REALIZATION OF HIGH-RISE MIXED-USE BUILDING IN WHICH RC COLUMNS AND CFT COLUMNS ARE CONNECTED WITH RIGID JOINTS

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Abstract

In recent years there has been an increasing trend towards mixed-use buildings in surburban re-development projects. For design of buildings on limited site areas, it is most efficient to stack the different uses vertically, and in this case it is ideal to adopt the structural form that is most suitable for the respective uses. However, to date there have been no methods of connecting the different structure types, and this has been an issue for many years. The high-rise mixed-use building introduced here is the West Block Building from the Kokubunji Station Redevelopment project, in which the high-rise residential part is an RC structure which is excellent for dwelling comfort, and the lower level commercial facilities part is a structural steel structure (CFT columns and structural steel beams) which provides the required flexibility. In order to realize this hybrid structure a new connection method that can rigidly connnect RC columns and CFT columns was developed (the iRS System: integrate RC and Steel). The feature of this construction method is its versatility of application to various types of building regardless of use or scale, and the method is expected to be widely adopted. In the future it is considered that by applying this construction method to various mixed-use buildings, the ideal structural form can be proposed for each use.

1. Introduction

In recent years there has been an increasing trend towards construction of mixed-use buildings in suburban redevelopment projects. For design of buildings on limited site areas it is most efficient to stack the different uses vertically, and in these cases it is ideal to adopt the structural form that is most suitable for the respective uses.

The West Block Building that is introduced here is an ultra high-rise mixed-use building in which the high-rise residential part is an RC structure, which is excellent for dwelling comfort, and the lower level commercial facilities part is a structure (CFT columns and structural steel beams), which provides the required flexibility of use (Fig. 1). In order to realize this hybrid structure a new connection method that can rigidly connect RC columns and CFT columns was developed (the iRS System: integrate RC and Steel).

Figure 1. External view of west block building

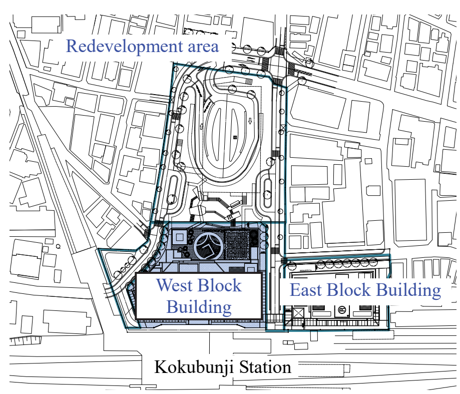

Figure 2. Building layout plan

2. Overview of the Building (West Block Building)

This building is part of the JR Kokubunji Station North Exit station front redevelopment project, and in accordance with an urban planning decision for this site, the station front roads, traffic plaza, West Block, and East Block are designated as a landmark project for development as the gateway to the Kokubunji City North Exit area (Fig. 2 Building Layout Plan).

The West Block and the East Block are connected to the station concourse with a large span free passage (elevated passage) and a pedestrian deck, with the aim of ensuring connectivity between the traffic plaza being developed and the existing commercial areas, thereby creating a vibrant area with improved convenience and safety.

The West Block Building is an ultra high-rise mixed-use building having 300 residential units in the high-rise part (6th to 36th floors) to promote residency in the area; commercial facilities, car parking, and bicycle parking on the 3rd and 4th floors for landowners and existing tenants, and a public benefit facility for Kokubunji City on the 5th floor.

This project was designed to bring out to the maximum extent the potential of Kokubunji City, which retains the features of Musashino while cultivating its long history and culture, and for high efficiency utilization of the station front site based on the theme "Kokubunji style".

