NIPPON STEEL TECHNICAL REPORT No. 66 JULY 1995

UDC691.328.4

Development of Composite Structures at Building Construction Division of Nippon Steel

Hideji Nakamura*1
Hideaki Yoshikawa*1
Toshiki Ohya*1
Sakae Maruyama*1
Minoru Hokari*1

Abstract:

The development of building structure technology at the Building Construction Division of Nippon Steel has traditionally focused on steel structures for industrial facilities and superhigh-rise office buildings. In recent years, the division has shifted attention to the development of composite structures of reinforced concrete and steel for apartment buildings with the aim of becoming a medium-scale contractor with leading-edge technology. Representative examples include concrete-filled tube (CFT) columns, which are receiving much attentionin in the New Urban Housing Project; steel-encased reinforced concrete (RC) columns for high-rise reinforced concrete apartment buildings; and PLRC (steel plate-reinforced concrete) columns, which are cruciform columns composed of steel plate and reinforced concrete developed for medium- and high-rise apartment buildings.

1. Introduction

The Building Construction Division of Nippon Steel started as the Steel Structures & Building Construction Division in 1974, and expanded its business with H-shape utilization technology and steel frame fabrication technology. Around 1975, the division commerced general building construction on a full scale, mainly constructing superhigh-rise office buildings and industrial facilities, playing a role in the company's diversification.

The division's technological developments initially concentrated on steel structures, but then expanded to embrace reinforced concrete structures as well, befitting that of a general contractor with comprehensive technological capabilities. This change nurtured concrete specialists within the division, marking a jump in status for the division as general contractor.

The division developed of composite structures to make the best use of steel produced at Nippon Steel, and consequently engaged in the construction of reinforced concrete buildings, such as apartment buildings. More recently, the division has developed technology for pure reinforced concrete construction, such as construction technology using superhigh-strength concrete (Fc 600 kgf/cm^2).

Some of the Building Center of Japan's evaluation process involves examining not only design but also construction technology. The Building Construction Division's concrete-filled tube (CFT) columns receive a general evaluation from the Building Center of Japan and a technical evaluation from the Building Center of Japan's High-Rise Reinforced Concrete Building Technology Study Committee. From that process, it has steadily gained a reputation as a general contractor in the construction

*1 Building Construction Division

industry. Not initially recognized as a general contractor, the division had to explain its motives when having its technology evaluated by the Building Center of Japan and related organizations. Now that it has secured its position as general contractor in the construction industry, such an explanation is unnecessary.

This article introduces the concrete-filled tube (CFT) columns, steel-encased reinforced concrete (RC) columns and the steel plate-reinforced concrete (PLRC) composite members from among the composite structures developed by the Building Construction Division, and describes the construction technologies developed by the division, other than those for steel structures.

2. Development of Concrete-Filled Tube (CFT) Columns

2.1 Types of concrete-steel pipe composite columns

The Architectural Institute of Japan's Standard for Structural Calculation of Steel Reinforced Concrete Structures states that concrete-steel pipe composite columns are available in the concrete-covered type, concrete-filled type, and concrete-covered and concrete-filled type as shown in **Fig. 1**.

The CFT column is a concrete-filled structural member with a square or round steel pipe filled with concrete. CFT columns are receiving attention because they are structural members featuring the advantages of both steel and concrete.

Columns and girders are generally of the through diaphragm type (including the internal diaphragm type) or the external diaphragm type as shown in **Fig. 2**. Whether or not the tube can be properly filled with concrete below the bottom surface of the diaphragm is a construction problem particular to the through diaphragm type.

2.2 Administrative factors

The concrete-covered type and concrete-covered and concrete-filled type are treated as steel frame-reinforced concrete (SRC) columns and do not require additional evaluations. The concrete-filled type cannot be considered as an element of SRC construction because it has no concrete cover, which is supposed to be at least 5.0 cm thick. If the concrete-filled type is categorized as an element of steel frame construction, the stiffness of the concrete can be evaluated, but the strength of the concrete cannot. The authorities concerned are considering approving the CFT column structure as a composite structure, but has not yet done so. Under the present circumstances, CFT structure designs must be individually evaluated by the Building Center of Japan.

2.3 Participation in the New Urban Housing Project and general approval

In 1992, Nippon Steel's CFT technology received general approval from the Building Center of Japan and it also acquired the expertise to design and construct CFT columns at the level where it could apply for building confirmation. The background to this development is outlined below.

Five companies participating in the New Urban Housing Project structurally experimented CFT columns, using 48 short-column compression test specimens and 38 axial bending shear test specimens. In fiscal 1989, the Building Center of Japan's Skeleton Structure Committee evaluated the performance of the CFT structure (hereinafter referred to as CFT evaluation).

