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Beam-Column Joints in Precast Concrete Construction in Japan

by Y. Kurose, K. Nagami, and Y. Saito

Synopsis : Precast concrete systems are used mainly to construct residential buildings in Japan. The systems include precast concrete wall structures for low to medium-rise buildings and frame structures for medium to high-rise buildings. Most of the precast members are produced in fabricating plants and shipped to the site. Beam-column joints in precast systems are designed using essentially the same design philosophy but considerably different details as used in cast-in-place construction. The details of the joints are usually examined from the structural viewpoint by experimental tests and from the construction viewpoint by mock-up tests. This paper is intended to give an overview of beam-column joints used in precast concrete moment-resisting frame structures. Aseismic design and details of the joints are described and a few examples of construction practice are illustrated. Emphasis is placed on joints in high-rise construction using precast concrete systems.

Keywords: Beams (supports); columns (supports); construction; earthquake-resistant structures; high-rise buildings; joints (junctions); precast concrete; reinforced concrete; structural design

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INTRODUCTION

Precast concrete structures in Japan have been developed mainly to construct residential buildings. The Japan Housing Corporation has constructed about 150,000 apartments using precast concrete systems until 1984 [1] . The precast concrete systems produced a large number of standardized houses and helped solve the housing shortage problem in the 1970s. Japanese construction companies made every effort to increase productivity in precast concrete construction and to prefabricate as many members as possible at that time. However, the situation has recently changed so that standardized houses are no longer preferred. Today, housing developers need to provide a variety of houses to present occupants with a wide choice. This trend makes it difficult to standardize structural members and to maintain high productivity in precast concrete construction.

On the other hand, the situation in construction employment has also changed so that it is rather difficult to hire a large number of skillful on-site workers, particularly workers specializing in formwork or reinforcing work. A construction job is hardly attractive to the young generation, and active construction workers are getting old. The decreasing number of on-site workers raises the cost of cast-in-place construction. Recently the amount of building construction in Japan has rapidly increased and accelerated this trend. The use of precast concrete originally aimed for a short construction period, high productivity and high quality control. Now the precast systems are also used to reduce the amount of on-site construction work.

This paper is intended to give an overview of beam-column joints used in precast concrete construction in Japan. Aseismic design of the joints, details of reinforcement and construction practice are described herein. Emphasis is placed on joints in high-rise construction using precast concrete systems.

PRECAST CONCRETE SYSTEMS

Precast concrete structures constructed in Japan are roughly classified into two types. One of them is the precast concrete wall structure for low to medium-rise buildings as shown in Fig. 1 [2]. This type is a form of tilt-up construction. The following discussion, however, is focused on the other type, the precast concrete frame structure for medium to high-rise buildings [3]. Figure 2(a) shows the precast concrete frame structure in which most of the structural members are prefabricated. The frame structure shown in Fig. 2(b) uses both precast and cast-in-place members to optimize the overall construction.

The majority of precast concrete used in Japan is produced in fabricating plants and shipped to the site. Each plant has several fabricating lines in which concrete is cast into metal forms and cured with steam. The metal form is smooth enough to minimize on-site finishing work of precast members. Sometimes finishing materials such as porcelain tiles are placed on the form surface in order to be cast monolithically with the precast concrete. The fabricating plants produce various precast members such as beams, columns, slabs, walls etc. Dimensions of the precast members are limited by shipping and hoisting operations. Thus, precast assemblies, such as beam-column units, are less preferable than single precast members.

The degree of prefabrication depends on the method of construction. Figures 3 and 4 show beam and column sections with various amounts of precast concrete. The fully-precast beam section shown in Fig. 3(a) is less popular than those shown in Figs. 3(b) and 3(c) because it is generally deeper after the slab is cast. The top of the beam section shown in Fig. 3(b) is cast-in-place with the slab concrete after arranging and splicing the top beam bars. The sections shown in Figs. 3(c) and 4(c) consist of precast cover concrete and cast-in-place core concrete. This technique is used to reduce the amount of on-site formwork and to minimize the weight of the precast member for shipping and hoisting. The column section shown in Fig. 4(b) is made using the centrifugal method in which the concrete-filled form is rotated at a high speed to impose centrifugal force on the concrete [4].

Precast concrete members are fabricated and assembled in various fashions as shown in Fig. 5. For example, precast concrete beams can be connected at midspan locations or at columns. Precast concrete columns are connected at beam or slab levels. The connections are cast-in-place so that the precast members are joined together. Sometimes, prefabricated subassemblies, including precast concrete beam-column joints, are used in the longitudinal direction of a structure in which precast concrete shear walls are installed in the transverse direction.

