Design and Construction of Tension Chord Structure Using Plate-like Precast Prestressed Concrete Members
— Shirokane-no-oka Elementary and Junior High Schools —

板状の PCaPC 部材を用いた張弦構造の設計と施工
— 白金の丘学園 —


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Synopsis
This paper describes the design and construction of a tension chord structure using high-stiffness and load-resistant plate-like precast prestressed concrete (PCaPC) members. These members are used within a school facility in a single-story large-span gymnasium whose roof is used as an exercise area. The building is located in Minato-ku, Tokyo. In addition to satisfying the structural performance by using circular arc-shaped plate-like PCaPC members as the bottom chord, a structure with a characteristic appearance was realized (**Fig.1**).

Structural Data
Building Area: 7,519.50m^2
Total Floor Area: 17,967.66m^2
Number of Stories: 1 basement level, 6 stories above ground, 1 penthouse level
Maximum Height: 29.7m
Main Structure: Low-rise building, reinforced concrete structure with part PCaPC structure
High-rise building, reinforced concrete structure

1. Architectural Scheme
The site slopes downward to the north west, therefore the two-story low-rise building was placed at the northern foot of the slope along a road. It is here that the "community liaison zone," which includes a gymnasium, hall, and meeting rooms and which is open to the community, was placed, producing a space that links the local community and the school. In addition, a "second ground" was produced by making the rooftop of the low-rise part continuous with the sloping surface, and here the "ground" was placed.

2. Structural Scheme
(1) Overall Scheme
One of the features of the scheme is the use of the gymnasium roof as an exercise area for effective utilization of the site with large differences in level. (**Figs.2**, **3**) In this way, it was possible to arrange the

Fig.1 Tension chord structure

Fig.2 Overall view

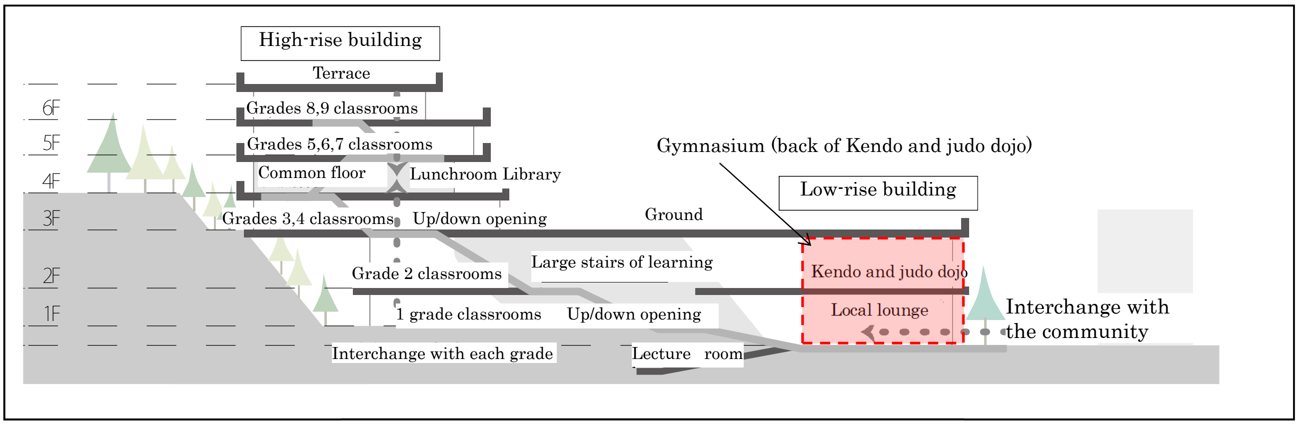

Fig.3 Cross-sectional composition

site with some margin. However, because the roof structure is to be used as an exercise area, in other words a floor on which the children exercise every day, it was an absolute condition that there be no problem with respect to dwelling comfort in the performance of the structure.

Therefore, the bottom chords were not made from cable tension members but from thick band-shaped concrete slabs. By applying an initial tension force (a prestress force), the slabs themselves remain in the compressed state under long-term loads, thereby ensuring stiffness as well as durability. In this way, the frequency of natural vibration is around 4Hz, away from resonance with walking vibrations, and the required performance was achieved.