Building name:	City Tower Kokubunji The Twin
Location:	3001 Honcho 3-chome, Kokubunji City, Tokyo
Building uses:	Condominiums, offices, retail, leisure facilities
Building owner:	Sumitomo Realty & Development Co., Ltd. (designated builder)
Design and construction:	Takenaka Corporation
Total area:	57,442.96 m²
Maximum height:	134.973 m
Eaves height:	134.373 m
Building scale:	Basement 3 floors, above ground 36 floors, penthouse 2 floors
Building type:	Reinforced concrete structure, steel structure (CFT columns, structural steel beams)
Construction period:	July 2015 to March 2018 (total construction period 33 months)

3. Structural Overview

3.1 Overview of Structural Design. In the structural scheme the structure type switches at the 6th floor level, as shown in Fig. 3. The 6th floor and higher columns have mainly an RC moment-resisting frame (tube structure on the outer periphery and an internal parallel cross frame around the core common parts), and for the floors below the 6th floor a structural steel (CFT columns, structural steel beams) pure moment-resisting frame was adopted. In order to create a space with no columns in the free passage part on the 1st floor (elevated passage), a truss was formed by installing inclined columns at grid line W6 on the 5th floor, so that 4 columns could be eliminated directly below the high-rise part. Also, as shown in Fig. 4, the 6th floor corner columns C1 (the 2 columns between grids W2-3/WB and W2/WC, and the 2 columns between grids W8-9/WB and W9/WC) were inclined in 2 orthogonal planes over 3 stories, and were combined together at the 3rd floor into a single column, C21 and C21R respectively.