DESIGN CRITERIA

Design Criteria for High-Rise Buildings

Earthquake resistance generally governs the design of reinforced concrete high-rise buildings in Japan [5]. The buildings are designed so that they will resist strong earthquakes without significant structural damage and catastrophic earthquakes without major failure of the structural frames. As shown in Table 1, earthquake-resistant design consists of the working stress method for strong earthquakes (1st level design) and the ultimate strength method for catastrophic earthquakes (2nd level design). The ultimate strength design is to prevent brittle failure of structural members and joints and to ensure ductile behavior of the overall structure under a beam-sidesway mechanism. The design is always followed by dynamic response analysis to determine whether the maximum response will meet the drift limitations. Maximum velocity is usually used to measure the intensity level of input ground motions in the analysis.

Although there are no code provisions for reinforced concrete beam-column joints in Japan, design of joints has been established empirically as shown in Table 2 [6]. The joints are generally designed assuming a beam-sidesway mechanism and using the ultimate strength method. The nominal shear strength of a joint horizontal section is defined as the sum of a concrete and a reinforcement contribution. Several equations have been proposed to evaluate the joint shear strength, but have not yet led to a common design formula. Figure 6 illustrates conventional Japanese joint design in comparison with U.S. and New Zealand approaches [7,8]. The equations proposed by Kamimura [9] or by AIJ [10], plotted in Fig. 6(a), are usually used to estimate the shear strength resisted by joint concrete. When joint shear exceeds the concrete contribution, transverse reinforcement is proportioned to resist the excess of the shear as shown in Fig. 6(b).

In order to prevent a large amount of bond slip or anchorage distress along longitudinal bars within the joint, bar development should be examined, particularly for beam bars as shown in Table 2. Development of beam bars passing through the joint is taken to be the larger of 20 times the bar diameter or the length required to develop an average bond stress of $4\sqrt{Fc}$ or less (Fc = concrete compressive strength in kg/cm^2) when subject to tensile yielding of the bar at one end of the joint. Development length for a hooked bar, which is usually defined as the entire length from the column face to the end of the tail extension, is taken to be not less than 30 times the bar diameter. Note that there is no requirement for the lead embedment length of the hooked bar anchorage, except that the 90° hook should be located at least half the column depth beyond the face of the column.

Structural design methodology for reinforced concrete buildings in Japan has recently shifted toward the ultimate strength design (USD) concept. The Architectural Institute of Japan has currently issued a new design guideline for reinforced concrete buildings based on the USD concept [11]. The guideline contains provisions for design of beam-column joints but, as yet, has not been used in design practice.

Design Considerations for Precast Concrete Structures

Design of precast concrete structures is essentially identical to that of cast-in-place concrete structures. However, the use of precast concrete presents engineers with some unique problems. One of the problems is how to splice longitudinal bars in precast concrete. The longitudinal bars are usually spliced at the same section by various methods shown in Fig. 7 [2]. Enclosed welding, shown in Fig. 7(a), is an arc-welding method in which the ends of the bars are enclosed with a backing sleeve made of copper or steel. Although the welding operation may induce residual stresses in the bars restrained by precast concrete, this method is widely used in high-rise construction with large-size rebars. Mechanical splices, shown in Fig. 7(b), are also used for connecting rebars by clamping a mild steel sleeve over the ends of the bars. The sleeve is "squeezed" by a die or "gripped" by a press to interlock the sleeve with the bar deformations. A grouted sleeve splice, shown in Fig. 7(c), is a method in which non-shrink grout is injected into a cast-iron sleeve enclosing the ends of the bars. This method is usually used to connect longitudinal bars in vertical members. It should be noted that the mechanical and grouted sleeve splices may cause a small amount of bar slip and/or local stresses in the concrete during strong earthquake motions. Gas pressure welding, which is the most popular method in cast-in-place construction, is seldom used to splice rebars in precast concrete because of difficulties associated with bar shortening caused by the welding operation. Beam longitudinal bars in the section shown in Fig. 3(c) are lap-spliced with additional bars placed from one beam end, through the joint to the other beam end, as shown in Fig. 8.

Another problem in precast concrete structures is shear transfer in the construction joint between precast concrete and cast-in-place concrete. The surface of precast concrete in the construction joint should be roughened or keyed, as shown in Fig. 9, and/or provided with dowel or friction reinforcement, such as stirrups as shown in the beam section in Fig. 3(b).

