Committee Report: JCI- TC203A

Technical Committee on the Flexural Behavior of Unbonded Prestressed Concrete Members

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Abstract

We gathered information about unbonded prestressed concrete (UBPC) structures from civil and building engineering in Japan and overseas. We explained the effect of the bond of prestressing tendons on the resisting mechanism and structural performance of the UBPC members and described the methods to simulate the backbone curve. We introduced some applications such as external cable systems for bridge girders and cable-stay brides in civil engineering; and slabs, walls, and self-centering systems in building engineering.

Keywords: Unbonded prestressed concrete (UBPC), backbone curve

1. Introduction

In this technical committee, we focused on the flexural behavior of unbonded prestressed concrete (henceforth, UBPC) members. The external cables have been used since the 1990s for corrosion prevention and efficient maintenance of PT tendons in civil engineering. UBPC members had not been allowed to use in buildings except for secondary members such as slabs in building engineering until the revision of the notification was made in 2007. The PRESSS project in the 1990s[1)] clarified the UBPC system not only simplifies construction but also produces interesting structural performances. We summarized information on the UBPC structural system: resisting mechanisms for flexure and shear, their usage in structures, the accuracy of existing equations for backbone curves, and new methods and equations for backbone curves. All the committee members contributed to the original report and the chair and secretary made a summary in this article.

The technical committee started in April 2020. The chair and three secretaries had the first meeting to discuss a two-year activity policy at the JCI headquarters in June 2020. Face-to-face committee meetings were not held for the next two years due to the COVID-19 pandemic. However, the four WGs held regular online meetings and completed the report. We thank each member for their enormous contributions by listing all 16 members in **Table 1**.

Table 1 List of committee members

Chair： Susumu Kono (Tokyo Inst. of Tech.)	
Secretary： Kazuaki Tsuda (Kindai Univ.) Hiroshi Matsuzaki (NDA)	Kuniyoshi Sugimoto (Yokohama National U.)
【Beam WG】 ○Masanori Tani (Kyoto U.) Mistuyoshi Akiyama (Waseda U.) Kiwoong Jin (Meiji U.)	Sayuri Hashimoto (Pacific consultants) Takuya Kondo (Kochi Nantional College) Kazuaki Tsuda (Kindai Univ.)
【Column WG】 ○Kuniyoshi Sugimoto (Yokohama Nat. U.)	Toshifumi Takeuchi (Kenken) Yoshikazu Takahashi (Kyoto U.)
【Wall WG】 ○Taku Obara (Tokyo Inst. of Tech.) Hiroshi Matsuzaki (NDA)	Hiroto Takatsu(Takenaka Co.) Susumu Kono (Tokyo Inst. of Technology)
【Slab WG】 ○Kazunori Osako (PS Mitsubishi)	Takenori Kawamura (Oriental Shiraishi) Atsushi Takeda (Obayashi Co.)

Note: ○ stands for WG secretary

2. What is an unbonded PC structure?

The reinforced concrete (RC) structure is used as the representative concrete structure. In the RC structure, the concrete bears the compressive stress and the reinforcing bar bears the tensile stress to form an excellent structure that exploits the characteristics of each material. However, in recent earthquakes, there were many cases where large-scale repair or dismantling of damaged RC structures was required. Furthermore, even with small- or medium-scale earthquakes, crack formation in concrete must undergo repairs to prevent decreased durability. However, repair work of structures often imposes restrictions on using the structures, and even greater labor and cost are required for removing finishing materials. The PC structure may avoid seismic damage in economic terms and it can also avoid repairs caused by the damage. **Fig. 1** shows the PC structure that involves a compressive force (pre-stress) application to the concrete to suppress the formation and propagation of cracks. PC structure wherein the bond of PC tendons is intensionally removed is called an unbonded PC structure; we investigated this structure in this committee. The report contains information on the applicable members, construction methods, structural design methods, member structure performance calculation methods, and application examples.