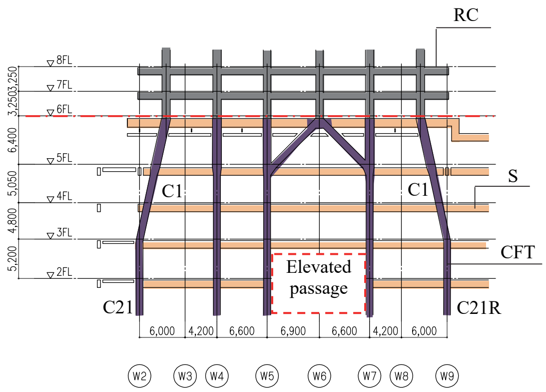

Figure 3. Structural overview

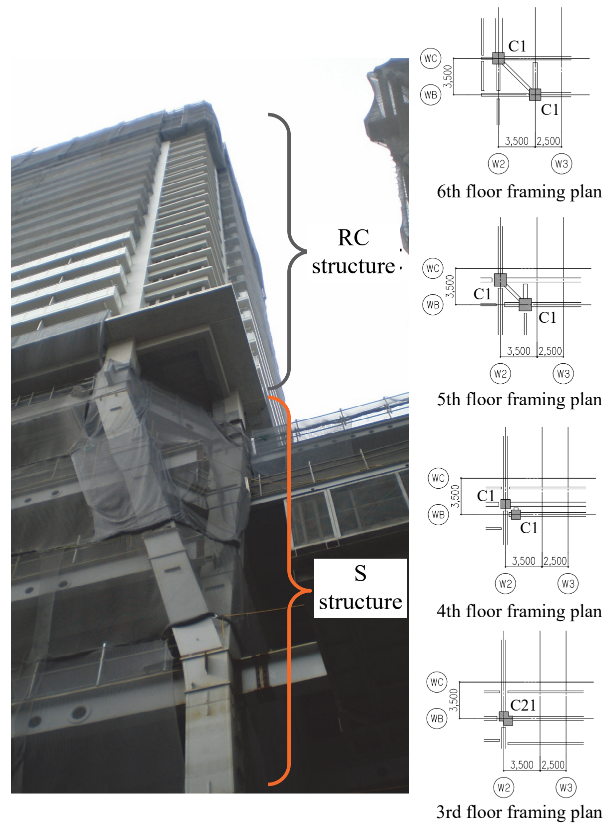

Figure 4. Branched columns

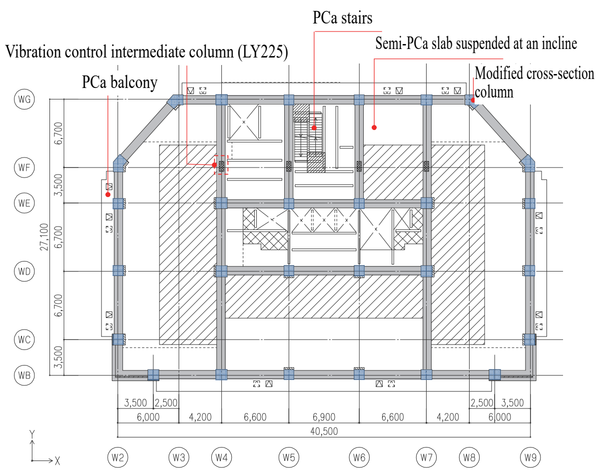

Figure 5. Standard floor framing plan

The standard floor has a polygonal shape in plan, with dimensions in the East-West direction (X direction) of 40.5 m, and in the north-south direction (Y direction) of 27.1 m, with inclined beams between WF-WG, as shown in Fig. 5. Therefore the columns on which the inclined beams are installed has a modified cross-section, which was replaced with the equivalent rectangular cross-section that can approximate the bending rigidity and load resistance for carrying out the analysis[1). On the 6th floor and higher the column spans in the X direction are 5 spans of 6.6 to 10.2 m, and in the Y direction 3 spans of 3.5 to 10.2 m. On the 5th floor and lower in the X direction there are 7 or 8 spans of 4.2 to 13.5 m, and in the Y direction there are 6 or 7 spans of 3.5 to 11.1 m. As shown in Fig. 6, the floor heights from the B3 level to the 4th floor are 4.13 to 5.2 m, on the 5th floor 6.4 m, on the standard floors 3.25 m, and on the 36th floor 3.75 m. The aspect ratio (height from the B1 level/distance between column outer surfaces) is 3.27 in the X direction, and 4.88 in the Y direction. Taking vibration, noise, and deflection into consideration, the floor slabs in the residential part are semi-precast composite floor slabs into which prestress was introduced, and in the common parts and commercial parts are RC construction using deck plates (built-in formwork).

Also, in order to improve the vibration properties and seismic performance, a total of 52 vibration control intermediate columns using low yield point steel shear panels were installed at 2 to 4 locations in the Y direction on each floor between the 7th and 24th floors.

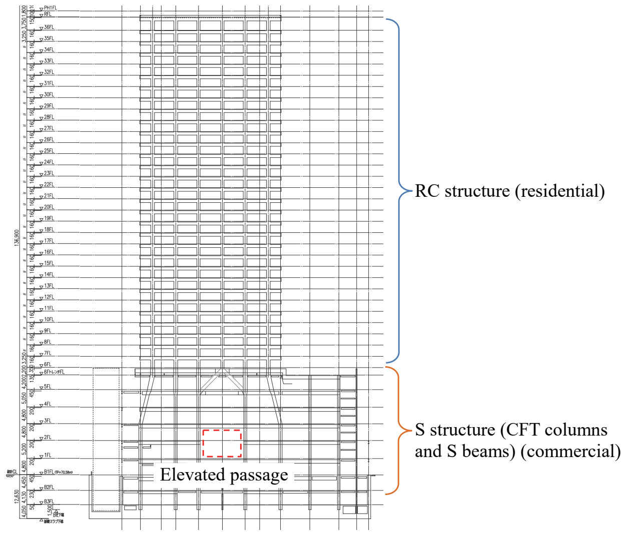

Figure 6. Framing elevation

The concrete design standard strength is Fc120 to 30, and Fc120 to 100 is used for the CFT filling concrete only. For the Fc80 RC columns, AFR concrete (ultra high strength concrete with polypropylene fibers) was adopted, taking into consideration fire resistance. The main reinforcement in the columns and beams is SD685B, SD490, and SD390, with diameters D41 to 29. For shear reinforcement of the columns and beams, high shear strength reinforcement with yield strength 685 N/mm^2 is used, in addition to SD295A normal strength material.