The other problem of great importance is related to details of connections between precast concrete members. The connections include beam-to-beam, column-to-column and beam-to-column joints. The beam-to-column joints are either precast or cast-in-place depending on the method of construction, as shown in Fig. 5. The details of the joints are strongly influenced by construction practice, and are usually examined from the construction viewpoint as well as the structural viewpoint. Details which are considerably different from those in cast-in-place construction are usually verified through experimental testing of joint specimens fabricated according to the construction practice. Figure 10 illustrates results of tests on interior and exterior joint specimens with precast concrete beams modeling those shown in Fig. 9. While bottom beam bars are anchored with 90° hooks in the interior and exterior joints, top beam bars are developed continuously through the interior joint or anchored with 90° hooks in the short stub extending from the exterior joint. The two specimens failed in beam flexure and demonstrated the ductile behavior anticipated in the design. Figure 11 shows various details of beam-column joints: (a) top and bottom bars in precast beams are developed continuously in a U-shape within the interior joint [12], (b) top beam bars are anchored with 180° hooks in the exterior joint, (c) the joint is prefabricated simultaneously with beams [13], and (d) precast concrete beams and columns frame into the cast-in-place joint [14]. These details have been verified by experimental tests and used in actual construction projects. If the joints are detailed appropriately, the frame structures using precast concrete will resist severe earthquakes in a ductile manner similar to cast-in-place concrete structures.

CONSTRUCTION PRACTICE

Two examples of reinforced concrete high-rise construction in Tokyo are shown in Figs. 12 and 13. In both cases, high-rise residential buildings were constructed using precast concrete systems. High-strength concrete (up to 6 ksi) and large-size deformed bars (up to a diameter of 1.6 in.) were used in the construction. The buildings will resist earthquakes by moment-resisting space frames.

Figure 12 shows construction photographs from the 25-story buildings [12]. In this project, columns were cast-in-place using ordinary forms or a precast concrete cover (see Fig. 4(c) for the section). Beams were prefabricated in various manners as illustrated in (b). The beam bars were spliced at midspan locations by enclosed welding as shown in (c), or anchored in the beam-column joint with the U-shaped bar development as shown in (d) (see Fig. 11(a) for details). The beam-beam and beam-column joints were cast-in-place with slab concrete. The exterior side of precast beams, columns, and walls were covered with tiles in the fabricating plant.

Figure 13 shows the construction of a 30-story building. The building has an opening at the center of each floor as illustrated in (a). In this project, beams in exterior frames and around the opening were prefabricated as shown in (b) (see Fig. 9 for photograph of beams before shipping). While the top beam bars were spliced at midspan locations by enclosed welding as shown in (c), the bottom beam bars were anchored with 90° hooks in the beam-column joint (see Fig. 10 for details). The joints were reinforced with closed hoops and were cast when concrete was placed on the top of slabs and beams. Precast concrete decks were produced in the site plant and were used to construct composite concrete floor slabs. The other precast members, including beams, walls, and stairs, were produced in the contractor's fabricating plants and shipped to the site. Beams in interior frames and columns were cast-in-place with large reusable form systems.

CONCLUDING REMARKS

Major construction companies in Japan have developed various structural systems using precast concrete and operate their own fabricating plants to produce precast concrete members. The precast systems have been verified through experimental tests on specimens representative to connections used in actual construction projects. Details of the systems strongly depend on the specific construction practice developed by the individual company. This situation makes it difficult to establish building codes that uniformly treat precast concrete structures.

Design of beam-column joints in precast concrete construction is essentially identical to that used in cast-in-place construction. The design is based on the ultimate strength method assuming a beam-sidesway mechanism. However, special attention should be paid to reinforcement details, shear transfer across construction joints and bar splices to longitudinal reinforcement placed in precast concrete.

The increasing amount of building construction in Japan has accelerated the shortage of on-site construction workers and increased the use of precast concrete. Precast systems are now used to construct not only residential buildings but also factories, commercial buildings (office, shopping center, etc.), or educational facilities (college, school, etc.). Construction companies in Japan are eager to apply their precast systems to a wider range of applications, and are searching for better construction performance (lower cost, easier on-site work, shorter construction period, etc.). Current studies of precast systems by construction companies include the following topics:

- Precast systems with high-strength materials.
- Precast systems in nuclear power plants.
- Precast systems for composite or mixed structures.
- Precast systems for underground structures.

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The valuable suggestions and materials provided by Messrs. S. Bessho (Kajima Corporation), K. Yoshioka (Ohbayashi Corporation), S. Sugano and T. Nagashima (Takenaka Corporation), and J. Kobayashi (Taisei Corporation) are gratefully acknowledged.