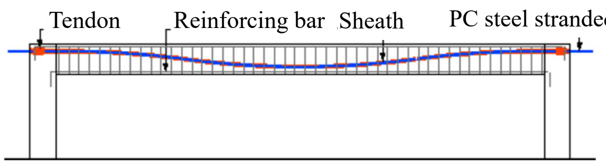


Figure 1 Arrangement of PT tendon in prestressed concrete beam[2)]

3. Applicable structural members

In the civil engineering field, the methods include the inner and outer cable-construction methods (installation inside and outside the concrete skeleton, respectively). The bonded construction method is used for the inner cable construction method, whereas the PC steel material placed in the sheath is presented in a tense state after which the sheath interior is filled with grout. This inner cable construction method is often used for PC bridge girders and used in civil engineering structures. The PC steel materials coated with epoxy resin are used instead of bare PC steel materials to improve rust prevention when adopting the inner cable construction method in regions where special salt damage countermeasures are considered. In contrast, the part where the cable is fixed is separately made of concrete or steel members when adopting the outer cable-construction method. Further, this method is used for the inside of box girders during new construction, the beam part of the bridge girder or column during reinforcement, or fuel tanks and reactor containment vessels for improving the flexural yield strength of the bridge girder and beam.

In the civil engineering field, durability is prioritized; there are hardly any cases where unbonded PC steel is used. Thus, the unbonded PC steel material in the civil engineering field refers to "PC steel stranded wires obtained by applying grease to the steel material and coating it with polyethylene," which is also known as the after-bond construction method. This method involves installing PC steel materials in a polyethylene sheath in advance at a factory and using grease-filled unbonded PC steel materials to avoid inserting PC steel materials in a sheath pipe at the construction site and performing grout work. Therefore, there is less on-site construction work and better workability when compared to the conventional bonded construction method.

In the architecture field, the application examples of unbonded PC steel materials in Japan were collected from the journal of the Japan Prestressed Concrete Institute. Unbonded PC structures were mostly applied to slabs and beams, and there were very few cases where they are applied to structural members. Among the collected examples, only five examples included applications to structural members such as girders and foundation beams: Kinki Post Office Materials Department Warehouse (completed in September 1980), Mitsui Bank Toyonaka Branch (completed in November 1980), Tokyo / Kanto Post Office Materials Department Warehouse (completed in June 1982), Rakusai Takashimaya Store (completed in 1982), and Osaka City Nagai Park Stadium (completed September 1985). All examples were those of cast-in-place unbonded PC structures that used ordinary-strength steel bars, and only the Nagai Park Stadium had a structure that combine the use of unbonded PC steel in SRC beams.

In the report, we collected information on the handling and construction methods of unbonded PC steel in structural design, and we summarized its problems and issues. Examples of use overseas show a slightly wider range of applications than that in Japan, with examples like its use in slabs and PCa walls to prevent bending and cracking, and its use in self-centering systems to realize damage control.

4. Construction method

The construction is conducted following the Specifications for Highway Bridges[3),4)], Handbook for Concrete Highway Bridge Construction[5)], and the standards of each fixing construction method when constructing civil engineering structures. It is necessary to secure space to arrange the tension machine when placing the PC cable under tension. In addition, it is important to secure the space between the fixing parts, arrange the reinforcing bars, and confirm the concrete strength so that the fixing parts will not be crushed during tension.

In the architecture field, the PC steel rods are used when introducing prestressed force to columns. The PC construction method is rarely applied to columns because there could be a further increase of compressive force on the columns, where the weight of the columns always acts from the upper floors. The PC structure is adopted if the PC pressure bonding construction method is used or if the moment strength of the stigma of the long-span part on the top floor where the flexural moment becomes large is secured. However, the bonded PC construction method is used even in such a scenario, and the unbonded PC construction method is rarely used. This is because the unbonded construction method can be legally used only for secondary members. Even today, the entire building needs to be designed following the limit yield strength calculation method; few experimental reports have been published on unbonded PC pillars. There are few cases where unbonded PC tendons are used for the seismic walls of buildings, and therefore, in this report, we introduced the construction of a four-story PC seismic wall building at the 2010 E-defense tests.

5. Status of structural design system

We provide an overview of the current status in the civil engineering and architecture fields about the design standards and guidelines used when designing structures.

5.1 Civil engineering field

We focus on the design systems in the civil engineering field and explain them using the Specifications for Highway Bridges[3)], which is a reference for many design standards for PC tanks and river structures.