Based on the CFT evaluation, the five companies separately performed CFT construction tests to confirm concrete filling methods, received individual evaluation, and conducted further studies before their CFT designs received Building Center of Japan approval.

An example of construction in which Nippon Steel made a column-girder joint of the through diaphragm type by the tremie method is presented here. Concrete filling below the diaphragm bottom surface is confirmed as shown in **Fig. 3** and **Photo 1**. The concrete filling ratio is over 90% as a proportion of the total cross-sectional area of the column. When mixing the concrete for CFT columns, attention is paid to bleeding and settlement to ensure proper concrete filling. In particular, the water/cement

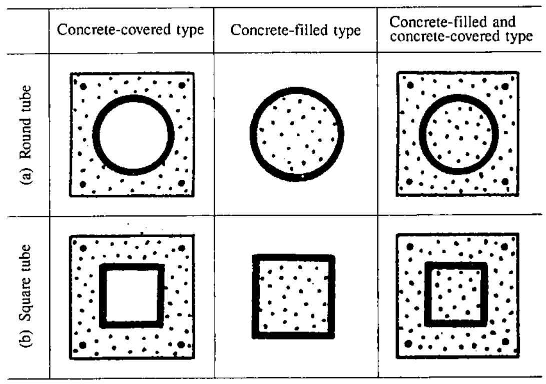


Fig. 1 Cross-sectional shapes of concrete-tube composite columns

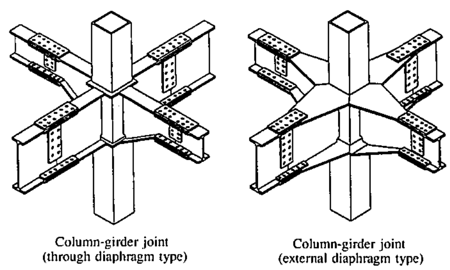


Fig. 2. Diaphragm types

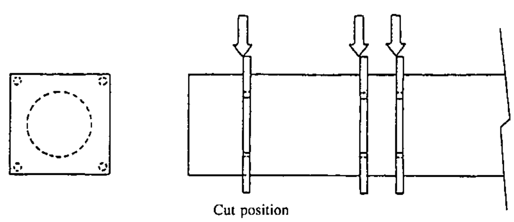


Fig. 3 Cut positions

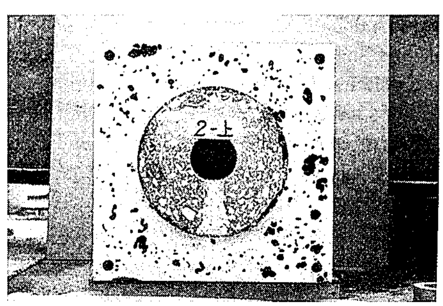


Photo 1 Concrete filling of CFT column

ratio is set at a maximum of 40%.

The particulars of the CFT column general approvals gained by the five companies are based on the CFT evaluation and are not appreciably different from each other. The particulars of Nippon Steel's general approval may be summarized as follows:

- In principle, Nippon Steel designs and constructs its CFT columns by itself.
- The confinement effect is expected to increase the strength of concrete.
  $F_c \leq 600$ kgf/cm^2
  where F_c is the specified design strength of concrete in kgf/cm^2.
- Steels up to JIS G 3106 Grade SM570 can be used.
  Specified strength F of steel: $F \leq 4{,}100$ kgf/cm^2
- The width/thickness ratio is relaxed (see **Fig. 4**).
  $B/t \leq 55$ (square tube)
  $D/t \leq 67$ (round tube)
- A CFT evaluation equation can be used to advantage when evaluating deformation performance during the calculation of the horizontal load carrying capacity of the CFT column.
- The limitation of the axial force ratio of the CFT column is significantly relaxed during the calculation of the horizontal load carrying capacity.
  $N \leq 0.7 \cdot Nu$
  where N is the axial force of the CFT column to be used for calculating the horizontal load carrying capacity (t) and Nu is the central compressive strength of the CFT column (t).
- Although not described in detail, generalized superposed strength equations can be used as design equations for the short-term bending strength and ultimate bending strength of the CFT column.

2.4 CFT utilization technology and Nippon Steel's performance

The greatest advantage of the CFT column is that it can be designed with a small cross section to achieve a high compressive force. It provides a sectional configuration with greater efficiency than the reinforced concrete column, even when its fire-resistant coating is included. It may be more readily understood that the compressive force and bending moment are carried by the concrete and tube of the CFT column, respectively. CFT columns can be used to great advantage in superhigh-rise office buildings, superhigh-rise apartment buildings, multistory warehouses, and other buildings where the columns are subjected to high axial forces over the short and long term.