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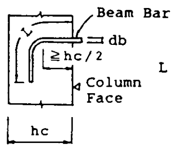
14. "Prefabrication Systems in Concrete Structures", (in Japanese), Structure, No.27, July 1988.

Table 1--Aseismic design criteria for reinforced concrete high-rise buildings (standard values)

Design level	1st level	2nd level
Intensity of ground motions (max. velocity)	25 cm/sec	50 cm/sec
Design method	Working stress	Ultimate strength
Allowable story drift angle	0.5 %	1.0 %

Table 2--Design criteria for beam-column joints

Design of beam-column joint for shear	Development of longitudinal bars
① design shear stress $Vu = \min\left[\frac{\Sigma Mbn}{(1+\xi)cVe}, \frac{\Sigma Mcn}{(1+\eta)cVe}\right](kg/cm^2)$ $\xi = hb/H'$, $\eta = hc/L'$ $cVe = bj \times j_b \times j_c$ $bj = (b_b + b_c)/2$ where Mbn: beam moment capacity (kg cm) Mcn: column moment capacity (kg cm) cVe: joint effective volume (cm^3) bj : joint effective width (cm) b_b, bc: beam or column width (cm) hb, hc: beam or column depth (cm) jb, jc: internal moment arm in beam or column section (cm) H' : column clear height (cm) L' : beam clear length (cm) ② nominal shear strength in the joint $Vn = Vcn + (1/2)Pwfwy \quad (kg/cm^2)$ where Vcn: shear stress carried by concrete (kg/cm^2) pw : transverse reinforcement ratio in the joint fwy: yield strength of transverse reinforcement (kg/cm^2)	① beam bars passing through the joint $\frac{hc}{db} \geq 20$ or $\frac{hc}{db} \geq \frac{fy}{4(4\sqrt{Fc})}$ where hc: column depth (cm) db: beam bar diameter (cm) fy: yield strength of beam bars (kg/cm^2) Fc: compressive strength of concrete (kg/cm^2) ② anchorage by hooked bars  $L = 30 \cdot db$