The Specifications for Highway Bridges were completely revised in 2017 with the introduction of the limit state design and partial factors design method. A major change focused on reviewing the edition composition (Common Specifications, Steel Bridges, Concrete Bridges, Substructures, Seismic Design) to ensure that the performance required for a bridge can be clarified regardless of what combination is used for steel members and concrete members, instead of dividing the design based on the structural type of the bridge and the main materials used for the superstructure. The adoption of new materials and structures was facilitated by considering variations in load and resistance value, introducing a partial factors design method that can guarantee the limit state of bridges and members is not exceeded for design conditions, and abolishing the conventional allowable stress method.

The revised Specifications for Highway Bridges clarified the performance required for the entire bridge system. Furthermore, both the verification method of the performance of superstructures and substructures for checking the performance of the entire bridge system, and the verification method of the performance of the members that constitutes the superstructures and substructures are hierarchically defined as a combination of the required performance and standard verification method.

Thus, the state of each structure and member for ensuring bridge performance is defined, and conditions corresponding to the limit state of the members are uniformly defined regardless of the material and structural types used, which includes the steel members. Thus, a bridge that satisfies the required performance is realized by expressing the bridge limit states 1‑3 as limit states of the members, in the hierarchy of (limit state of bridges) →(limit states of superstructures, substructures, and their connection parts)→(limit states of members, etc.). Thus, the revolutionary revision point was that this enables a design that flexibly incorporates not only the conventional concrete members and steel members but also composite members and new types of members.

Therefore, the application of an unbonded PC structure to a bridge requires stipulating the limit states 1–3 of the members and determining the partial factors for ensuring the required reliability for those limit states.

5.2 Architecture field

We explained the status of PC building design methods in Japan and the positioning of unbonded PC members. The use of an unbonded PC member as a seismic member requires a limit yield strength calculation (or ministerial approval); a possessed horizontal yield strength calculation is not permitted. The unbonded PC member shows a unique load–deformation relationship in which the yield of the PC steel material is delayed; the deformation that exerts the maximum yield strength is larger than that of the bonded PC member. In the limit yield strength calculation, an explicit evaluation of the response deformation of the building is conducted for verifying not only the yield strength but also the deformation of the unbonded PC member. In this report, we summarized the long-term allowable stress design, and if necessary, the primary design for confirming the allowable stress at the time of introducing prestress as the design required for the unbonded PC structure based on the stress obtained from elastic analysis in addition to the limit yield strength calculation. Through this report, we hope that the understanding of these design methods for unbonded PC will deepen, and that simple design methods will be proposed in the future.

Overseas, the unbonded PC is used on floors of flat slab structures that have a relatively large span of over 7 m. In the United States, unbonded PC steel is used as a reinforcing material for the slab-on-ground method, and it is directly based on the floor laid flat with concrete, without creating an underfloor space. In addition, the unbonded PC construction method can be used to prevent cracks in the PCa wall with openings. The unbonded PC construction method is used to prevent cracks on the PCa wall of multistory car parks, and they have a general precast structure. The use of an unbonded PC member increases strength and stiffness, reduces the number of columns, and achieves a highly economical PCa structure. Meanwhile, with the precast seismic structural system (PRESSS) project[1)] started in the United States in the early 1990s, experimental and analytical research on PCaPC columns/beam joints and PCaPC walls that used unbonded PC was conducted in the United States and New Zealand. These results were presented in the State-of-the-Art Report on The Seismic Design of Precast Concrete Building Structures[6)] compiled by the FIB seismic committee. In New Zealand, Appendix B of the New Zealand standards[7)] (NZS3101: 2006 Part 1: The design of concrete structures) stipulated a PCaPC hybrid system using unbonded PC, and a more detailed design method was reported in the PRESSS Design Handbook[8)].

6. Structural performance calculation method for members

We introduce the structural performance calculation method for unbonded PC structural members. The maturity of establishing the structural performance calculation method varies depending on the part and structure type. There are some areas where research has not progressed considerably, and other areas where there has been relative progress. Therefore, we provide an overview by dividing it into two categories: content summarized by standards and guidelines (6.1), and recent research contents reported by each research institution/researcher (6.2).

6.1 Calculation method in standards

We introduce the calculation methods reported in the academic society standards and guidelines. In the civil engineering field, unbonded PC structures are not often applied to bridge columns even though they use outer cables for bridge girders. In the architecture field, the 2007 notification revision enabled the use of unbonded PC structures for structural members. Therefore, we introduce a method for predicting skeleton curves in the architecture field.