Nippon Steel has not undertaken many CFT column projects, as evident from its annual building construction business scale of about ¥130 billion. Nippon Steel used CFT columns in the construction of ENICOM HAICOM Station (a 6-story steel frame building) and the New Morinaga Building (a 7-story steel frame building) in Japan, and in the Republic Plaza Hotel in Singapore (see **Photo 2**), World Plaza in Shanghai (see **Photo 3**), and Trade Center Building in Shenzhen, China. With the Trade Center Building in Shenzhen, the use of CFT approximately halved the weight of steel used in the columns, resulting in an economical design.

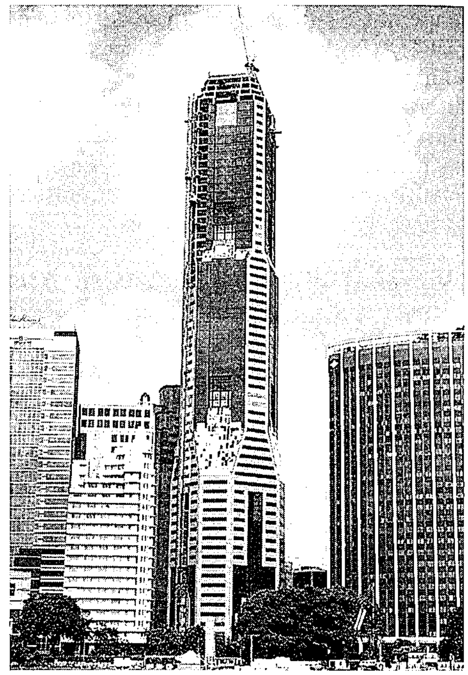


Photo 2 Republic Plaza Hotel in Singapore

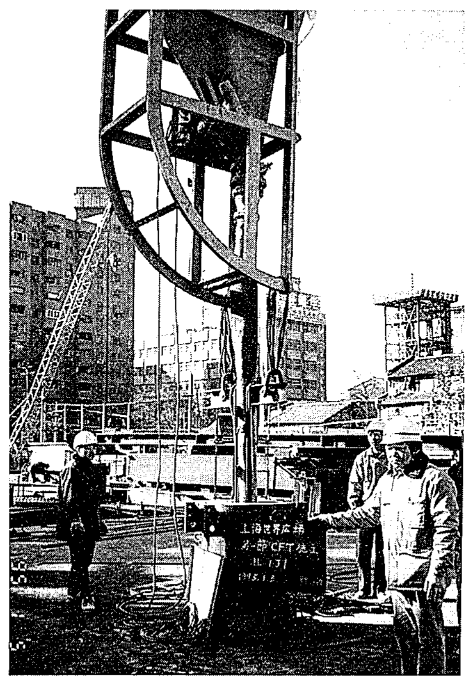


Photo 3 World Plaza under construction in Shenzhen, China

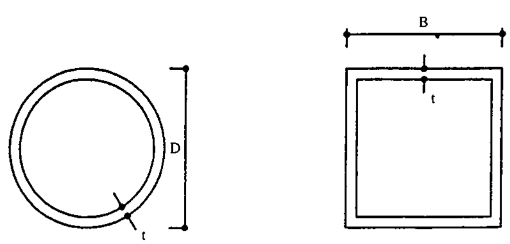


Fig. 4 Width/thickness ratio

2.5 Future development of CFT columns

The previously mentioned five companies had the CFT technology generally approved by the Building Center of Japan and control the use of CFT technology. There is a movement to disclose the CFT technology to other contractors, but this is not expected to happen in the short term. There is no doubt that once the CFT technology is transfered to other contractors, its use will rapidly spread throughout the construction industry. Nippon Steel is studying the possibility of making CFT columns from 80 kgf/mm² (780 MPa) steel and from high-performance concrete made using finely ground blast furnace slag.

3. Development of Superhigh-Rise Apartment Buildings Using Steel-Encased Reinforced Concrete (RC) Columns

3.1 Nippon Steel-constructed superhigh-rise apartment buildings

In the past decade, reinforced concrete construction has been adopted in many buildings exceeding 20 stories. This trend stems from to the progress of material, structural design, and construction technology concerning reinforced concrete, including high-strength concrete (Fc 480 kgf/cm²) and high-strength large-diameter reinforcing bars (SD390 and D41).