The form of the foundations is direct foundations (raft foundation) with the Kazusa Formation (consolidated silt layer) at GL -12.63 m as the bearing stratum.

The main specification for the external walls is aluminum sashes and ALC panels in the residential parts, and aluminum panels and ALC panels in the commercial part.

An expansion joint was provided between the adjacent East Block Building in the part above the elevated passage. The pedestrian deck connecting the station concourse with the East and West blocks is partially a suspended structure, designed so that the columns do not extend into the floors below.

3.2 Overview of Connection between RC Columns and CFT Columns.

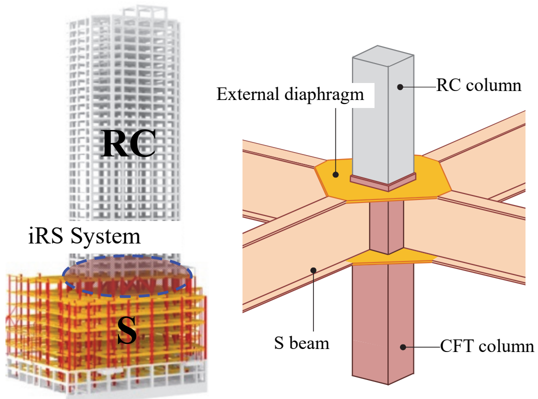

Figure 7. Structural method for connecting RC columns and CFT columns

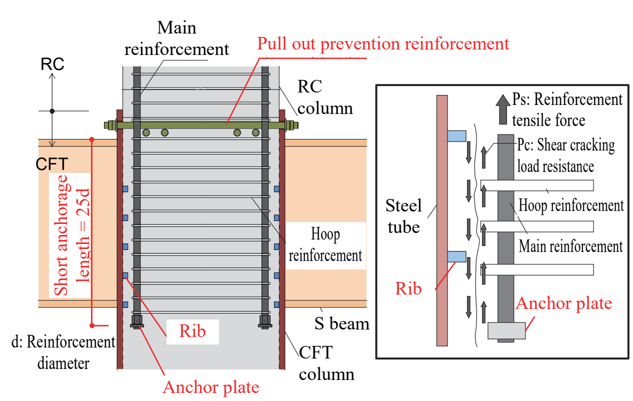

Figure 8. Detail of the structural connection method

In this scheme the main building needs was for a columnless elevated passage passing north-south through the 1st floor of the building, and in order to achieve this the lowrise part was given a structural steel form (CFT columns, S beams), and an RC structure was adopted as a structural form for the high-rise part. However at the time of the design there was no structural method for rigidly connecting CFT columns and RC columns, so in parallel with the basic design a new structural connection method (iRS System) was developed as shown in Fig. 7. The characteristics of this structural method are: (1) there is a mechanism by which the forces flow naturally from the reinforcement to concrete to steel tubes in order to smoothly transmit forces from the RC columns to the CFT columns, (2) in order to make the connections more compact, the anchorage length of the main reinforcement of the RC columns is the minimum 25d, (3) reinforcement is provided to prevent pull out in order to ensure robustness, and detailing was carried out so that filling with concrete can be reliably carried out (Fig. 8).

Structural tests were carried out in order to confirm these properties of the structural method, which enabled the stiffness and load resistance to be evaluated, following which the detailed design was carried out.

3.3 Structural Tests. Three types of structural test were carried out: anchorage tests on partial models, column tests on overall models, and connection tests[2)]. The anchorage tests were carried out in order to confirm the ideal main reinforcement anchorage length, and the column tests were carried out in order to confirm that the main reinforcement was properly anchored in the connection, and that the normal behavior of an RC column will be exhibited. Also, the connection tests were carried out in order to confirm that beam failure occurred first, and to evaluate the frame stiffness.