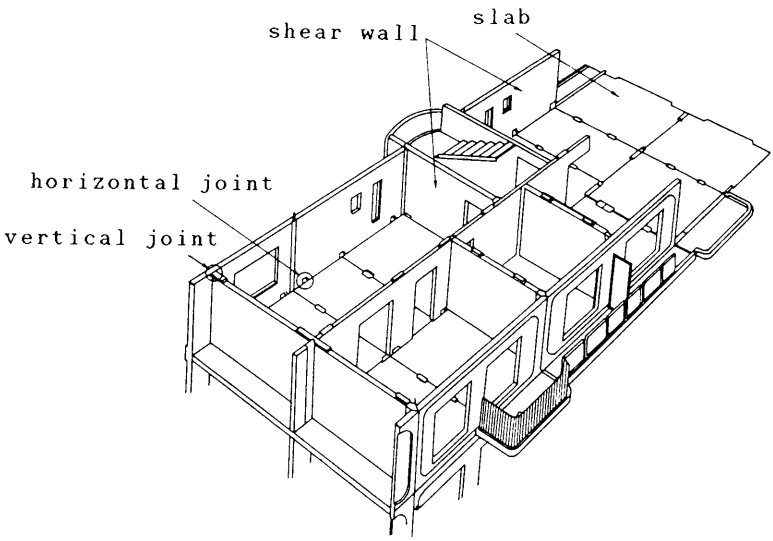


Fig. 1--Precast concrete wall structure

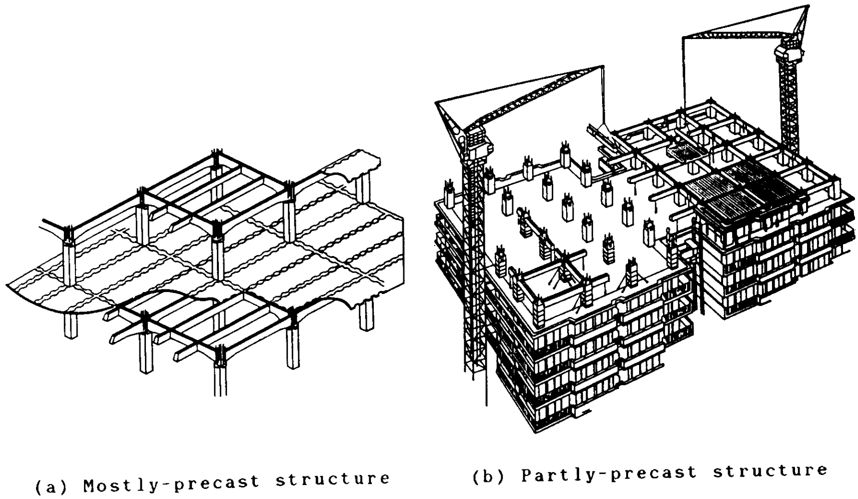


Fig. 2--Precast concrete frame structures

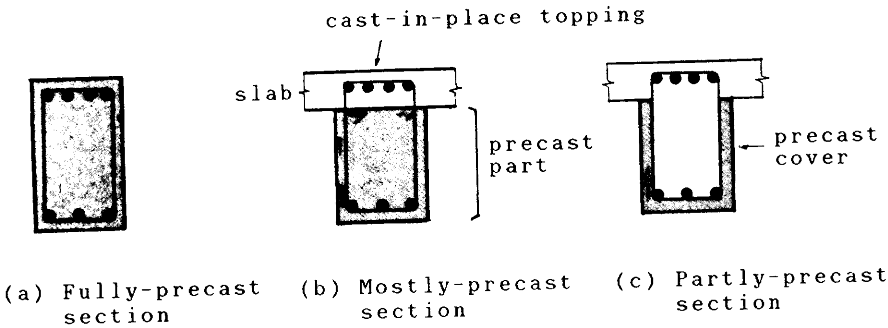