The design and construction of such superhigh-rise reinforced concrete buildings must be technically evaluated and approved by the Building Center of Japan. Some 20 general contractors have gained approval to date. After about three years of preparation from 1990 and 10 months of review, Nippon Steel's Building Construction Division received, in cooperation with the Steel Structure Development Center, the technical evaluation "Nippon Steel Superhigh-rise Reinforced Concrete Building Construction System 'NS35 System'" by the Building Center of Japan in December 1993. Approval of Nippon Steel Superhigh-rise technology consolidated the Company's technical foundation in the superhigh-rise apartment building field.

Fig. 5 shows a 35-story, 40,000-m² apartment building designed on a trial basis. The Building Center of Japan reviewed the NS35 design and construction system using this building as a model for its technical review.

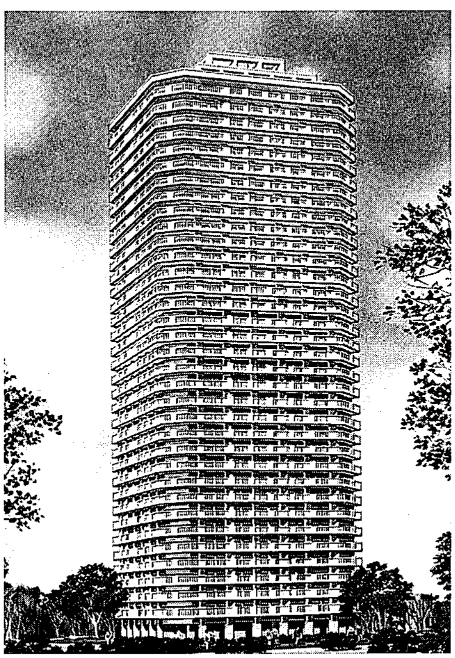


Fig. 5 NS35 (35-story apartment building)

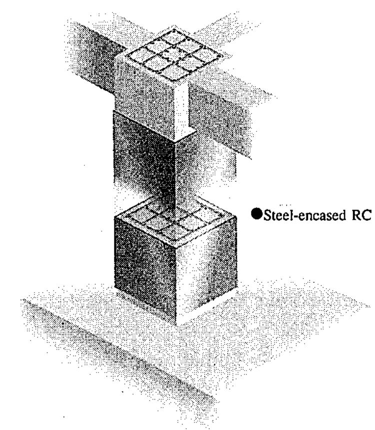


Fig. 6 Steel-encased RC column

3.2 Steel-encased reinforced concrete (RC) columns

The superhigh-rise reinforced concrete (RC) building construction system uses a pure rigid frame structure as the frame type. This type absorbs the energy from large earthquakes by means of the plastic deformation of structural members. Since it is assumed that the collapse mechanism is involves total collapse of the girder bending yield type, the girders must remain tough enough after the occurrence of plastic hinge. In order to assure high ridgidity under high axial forces, Nippon Steel developed steel-encased RC columns for the ground-floor outside columns, and corner columns that allow the occurrence of yield hinge under complex stresses with a high axial force.

The steel-encased RC column is a conventional RC column encased in a steel plate welded into a closed section, so that the concrete can be restrained and reinforced in plane (see **Fig. 6**). The steel plate also plays the role of a form during the construction of the steel-encased RC column. Unlike the CFT column, the steel-encased RC column has gaps provided between the steel plate and girder at the top and bottom, so that the steel plate acts only as a reinforcing material and the axial force of the column is not transmitted to the steel plate. Initially in the development phase, the restraint of the concrete by the steel plate was expected to reduce axial strength loss of the column after the concrete collapsed. Structural experiments showed that the steel-encased RC column has the same initial rigidity as a non-steel-encased RC column. This finding helped to simplify the steel-encased RC column design technique to a great extent.

3.3 Performance of steel-encased RC columns

Three experiments have been conducted for the development of steel-encased RC columns. Conducted since December 1991, the first experiment was the bending shear experiment (see **Photo 4**) on two steel-encased RC columns (axial force ratios* of 0.65 and 0.70) for use in a trial design building. This was the preparatory period for the technical evaluation of steel-encased RC columns and of two non-steel-encased RC columns (axial force ratios of 0.65 and 0.70) as controls. This and second experiments were conducted at the Civil Engineering & Marine Construction Divisions Sagamihara Research & Engineering Center.

* The axial force ratio of a column is the ratio of the axial force to the ultimate axial strength of the column.