Another theme of the structure of the gymnasium roof was how to join the large-span two-story low-rise building with the high-rise building that extends over six stories and four stories on the site with a 12m difference in level. Because the plans for the first and second stories were integrated in terms of utilization, the authors wanted to avoid providing a waterproofing line if at all possible. However, the low-rise building has a direct raft foundation (partly on improved ground) and is mainly a wall structure, while the high-rise building is founded on existing concrete piles and has a moment-resisting frame structure with walls. Because the foundations and structures are different, an expansion joint was provided to separate the structures (**Figs.4**, **5**).

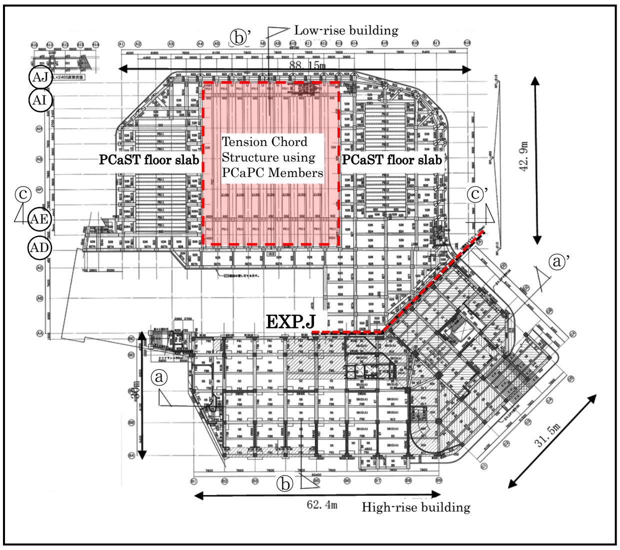

Fig.4 Third-story floor beam framing diagram

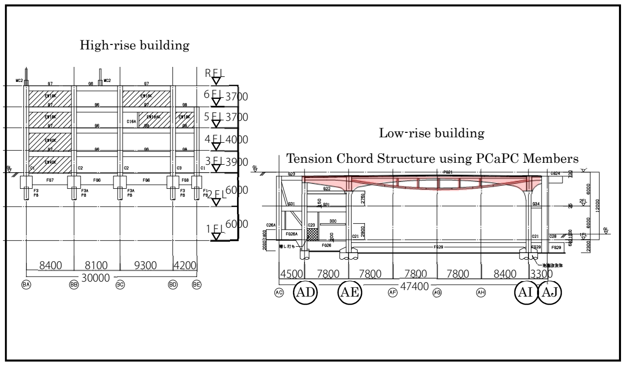

Fig.5 Framing elevation at B5-AB and framing elevation at AJ (ⓑ-ⓑ')

(2) Tension Chord Structure Using Plate-like PCaPC Members

The maximum span of the tension structure using the PCaPC members is 31.8m, and by providing rigid connections at the ends, the stiffness was increased with continuous beams (**Fig.6**). It was anticipated that the outer end columns on baseline AJ on the short span would be subjected to tension under long-term loads. Therefore, a pre-compression force (of 1,196kN) was introduced using PC steel rods (2–32φ)to ensure fixity. The thickness of the foundation slab at the part near baseline AJ was increased to 1,800mm to provide a counterweight (**Fig.5**).

The lower chords also served as ceiling members and were made from PCaPC slabs of 150cm in width and 25cm in height, with an arc shape in the height direction approximating a parabola. At the center of the span, the distance from the bottom end of the lower chord to the top end of the top chord was 2,400mm. The bottom chords between baselines AE to AF and AH to AI were integral with the top chords to allow the axial force to be transmitted to the top chords (**Fig.6**). The bottom chord members were designed as fully prestressed by applying a pretension force so that they would resist the tension stresses under long-term loads as compression members. The width of the upper chords is 175cm, and the depth is 75cm at the center of the span and 250cm at the ends. The spacing of the tension structures is 390cm, and semi-precast slabs are provided between the chord members (**Fig.6**).