Fig. 3--Precast concrete beam sections

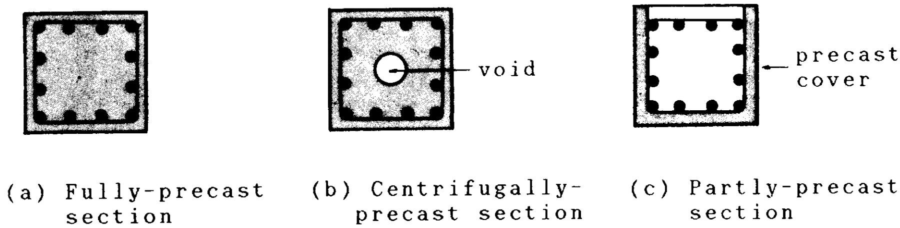


Fig. 4--Precast concrete column sections

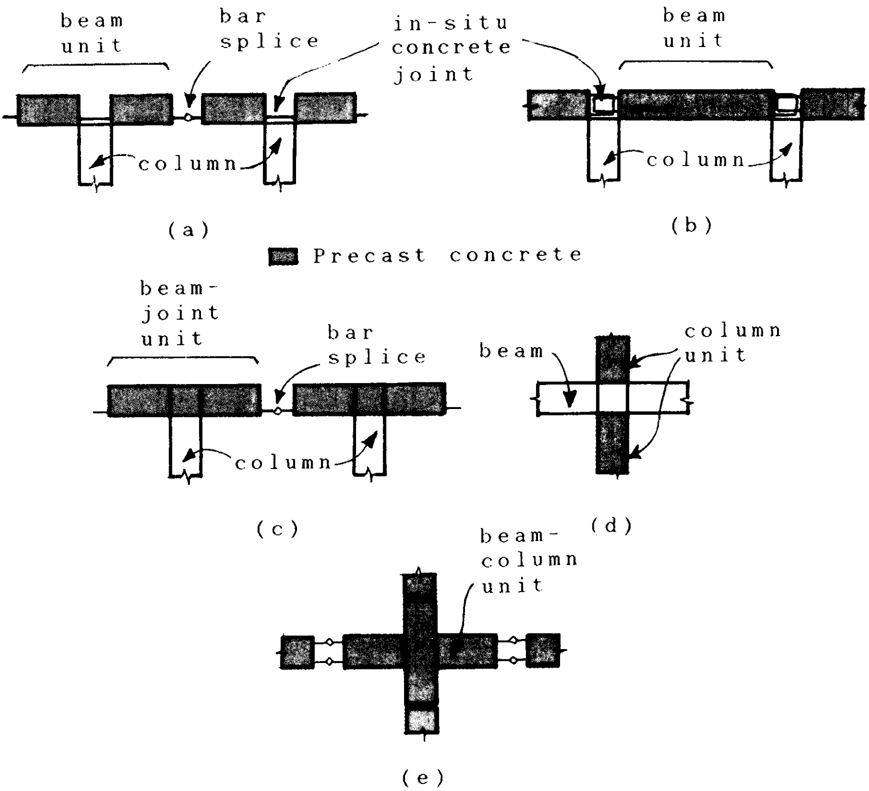
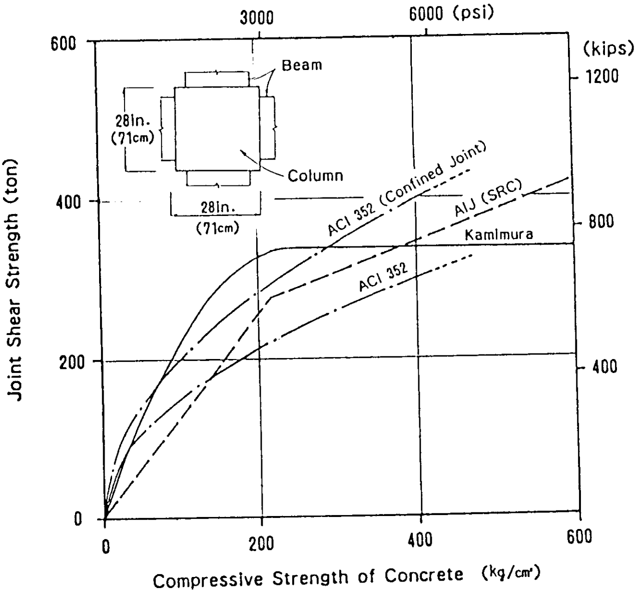
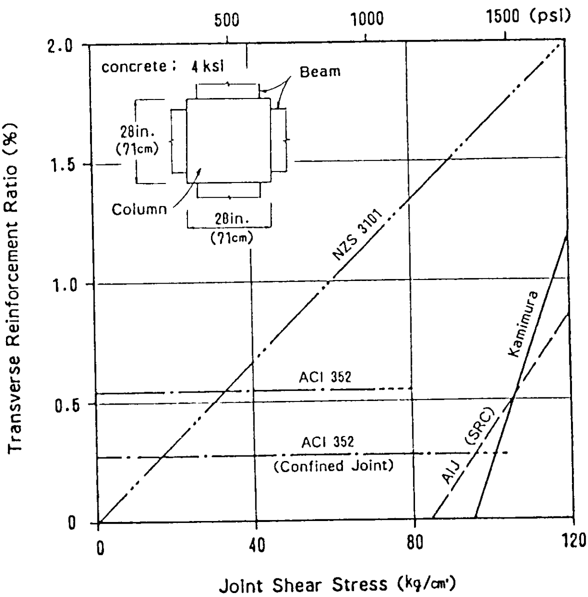