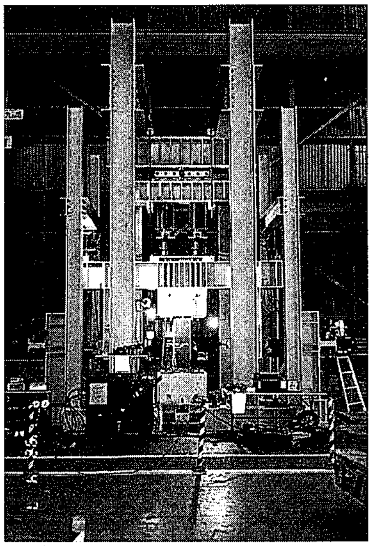


Photo 4 Loading frame

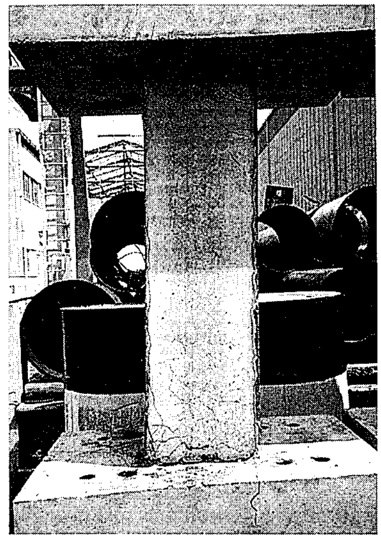


Photo 5 Steel-encased RC column with some steel plates removed after experiment

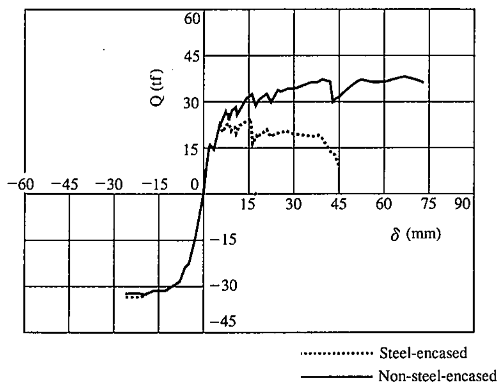


Fig. 7 Load-deformation curves (axial force ratio of 0.70)

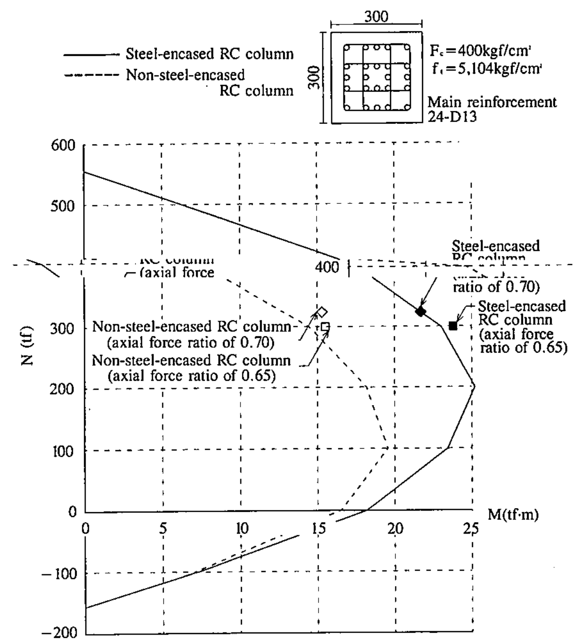


Fig. 8 Moment-axial force interaction curves of RC columns

Fig. 7 shows the load-deformation curves of a steel-encased RC column and a non-steel-encased RC column subject to an axial force ratio of 0.70. The axial force is compressive when the specimen is positively loaded (axial force ratio of 0.70) and is zero when the specimen is negatively loaded. The two specimens do not initially change in rigidity. The strength of the steel-encased RC column does not decline under the compressive axial force. When the steel plate was removed from the steel-encased RC column after the experiment, few cracks were observed in the concrete, and there was no evidence of crushing and shear fracture in the column (see **Photo 5**). Since the ratio of the top and bottom steel plate gaps to the length of the column was 1/30 in the experiment, the contraction of the concrete due to the axial compression added to bring the steel plate into contact with the upper and lower girders and to start the transfer of the axial force to the steel plate when the rotation angle of the column exceeded 1/50.

To increase the gaps so that the steel plate would not come into contact with the upper and lower girders, a central compression experiment was conducted in September 1993 during the review period to confirm the effect of steel plate gaps on column strength. The experiment confirmed the confinement effect, which involves restraining the concrete by the steel plate, raises the compressive strength of the steel-encased RC column, and yields the appropriate gap range where the design equations are valid.