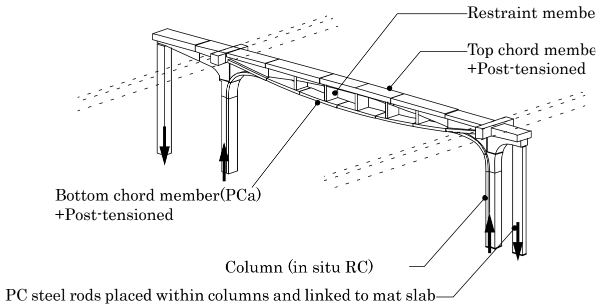

Fig.6 Conceptual diagram of PCaPC tension beams

Fig.7 Tension chord structure (on baseline AI)

(3) FEM Analysis

Finite element method (FEM) analyses were carried out to check the stress and deformation states of the PCaPC-member tension chord structure at each stage of construction. The analysis software MIDAS was used, and the PCaPC members were modeled with solid elements. Taking the construction sequence into consideration, the analyses for the finishes and the superimposed loading acting after the top concrete was poured were carried out using a separate model of the top concrete cross-section (**Fig.8**).

It was confirmed that under long-term loads, no tension stresses would be produced in any members of the PCaPC tension chord beam.

The deflection of the center of the span after tensioning was roughly 5mm upward and 6mm downward under long-term loads (**Fig.9**). There was very good agreement between the measurement results using laser rangefinders and the analysis results for the amount of deflection at each stage.

The natural frequency in the vertical direction under both fixed and superimposed loads was around 4Hz.

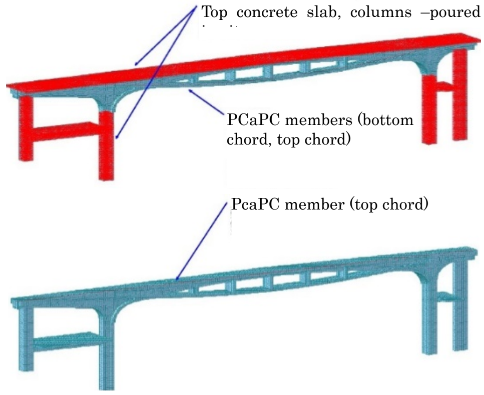

Fig.8 Analysis model

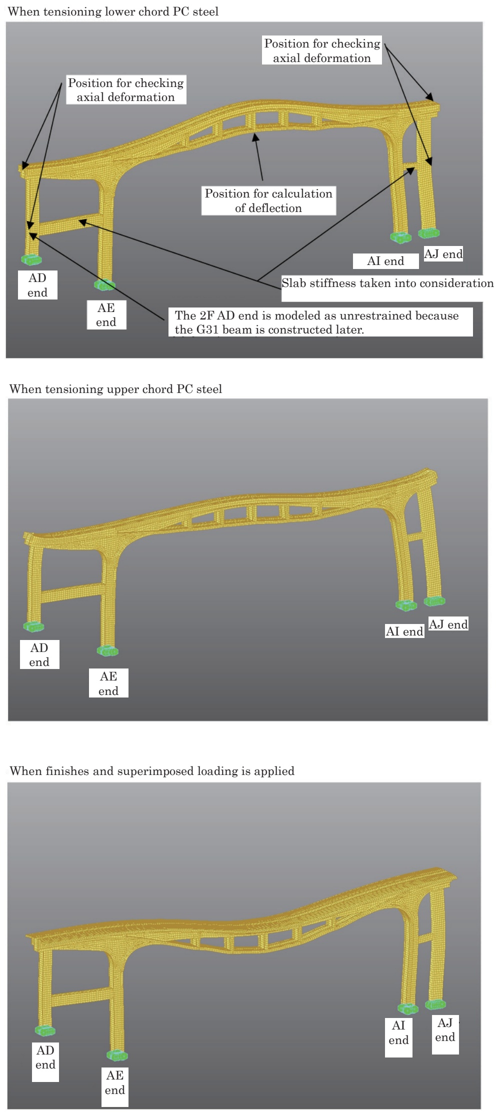

Fig.9 Analysis results

3. Construction Scheme

(1) Manufacture of PCa Members

Figs.10 and **11** show examples of PCa members during manufacturing. The total number of pieces of the top and bottom chords and the restraint members was 160, weighing a total of 1,730t.