In the architecture field, a required option when using an unbonded PC structure as a seismic member is the limit yield strength calculation method. This method performs the static incremental analysis of structures, and there is a need for evaluating the restoring force characteristics, which includes the nonlinear region of the unbonded PC structural member. The nonlinear restoring force characteristics of the beams and column members that constitute the framework when referencing the Guidelines for Structural Design and Construction of Pre-stressed Concrete Buildings Based on Performance Evaluation Concept by the Architectural Institute of Japan[9)] or the Guidelines for Long-Lifespan Construction of Pre-stressed Concrete Design and Construction[10)] are schematically shown in **Fig. 2.**

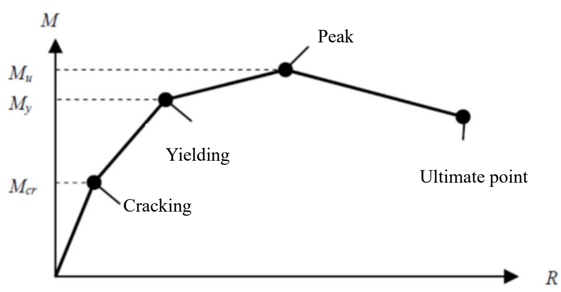


Figure 2 Simplified backbone curve for UDPC member

The skeleton curve of concrete-based members changes because of cracks and flexural yielding; however, the skeleton curve of unbonded members shows an almost identical shape. There are three characteristics of the unbonded PC structural skeleton curve: the first flexural point, which is attributed to the separation of the pressure bonding surfaces; the flexural yield strength point; and the limit deformation point. At the flexural strength point load (moment), the assumption that a flat plane is maintained in the unbonded PC member does not hold, and thus, the issue is identifying how to handle the tension increment of the PC steel member; the accuracy of various methods has been verified.

A method in which the curvature distribution that considers the equivalent plastic hinge length is integrated into the material axis direction and converted to the member deformation angle is used for the deformation at the limit deformation point. For the flexural yield strength point, the strength is set to 90% of the ultimate flexural point, and the stiffness is obtained by applying and expanding the yield point stiffness reduction rate used in RC members. For the limit deformation point, there is a method wherein this point is evaluated as a limit point that can maintain the strength after reaching the flexural strength point. For actual members, the fracture of steel materials, shear fracture after flexural yield, etc., are assumed as limit deformation points; however, the prediction methods for such cases are a topic for future study. A shear design method is required to guarantee the predominance of flexural yield, but unbonded PC steel materials often have a relatively large safety margin if the conventional method is extended and applied with the necessary modifications.

6.2 Examples of research on evaluation methods

More detailed evaluations of the flexural characteristics of concrete-based members include the cross-sectional moment-curvature relationship (cross-section analysis) evaluation method; load-deformation relationship evaluation method that uses a multi-spring model that divides elements in the member length direction to express nonlinearity over the entire length of the member; and the material end spring model method, which is an intermediate model of the above two in which nonlinear springs are integrated at the material end. Such conventional evaluation methods can be expanded and used for unbonded PC members by considering the tension evaluation of PC steel materials and the conformity conditions for the deformation in the total length of the member. We describe the latest research trends related to these topics below.

6.2.1 Evaluation of the restoring force characteristics of beams and wall members

The evaluations of the restoring force characteristics of a cross-shaped or T-shaped frame when constructing a frame by pressure bonding precast beam members includes the restoring force characteristic calculation method that can evaluate the deformation of the member at the characteristic point using the elongation of the PC steel material caused by the concrete compressive strain and separation; they are assumed to be concentrated on the at-risk cross-section[11)] (**Fig. 3**). Meanwhile, evaluations of the flexural yield strength point include the method of evaluating the yield strength that considers the increased strength of the core concrete attributed to the restraining effect of the reinforcing bars, and the method of evaluating the deformation using the tension increment and tension material length of the tension material as variables[12)]. These methods have a better yield strength evaluation accuracy than the conventional methods.

