildings, logistics warehouses, offices, hospitals, and educational facilities). As for the civil engineering area, a total of 21 cases were presented and classified according to target structures (eight cases: railway bridges, rigid frame viaducts, highway girders, floor slabs, concrete guard fence, bridge piers, box culverts, shield tunnels, and liquefied natural gas (LNG) storage tanks).

5.2 Examples of Design and Construction for Buildings

In the case of residential buildings, an all-PCa construction method was adopted in multiple cases, in which even the beam-column connections were composed of PCa. After assembling the column and PCa beam-column connections, all the main reinforced bars of the column and beam, and joints of the PCa members were grouted with high-strength mortar to rationally construct super-high-rise RC building frames with high quality. **Photo 2** shows the assembly status of PCa members in which beam and column joints were integrated[1).

In the case of stadiums, there was an example in which the PCa method was applied aiming at shortening the construction period and improving the production efficiency of on-site construction. **Figure 5** shows an example of stand framing elevation in the stadium constraction[2). In this case, the construction period was significantly shortened by constructing most of the foundation members using the PCa construction and applying cast-in-place concrete in the limited location.

Photo 2: Assembly Status of PCa Members with Integrated Beam-Column Connections [1)]

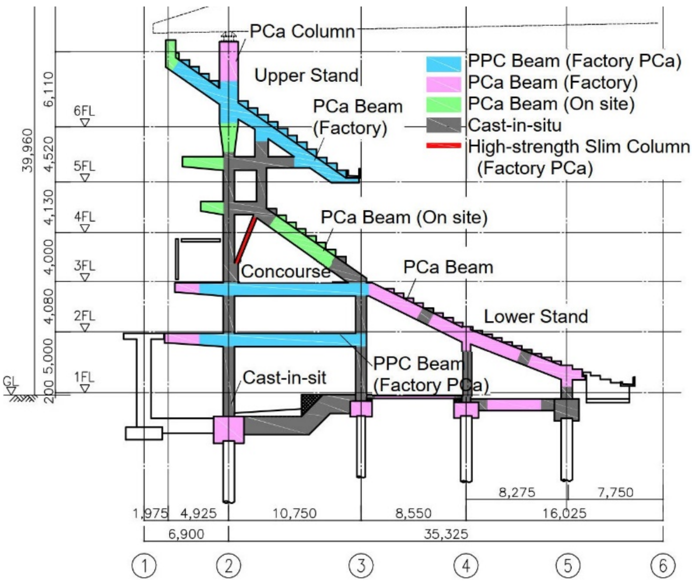


Fig. 5: Elevation Plan of Stand Framing with Partially PC Beams and PCa Members [2)]

5.3 Examples of Design and Construction for in the Civil Infrastructure

The example of construction shown here is a viaduct of the Shinkansen high-speed train network, which was built adjacent to a conventional railway bridge in-service. The structure was a rigid frame viaduct in which all structural components were PCa beams, columns and beam-column connections which were integrated in the construction site. **Figure 6** shows a structural concept of the all-PCa construction in the railway viaduct [3)]. This method was adopted to improve the durability of the structures, shorten the construction period and improve the quality under construction conditions with very severe restrictions.

Another example is a box culvert. In this case, PCa plates were used for the side walls of the box culvert in the construction of an express roadway to save labor works and shorten the construction period. **Figure 7** shows the structural concept of the half-PCa box culvert [4, 5].