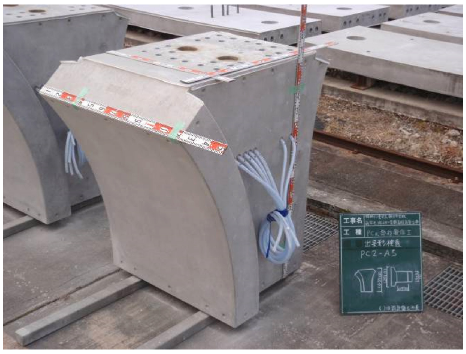

Fig.10 Column PCa member

Fig.11 Bottom-chord PCa member

(2) Erection of PCa Members and Tensioning Operation

Fig.12 shows the erection scheme. The site conditions made it necessary to move the crane after the erection from baseline A5 to baseline A12. Therefore, a system was adopted in which the falsework was moved as a whole by jacking after erection. The erection was carried out using a 150t crawler crane, dividing each construction area of eight beams into three, two, and three beams[1].

Each group of beam members was erected in the sequence (i) column members, (ii) end beam members, (iii) lower chord members, (iv) restraint members, and (v) top chord members.

To install the top chord members on the bottom chord members, temporary members were installed to support the top chord members after installation of the bottom chord members and the restraint members.

The falsework for the heavy members had sufficient strength not to collapse in the event of an earthquake.

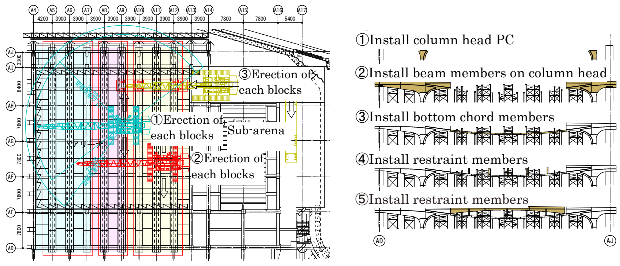

Fig.12 Erection scheme

While tensioning operations were carried out, the strains and deformations were measured and compared with the aforementioned FEM results to check whether the prestress had been introduced properly and whether the performance of the tension beam members could be realized. The scope of the post-construction work was planned so that the constraint conditions of the surrounding structure when introducing the prestress were the same as those of the analysis model (**Fig.8**).

4. Conclusion

It was possible to achieve the necessary stiffness and durability for an exercise area by using a tension chord structure with plate-like PCaPC members. In addition, an interesting form has been realized aesthetically using the plate-like bottom chord members for spatial expression. This project won the Award of the Japan Concrete Institute in 2017.

Reference

[1] Hiroaki HARADA, Takaaki UDAGAWA: *Design and Construction of a building using PCaPC Tension Chord Beams for an Exercise Area Roof (Part 1, Structural scheme; Part 2, FEM analysis taking construction sequence into consideration; Part 3, Construction scheme and measurements results)*, Summaries of Technical Papers of Annual Meeting of Architectural Institute of Japan (Kinki), pp. 811–816, Sem. 2014. (in Japanese)

概　要

1 階を体育館，その上部屋根を運動場とした学校施設において，剛性・耐力が高い板状の PCaPC 部材を用いた張弦構造を屋根梁とした。

本建物は，大スパンの体育館屋根の構造を安全な架構とすることが設計のテーマであった。加えて体育館屋根は非歩行が一般的であるが本建物は，運動場つまり子供たちが日常的に運動を行う屋根・床の用途であるため，居住性の点で問題のない性能確保がもう一つの重要な設計テーマでもあった。そのため，張弦材の下弦材をテンション材の線材ではなく，厚みのある帯状のコンクリートの板とし，初期張力，プレストレス力を入れ，版自体を長期荷重にも圧縮状態とすることで，耐力に加え，剛性にも寄与させた。

この構造設計により，プレキャストプレストレスト構造の特徴を生かしながら，性能に加え美観にも配慮した建築や構造を実現させることができた。