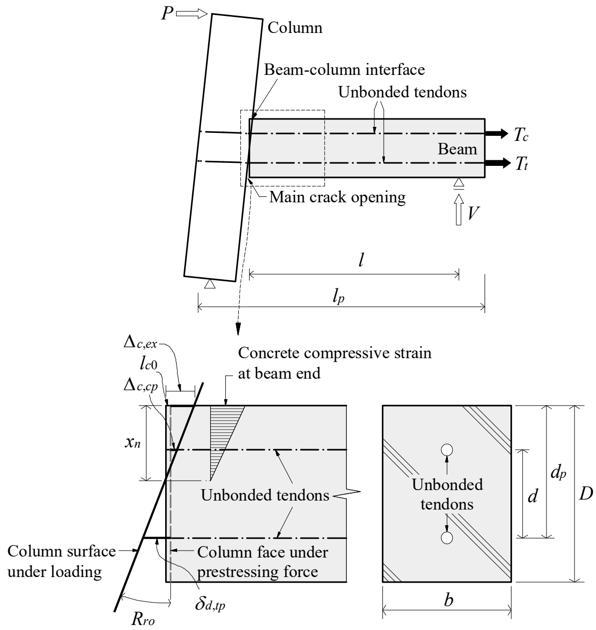


Figure 3 Numerical model for T-shaped beam-column connections[11)]

The methods for evaluating the restoring force characteristics of unbonded PC wall members include methods that provide a multi-spring setup on the wall leg and model the unbonded PC steel material separately[13)]. The wall member has a small cross-sectional width and large depth, and therefore, the evaluation of the extent of concrete restraint and vertical rebar buckling at the wall edge and the evaluation of the equivalent plastic hinge length are different from those of the columns. If such situations are appropriately modeled with an unbonded PC wall, the restoring force characteristics can be properly evaluated up to the ultimate limit.

6.2.2 Design of beam-column joint

We described performance evaluation with a focus on flexural behavior; however, achieving a beam flexural yield-predominant-type frame requires preventing the fracture of other parts. In unbonded PC structures, cross-sectional defects are generated in the through holes of the PC steel material in the joint, and the behavior of the joint should be considered. According to the previous research introduced to verify the accuracy of evaluation equations[14)], the shear yield strength of the beam-column joint becomes low because of the cross-sectional defect attributed to the through holes when using the unbonded PC.

6.2.3 Research examples of civil engineering structures

The bridge girder with an outer cable can be said to be the unbonded PC construction method for civil engineering structures. In addition, research has been conducted on methods that precast the columns and integrate them, and on structural types that improve performance such as high resilience and damage reduction caused by unbonding some reinforcing bars near the column base without introducing prestress and not plasticizing to maintain a stiffness that is relatively high even after the flexural yield. The PC construction method that reduces residual deformation through prestressing, regardless of whether it is the bonded PC construction method or the unbonded PC construction method, is a major advantage.

6.2.4 Durability evaluation

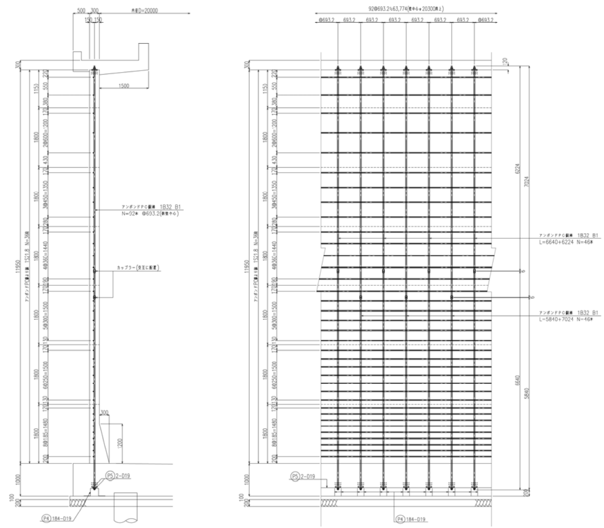
There is no concrete or grout around the PC steel with unbonded PC members. The rust preventive action of the unbonded PC steel material is secured using a resin material such as grease. Exposure tests that focus on durability are conducted based on these different points with RC structures or bonded PC structures that have grout adhesion. Though there are a few examples, there have been reports on the durability of unbonded PC members and structures such as the performance of unbonded PC steel not deteriorating in exposure tests of approximately 10 years and the deterioration status of unbonded structures after approximately 40 years[15)].

7. Application examples

We introduce the application examples of unbonded PC structures to various structures. From the report, we consider the following two examples: farm ponds and PC containment vessels at nuclear power plants.