Fig. 5--Framing variations in precast concrete construction



(a) Joint shear strength carried by concrete



(b) Required ratio of joint transverse reinforcement

Fig. 6--Design of beam-column joint for shear

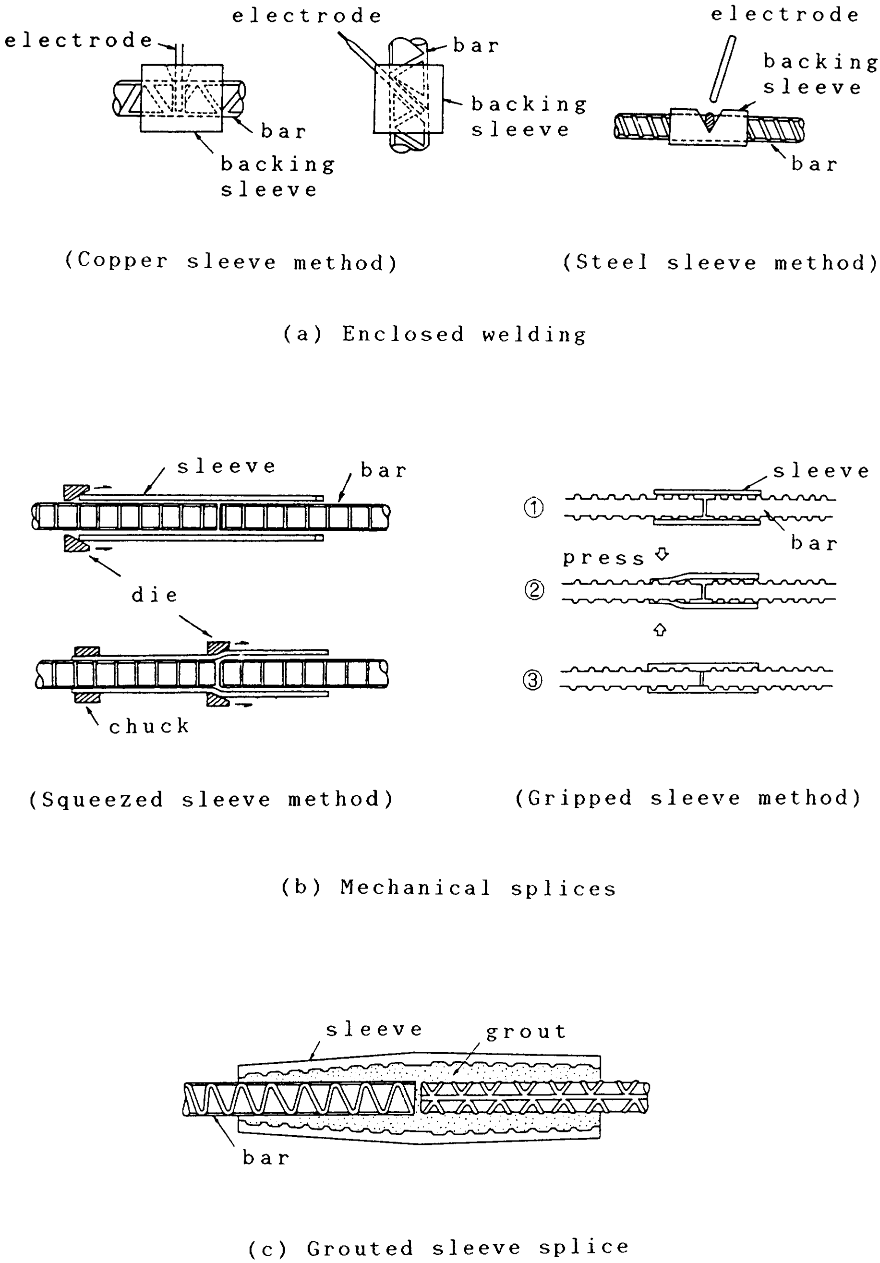
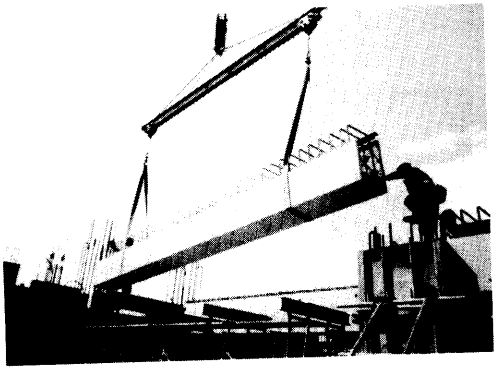
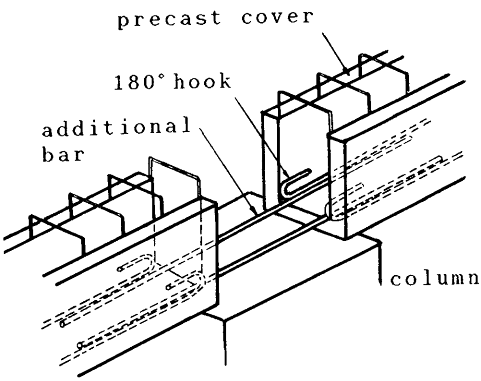