These experiments verified the following:

(1) The steel-encased RC column has about 1.5 times higher bending strength than the non-steel-encased RC column, (see **Fig. 8**) and does not suffer shear fracture.

(2) The steel-encased RC column has excellent deformation performance, and does not diminish in strength when the rotation angle exceeds 1/50.

(3) The maximum strength of the steel-encased RC column can be calculated by assuming that the stress-stain relationship of the concrete is free from the confinement

effect and strength decreases.

(4) The steel-encased RC column is as rigid horizontally as the non-steel-encased RC column.

(5) There is the steel plate gap range where design equations hold true for the steel-encased RC column.

(6) When used as ground-floor columns the axial force ratio of steel-encased RC columns can be increased to 0.65-0.70 of that for non-steel-encased RC columns.

3.4 Application of steel-encased RC columns in other fields

The excellent performance of steel-encased RC columns may be effectively used in not only superhigh-rise RC apartment buildings, but also other RC structures. A medium-rise apartment building that has a slab-type plan view, a first story of the piloti type, and second and higher stories with earthquake-resistant walls is an ideal example. In this case, the rigidity ratio of the first story decreases, the deformation concentrates on the columns of the first story, and the columns of the first story become difficult to design as ordinary RC columns and excessive in cross-sectional area. This apartment building could designed with a relatively small column section by making use of the high strength and deformation capacity of steel-encased RC columns.

The Great Hanshin Earthquake caused widespread structural damage in the Kobe region. RC columns of buildings constructed before the enactment of the present earthquake-resistant design methods had insufficient shear strength under the current earthquake-resistant standards. These RC columns may be reinforced by a steel plate wrapping method. As compared with other reinforcing means, steel plate encasement does not alter the rigidity of the columns and the stress balance of the building, making it easy to study how the building is reinforced.

3.5 Future problems

Steel-encased RC columns have proved to be qualitatively very good structural members. The effect of steel plate on the bending strength of the column has been proved in practice, and the design technique has been established for steel-encased RC columns. By clarifying the effect of steel plate on the shear strength of the column and the mechanism of stress transfer, it will be possible to design steel-encased RC columns with higher accuracy and economy . Since June 1994, a structural experiment has been carried out on shear of steel-encased RC columns to study the stress transfer mechanism. This experimental study is augmented by numerical analysis.

4. Steel Plate-Reinforced Concrete (PLRC) Structure

4.1 Background for development of PLRC structure

At the peak of the bubble economy a few years ago, there was a severe shortage of skilled workers engaged in housing construction, especially in urban areas where were brisk construction activities. It is fully possible that this situation may be repeated in the future.

The durability of structural elements of buildings is not matched in terms of both materials and design, so that buildings cannot achive their intended functions over a long term. Buildings must function so that they do not decline in economic value. For example, a building may still be structurally sound, but its fixtures are obsolete, or the needs of the users of the building have changed.

To solve these problems, Nippon Steel proposed "NS-flex" as an industrialized housing technology that meets the needs of combining and systemizing production processes to eliminate excessive labor intensive activities in the construction industry. The technology also incorporates the concepts of the Century Housing System promoted by the Ministry of Construction. The steel plate-reinforced concrete (PLRC) structure forms the structural system for NS-flex. Nippon Steel and Yahagi Construction jointly acquired the structural approval from the Building Center of Japan for PLRC structures for two-story office buildings in 1990 and for seven-story apartment buildings in 1994.

4.2 Outline of PLRC structure

The PLRC structure is a pure rigid frame structure composed of columns of cruciform section and girders with the same width as the columns. The steel plates are the main reinforcement and shear reinforcement for the reinforced concrete. The columns, girders, and floor boards are precast and bolted together.

These industrialized production and simple joining methods sharply reduce the amounts of form and reinforcement work that call for skilled workers. Finish work can also be cut down greatly by laying tiles and the like onto the precast members. This precasting can also improve frame quality and durability, and shorten the construction period. Since the column shape does not intrude, interior space can be used fully and the rigid frame structure ensures a floor plan that can be easily changed to suit any future requirement.

4.3 Precast members

The column and girder sections are shown in **Figs. 9** and **10**, respectively. The column has a cruciform plate arranged at the center of the cruciform concrete section and a flat plate in each of the four wings. The interior columns and exterior columns are both of the same cruciform section. The girder has a full-web plate arranged in a rectangular RC section. A 6-mm diameter spiral reinforcement is placed at a pitch of 40 mm in an oval form around each steel plate in the column and girder.