7.1 Farm ponds

Farm ponds are cylindrical tanks used for adjusting the supply and demand of agricultural water. The construction of the side walls of circular PC tanks for agricultural use with a relatively small capacity involves the use of the bonded construction method for longitudinal prestressing and a combined unbonded PC construction method for transverse prestressing. The PC steel-stranded wire used in the unbonded PC construction method is coated with grease and a plastic sheath. Meanwhile, as shown in **Fig. 4**, there are cases where adopting the unbonded PC construction method for both longitudinal prestressing and transverse prestressing improves workability and decreases cost. In either case, the tension in the circumferential direction is not constant because of the effects of various losses, and therefore, multiple pilasters that fix the PC steel in the circumferential direction are placed to average the prestressing force.



(a) Vertical section (b) Elevation view

Figure 4 Arrangement of PT tendons in a farm pond

The design guidelines of farm ponds[16)] show the measured values of the friction coefficient caused by the angle change that corresponds to the length and arrangement shape of the PC steel material in the unbonded PC construction method; this is then compared to the commonly used values in the United States and the United Kingdom. These commonly used values use smaller values when compared to the actual measurement results of the friction coefficient in Japan.

7.2 PC containment vessels of nuclear power plants

The prestressed concrete containment vessels (PCCVs) at nuclear power plants require long-term monitoring of concrete shrinkage/creep, prestress loss caused by steel relaxation, and steel corrosion. The monitoring conceptualizations differ based on the adhesive properties of the PC steel material[17)].

PC steel materials with adhesive properties are used in France and Canada. The stress acting on the PC steel material cannot be measured if there is adhesion; further, actions such as direct inspection, re-tensioning work, and replacement of defective steel materials cannot be conducted. Therefore, pressure tests that measure the deformation state of the containment vessel under a predetermined pressure are conducted to confirm the structural performance.

Meanwhile, many nuclear power plants in Japan and the United States use unbonded PC steel, as shown in **Fig. 5**[18)]. The direct inspection of the PC steel material is easy because this is an unbonded steel material, and thus, lift-off tests should be conducted at a predetermined time to check if a predetermined tension force is applied. Furthermore, it has the advantage in that it can be easily replaced if a defect or corrosion is found because it is an unbonded steel material.

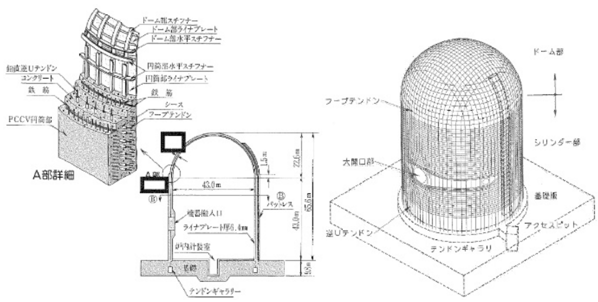


Figure 5 Arrangement of PT tendons in Genkai Nuclear Power Plant[18)]

8. Conclusions

This report summarized the works on the UBPC structures after two-year of committee activities (fiscal years 2020 and 2021).

We summarized the basic characteristics of UBPC structures in Section 2; the basic specifications, advantages, and disadvantages in Section 3; and their construction methods in Section 4, structural design procedure in Section 5, the methods to obtain backbone curves described in guidelines and recent research works in Section 6, and the application examples and research examples in Section 7.

We first anticipated the dissemination of UBPC structures through studies conducted through this committee. However, it was found difficult to realize the UBPC structures immediately as the Response and Limit Strength Calculation design method or time-history analysis should be used to design buildings design, and large capacity PT tendons are not available to fully develop the required member capacity. It is noted that the members are normally determined by the flexural capacity and the accuracy of its calculation method has improved considerably. The backbone curve and hysteresis curves may be simulated with small errors, and the design method has been considerably advanced. Further advances in the research will result in a simplified but better building design before too long. Consequently, we may expect increased demand for UBPC structures, and further development in large-capacity UBPC tendons with good durability. This will result in resolving various problems of UBPC structures. The widespread UBPC structures will allow the realization of undamaged structures/members where only a separation occurs at the joints under earthquakes. As a result, it is possible to provide structural systems to society to maintain their functions and recover quickly after an earthquake.

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