Table 1 shows a list of the test specimens. The ends of the anchorages of the main column reinforcement were either straight or had a mechanical anchorage, and the anchorage length was varied from $40d_b$ to $16d_b$ (d_b: nominal diameter of the main column reinforcement). The concrete was Fc80, and the CFT columns were HBL385B, the structural steel beams were SN490B, the main reinforcement of the RC columns was SD490, and the hoop reinforcement was SD785. The test specimens were about 1/3 scale.

Table 1. List of Test Specimens

Test Specimen Name	*Test Method*	*Connection*	*Anchorage End*	*Anchorage Length*
T-E-25	Anchorage tests	External diaphragm	Mechanical type	$25d_b$
T-E-16				$16d_b$
T-I-40		Internal diaphragm	Straight	$40d_b$
T-I-25				$25d_b$
C-E-25	Column test	External diaphragm	Mechanical type	$25d_b$
C-I-40		Internal diaphragm	Straight	$40d_b$
C-I-25				$25d_b$
J-E-25	Connection test	External diaphragm	Mechanical type	$25d_b$

Fig. 9 shows the test results for the anchorage tests specimens. The test variables in the anchorage tests were the form of the diaphragm and the anchorage length, and the method of applying the force was to simultaneously pull out one row on the tensile reinforcement side. In order to confirm the anchorage load resistance of the main reinforcement SD980 steel was used, but in all test specimens the reinforcement remained anchored up to a reinforcement stress of about 980 N/mm^2 (reinforcement failure).

Fig. 10 shows the test results for the column test specimens. The test variables were the form of the diaphragm and the anchorage length, and the load application was an antisymmetric bending shear test with variable axial load on 2 test specimens, and constant axial load on 1 test specimen, with a total of 3 test specimens. Comparing the test results with the results from the calculation equation shows that the test values exceeded the calculated values for all test specimens, so it was confirmed that it was possible to evaluate RC columns connected to CFT columns using the RC column evaluation equation (bending: AIJ approximation equation, shear: shear strength in accordance with the Guidelines for Seismic Design to Ensure Ductility).

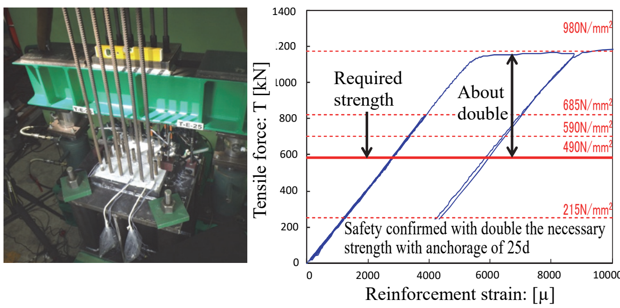

Figure 9. Test specimens and test results (Anchorage Tests)

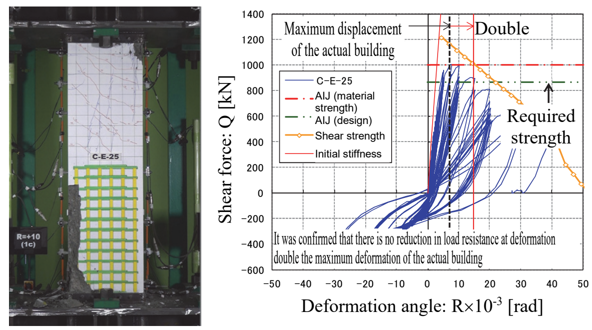

Figure 10. Test specimens and test results (Column Tests)