The column is entirely precast except for joints with the upper and lower girders. The girder is partly precast below the floor slab. The beam is of the same section as the girder. Half-precast concrete slabs are used as floor members (see **Fig. 11**). A

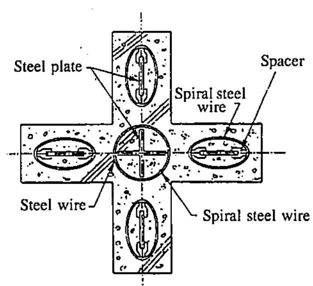


Fig. 9 Section of column

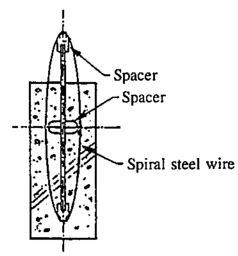
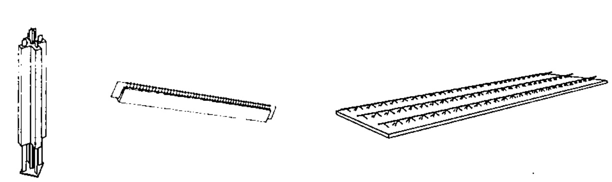


Fig. 10 Section of girder



(a) Column (b) Girder (c) Half-precast floor slab

Fig. 11 Precast PLRC members

steel plate configuration diagram is shown in **Fig. 12**.

4.4 Structural performance of members

A cantilever girder loading test specimen is shown in **Fig. 13**, and load-deformation curves of cantilever girder loading test specimens are shown in **Fig. 14**. PLRC girders do not decline in strength with maximum load until the rotation angle reaches 1/15. They are also very tough. Their hysteresis loops are spindle shaped, which means that their energy absorption capacity is high.

A PLRC column for the antisymmetric loading test is shown in **Fig. 15**. In order to improve the toughness of the PLRC column on PL-9, at the midlength of the test section, there is a tie plate used to connect the central cruciform plate to the flat plate in each wing. Load-deformation curves of PLRC columns without and with the tie plate are shown in **Figs. 16** and **17**, respectively. A PLRC column without the tie plate starts to develop longitudinal cracks between the center of the cruciform plate and the wings of the flat plates when the rotational angle is 1/200. A PLRC column without the tie plate undergoes a sharp loss of strength when the longitudinal cracks eventually connect from top to bottom. At this time, the column changes from the deformation mode of the entire cruciform section deforming as once piece to the deformation mode of the center deforming separately from the wings. Any longitudinal cracks in a PLRC column with a tie