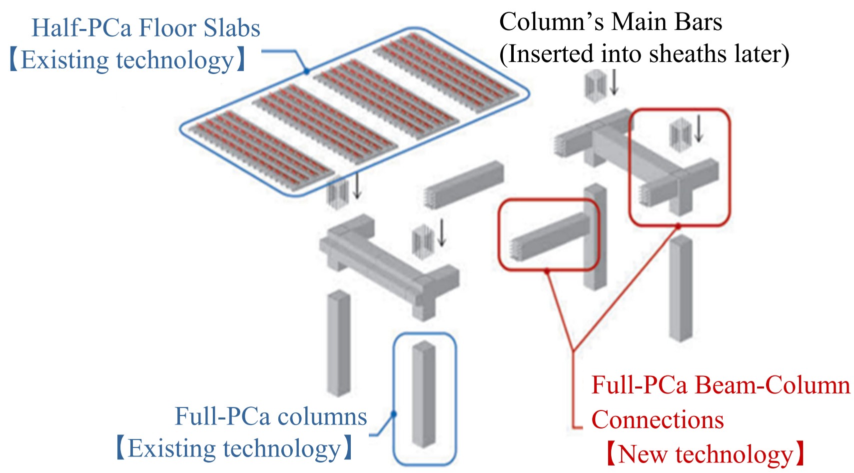


Fig. 6: Concept of All-PCa Construction Method for Railway Viaduct [3]

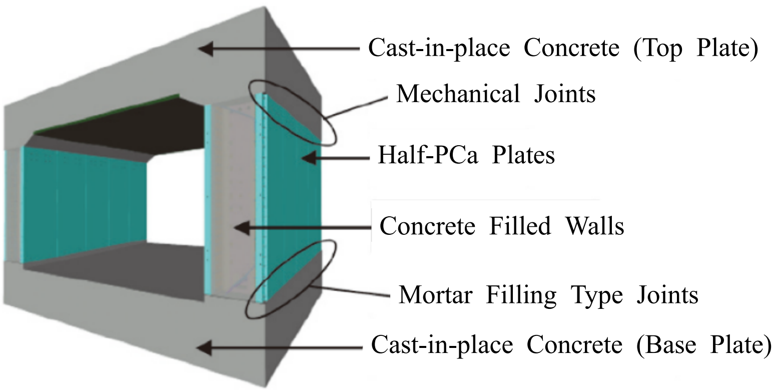


Fig. 7: Structural Concept of Half-PCa Box Culvert [4, 5]

5.4 Case Study Based on Examples of Design and Construction

Table 3 shows a list of reasons for the adoption of the PCa method in the architectural area. The PCa method was adopted in high-rise residential buildings in many cases in which a reduction of costs through the shortened construction periods was realized as a specific measure for reducing construction costs in the business operations of private entities. There are cases of stadiums that adopted PCa members in the foundations and large structural members. In the mixed-use office buildings, super-high-strength concrete and steel members were applied in several cases. However, in the architectural area, especially in urban areas, the situations to use the PCa construction method have not been generalized due to the peculiarities inherent of the method, in which there are restrictions of the transportation and lifting-up of PCa members. In addition, it is necessary in advance to manufacture PCa members in earlier stage of the construction period though the design details have been not set.

Table 4 shows a list of reasons for the adoption of the PCa constraction method in the civil engineering area. The PCa components are adopted for most members if structural types, cross-sectional dimensions, and details are unified, such as railway rigid frame viaducts, shield tunnels, and LNG tanks. There are many cases in road bridges adopting the PCa members as a construction process becomes short in limited and narrow space of constrictions. This is because the uniformity of member dimensions becomes unreasonable in the construction as topography and linearity are

Table 3: Reasons for Adoption of the PCa Construction (Buildings)

Building use	Reasons for adaption / Status of the PCa methods									
	Shortening of a construction period	Labor saving	Reducing costs	Improvement in quality	Improving performance				Harmonization of the surrounding environment	The others
					Usability	Safety	Durability	Conservation performance		
Residential bldg.1	○	○		○						
Residential bldg.2	○	○	○	○					○	
Residential bldg.3	○			○					○	
Residential bldg.4	○		○							
Stadium 1	○	○	○							New materials
Stadium 2	○	○	○	○						Design, Workability
Mixed-use bldg.1	○	○	○	○						
Mixed-use bldg.2					○	○	○			Weight reduction, New technologies
Mixed-use bldg.3		○		○						
Logistics warehouse	○	○	○	○						
Office bldg.1		○		○	○	○	○	○	○	Energy conservation, Design
Office bldg.2					○	○	○			New materials and technologies
Hospital	○	○		○		○				New materials and technologies
Educational facility										
Total amount (14 cases)	9	9	6	9	3	4	3	1	3	6

Table 4: Reasons for the Adoption of the PCa Construction (Civil Engineering)