Fig. 11 shows the test results for the connection test specimens. The test specimens had an external diaphragm on the CFT columns for connecting structural steel beams, the anchorage length of the main column reinforcement was 25d_b, and mechanical anchorages were provided within the CFT columns. In the test results the hysteresis curves showed hysteresis typical of structural steel, exhibiting stable spindle behavior until ultimate failure. Fig. 12 shows a comparison between the analysis model, test, and calculated values. The analysis model simulated the test specimen as cruciform, modeled as linear material having a rigid plastic rotational spring. A rigid region D/4 (D: RC column depth) was set at the beam ends, and the external diaphragm were modeled as a column width haunch. The calculated values agreed well with the test values for the initial stiffness, the cracking point for the RC column, the secondary slope, and the yield deformation angle. The yield resistance force was determined by the beam total plasticity moment, and the calculated values evaluated the test results on the safe side. Therefore, it was considered that this analysis model could be used for evaluating the positions where the CFT columns and the RC columns were switched.

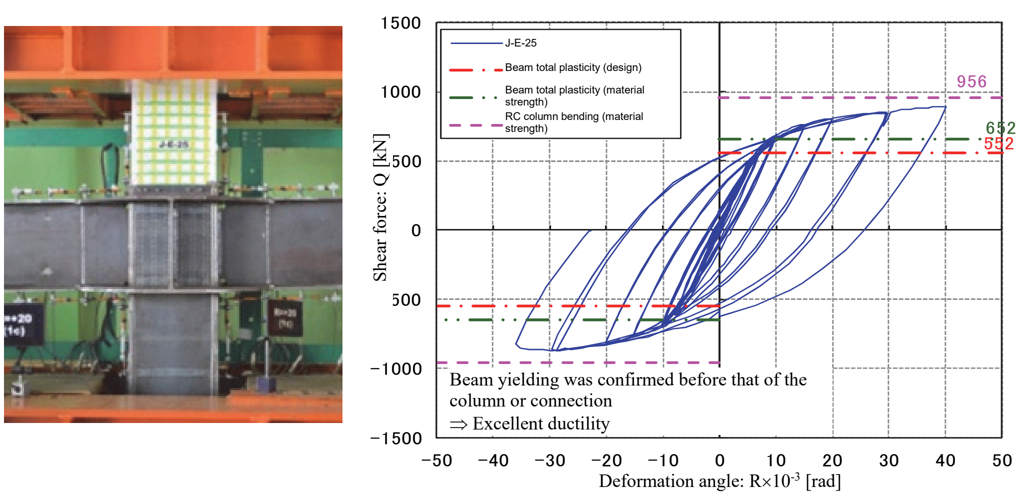

Figure 11. Test specimens and test results (connection tests)