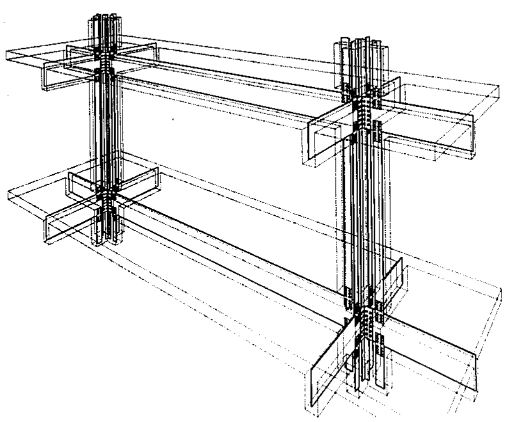


Fig. 12 Plate configuration diagram

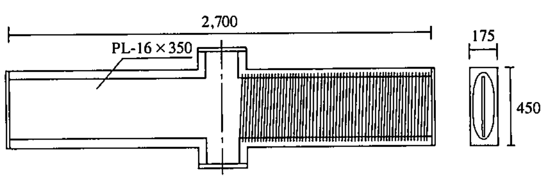


Fig. 13 PLRC girder test specimen

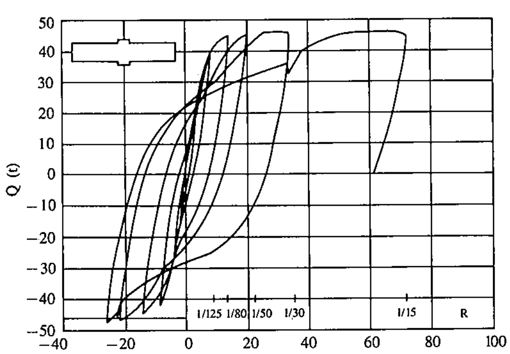


Fig. 14 Load-deformation curves of PLRC girders

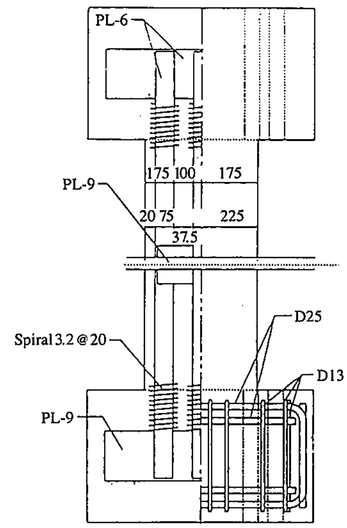


Fig. 15 PLRC column test specimen

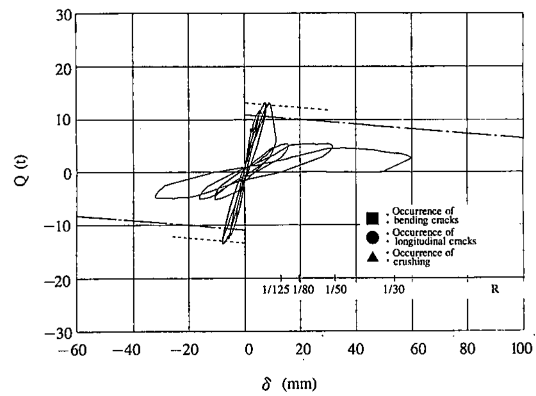


Fig. 16 Load-deformation curves of PLRC column without tie plate

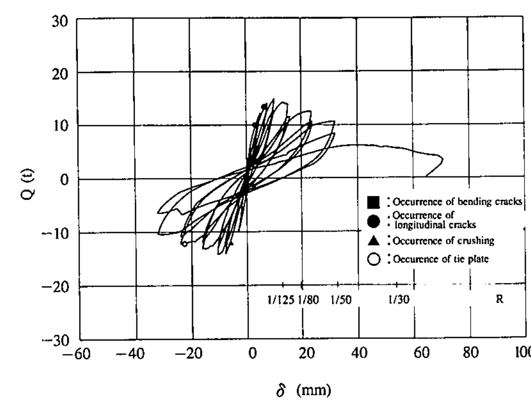


Fig. 17 Load-deformation curves of PLRC column with tie plate

plate stop at the tie plate at the midlength of the column. After the column reaches the maximum strength at the rotation angle of 1/150, the change in the deformation mode from integral deformation of the entire cruciform section to separate deformation of the cruciform center and the wings gradually occurs. The PLRC column does not appreciably drop in strength until the rotation angle increases to 1/67.

4.5 Design of seven-story apartment building

A seven-story apartment building of PLRC construction was designed according to the results of the structural experiments.

The columns and girders of the first floor both measured 28 cm in width, and measured 120 and 60 cm in depth, respectively. The columns and girders of a typical floor both measured 25 cm in width, and were 105 and 60 cm deep, respectively. The earthquake resistance criterion of the maximum-response story deformation angle of the first floor is specified at: 1/300 below the story deformation angle of 1/200 when longitudinal cracks occur in the columns during level 1 (20 cm/s) earthquake response analysis; and at 1/200 below the story deformation angle of 1/150 when the longitudinal cracks connect from the top to the bottom of the column to reach the maximum strength during level 2 (40 cm/s) earthquake response analysis.

4.6 Future problems

The Building Construction Division built an NS-flex model apartment building at the site of the Research & Engineering Center in Futtsu in June 1994, using the typical floor section of the seven-story apartment building (see **Photo 6**). The NS-flex development project, which initially concentrated on structural design, has now been augmented in terms of finish, equipment and construction as well.

For a 14-story and 45-m tall apartment building, we aim to develop a PLRC structure with superior strength and deformation performance by reducing strength loss due to longitudinal cracks in columns.

5. Conclusions

The technology development of the concrete-filled tube (CFT) columns, steel-encased reinforced concrete (RC) columns, and steel plate-reinforced concrete (PLRC) structure at the Building Construction Division has been introduced in this article. These composite columns and structures have been mainly developed for use in the housing sector. The Building Construction Division will continue its technological development of composite structures by making the best use of steel produced at Nippon Steel.

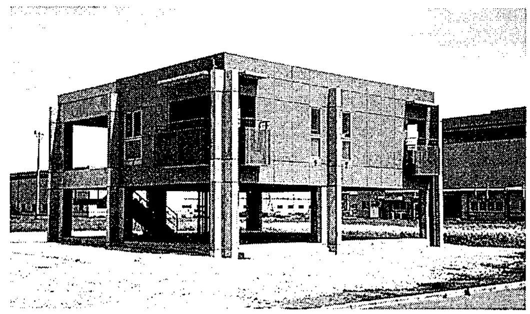


Photo 6 NS-flex model apartment building