Civil enginering	Reasons for adaption / Status of the PCa methods									
	Shortening of a construction period	Labor saving	Reducing costs	Improvement in quality	Improving performance				Harmonization of the surrounding environment	The others
					Usability	Safety	Durability	Conservation performance		
Railway viaduct 1	○	○		○			○			
Railway viaduct 2	○	○		○			○			
Railway viaduct 3	○	○		○			○			
Railway viaduct 4	○			○			○		○	
Railway viaduct 5	○	○		○			○			
Highway girder 1	○	○	○	○			○			
Highway girder 2	○	○		○			○	○		Weight reduction
Highway girder 3	○	○								
Highway girder 4	○	○		○		○	○	○		Limitation of girder height
Floor slab 1	○	○		○			○			
Floor slab 2	○						○	○		Restriction of passage
Floor slab 3	○	○	○	○			○	○		
Floor slab 4	○	○		○			○			
Floor slab 5	○	○		○			○			Weight reduction
Concrete guard fence 1	○	○		○						
Concrete guard fence 2	○	○		○			○	○		
Bridge pier 1	○	○		○						Safety of field-work
Bridge pier 2	○	○		○						Safety of field-work
Box culvert	○	○								
Shield tunnel		○				○	○			Improvement in water cut-off performance
LNG storage tank	○	○		○						Safety of field-work
Total amount (21 cases)	20	19	2	17	0	2	15	5	1	8

not usually uniform in the civil infrastructure. Other reasons to adopt the PCa method seem to be a weight reduction of superstructures and a safety assurance in site work construction.

Case studies based on these practical examples of design and construction reveal that a lesson to promote PCa conversion is to understand the merits of PCa construction in the process and costs benefits and consider the construction processes from the beginning of the design stage.

6. Summary and Future Prospects

This committee report presents a summary of a survey of the design codes and standards for PCa members in the civil infrastructure and architectural area in Japan and the United States. The report also summarized the load-carrying mechanisms and equations to evaluate the PCa connections. The trends of recent research and development for the structural components and new materials which are going to be applied in the architectural and civil engineering areas near future were indicated. Moreover, a case study based on design and construction examples was conducted and analyzed reasons for the adoption or development of PCa components including connections in the architectural and civil engineering areas. Based on the research, this committee pointed out the following three respects for the design and construction using PCa structural components.

1) Advantages in the construction using PCa members are assiduously recognized in the design and construction and can be further expanded with efficient design procedures. For example, the standardization of the evaluation method for the connection of PCa members is required. The development of a consistent design computational program considering appropriately the effects of connections is also needed. Standardization of PCa members and PCa construction will realize the automation of structural design and deployment in artificial intelligence (AI) utilization.
2) In an era when workers and specialist engineers are completely insufficient, labor savings, work assistance and/or automation by robots are required. The utilization of PCa members is one of the countermeasures in this issue. The transmission of various types of information during factory fabrication and centralized management of various types of information will be necessary. The platforms such as building information modeling (BIM) and city information modeling are frameworks for information transmission. Moreover, carbon-neutral, reduction of CO2 and other greenhouse gases emissions are also keen issues. Looking at construction sites, it can be considered that the reduction of environmental impacts, such as on-site

arrangement and reduction of waste materials in formworks and other processes during the construction can be contributed to sustainability. Weight reduction of PCa members provides further miniaturization of facilitating transportation and temporary installation. Reducing the total number of workers related to the PCa construction, the risk of work-related injuries may be also reduced.

3) The advantages of multi-faceted PC structural components in the concrete structure can provide design improvement, a reduction of environmental impact, and quality assurance. To integrate the PCa connections, an application of post-tensioned (PT) prestressing is promising. Structural improvement of the connection is also needed such as the application of devices to contribute an energy-absorbing performance. In the United States, the jointed connection was developed to control seismic damage and reduce the residual deformation using self-centering. The sophistication of the level of design for PCa connection differs according to how to control the structural behavior including the connections. Criteria controlling the behavior of the connections in the structural design is needed to be established. At the same time, public support systems for application development of PCa and/or PCaPC constructions, such as education for engineering designers to improve comprehension of PC structures and ordering/dealing operation systems are also required.

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