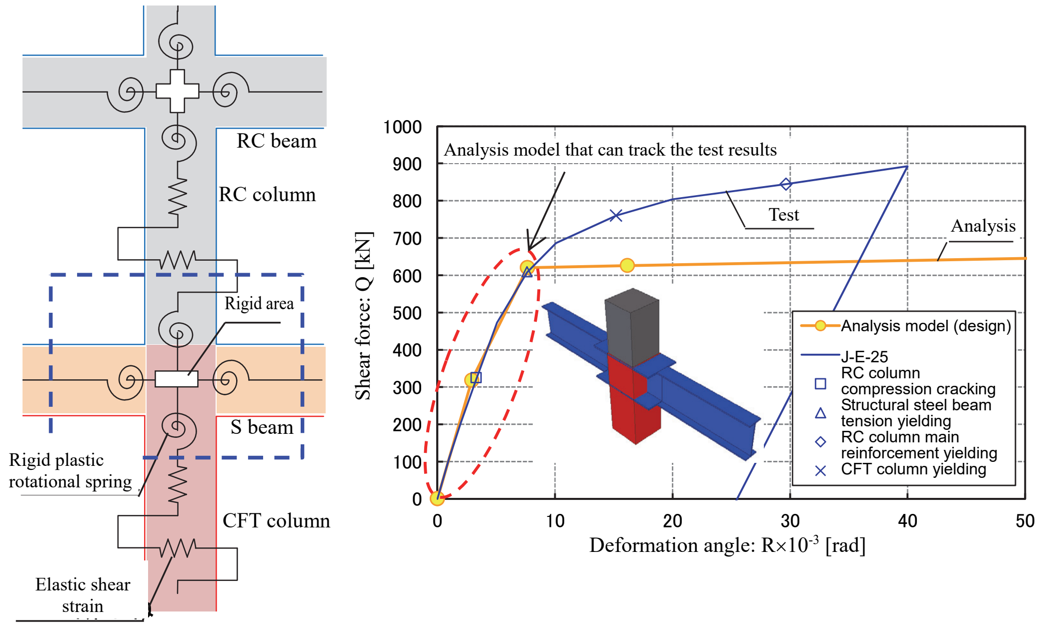

Figure 12. Comparison of analysis model and test results

4. Construction Plan

This building has a structural steel form (CFT columns, S beams) in the low-rise part from the B3 level to the 6th floor, and an RC structure in the high-rise part from the 6th floor upwards. By using precast concrete in the structural frame of the high-rise part (columns, beams, stairs, balconies, slabs), it was possible to construct one floor in 6 days, so together with the low-rise structural steel part the construction period could be shortened, and an overall short construction period of 33 months was achieved (Fig. 13).

Figure 13. Views of construction

Figure 14. Position of column switching on the 6th floor and erection of 7th floor PCa beams

Figure 15. Full-size model and view of concrete filling (3rd to 5th floor branched columns)

Rigid connections were used between the CFT columns of the 5th floor and the RC columns of the 6th floor, and the columns on the 7th floor upwards were precast. However the 6th floor columns were cast in situ, in order to absorb the small erection accuracy tolerances for the low-rise structural steel frame.

In the case of construction, importance was placed on the control of (1) switching from the 5th floor CFT columns to the 6th floor RC columns and the erection tolerances for the 7th floor PCa beams, (2) concrete filling of the branched CFT columns in the corners from the 3rd floor to the 5th floor, and (3) concrete filling of the CFT braces of the inclined columns on the 6th floor. Regarding (1), using a 2 stage template the positions of the column main reinforcement were fixed, and the 7th floor PCa beams were erected while the positions of the main column reinforcement of the in situ RC columns on the 6th floor were adjusted (Fig. 14). Regarding (2), the arrangement of each part and the filling holes were confirmed using full-size models and the concrete filling was controlled using ultra miniature cameras. Regarding (3), reliable filling of the CFT concrete was carried out by carrying out construction tests for the method of filling using a mockup (Figs. 15 and 16).

Figure 16. Mockup and view of concrete filling

In this project where a novel construction method was applied for the first time, the construction was completed on schedule as a result of forming a seamless cooperation organization of each of the relevant departments, and utilizing the strengths of design and construction.

5. Conclusion

In order to realize an ultra high-rise mixed-use building consisting of condominiums with an RC structure with excellent dwelling comfort and commercial facilities with flexibility of use, a new structural method for rigidly connecting RC columns and CFT columns was developed and applied (the iRS System). A characteristic of this structural method is that it is versatile for application to various types of building regardless of size, so it is expected that it will be widely adopted. Also, by adopting this structural method, the low-rise part could be constructed in structural steel, and the high-rise part with a precast RC structure, so the construction period could be shortened and labor saving was achieved.

It is considered that in future this structural method will be applied to various types of mixed-use building for which demand continues, and that the ideal structure type for each use will be used in combination.

References

1) Yuji ISHIKAWA et al., Mechanical Properties of Horizontally Inclined Connections, Japan Concrete Institute Annual Convention (Niigata), pp. 337-342, 2006

2) Yusuke TANABE et al., Research into Switching CFT Columns and RC Columns (Parts 1 to 3), Summaries of Technical Papers of Annual Meeting of Architectural Institute of Japan IV, pp. 329-334, 2015