Fig. 7--Longitudinal bar splices

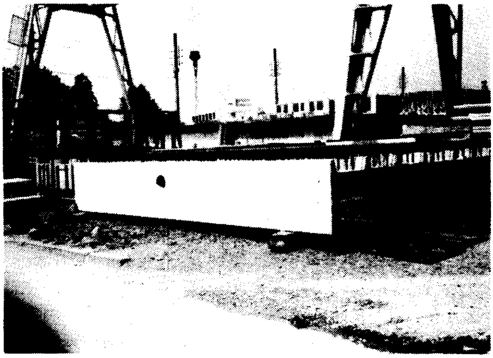


(a) Precast concrete beam

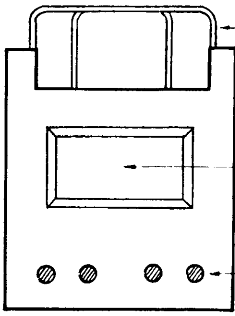


(b) Lap-spliced beam bars

Fig. 8--Lap-spliced beam bars at beam-column joint

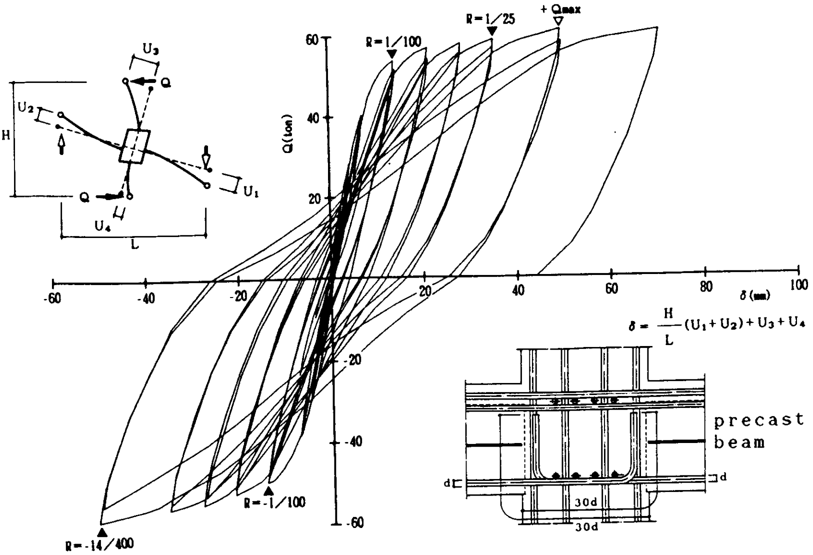


(a) Precast concrete beam

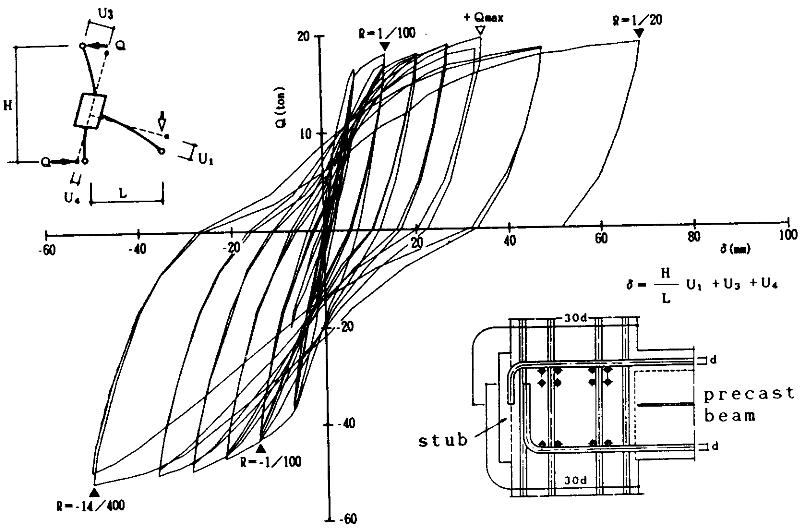


(b) Shear key at beam end

Fig. 9--Shear key on the end of precast concrete beams

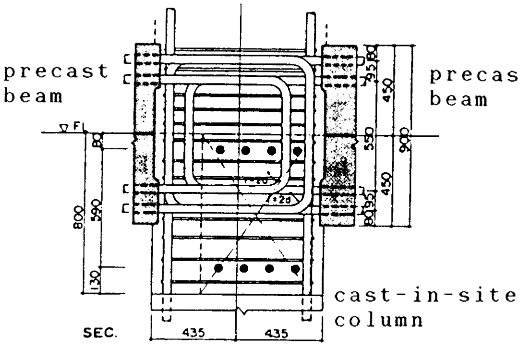


(a) Interior joint

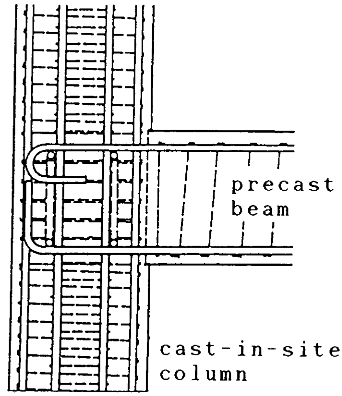


(b) Exterior joint

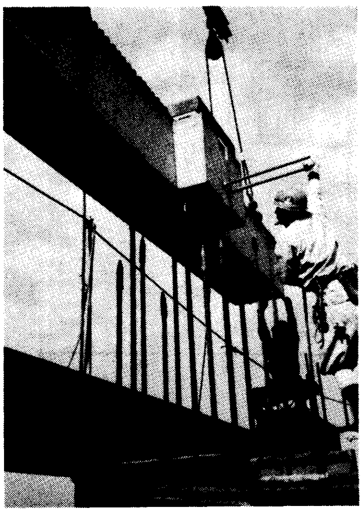
Fig. 10--Test of joints with precast concrete beams



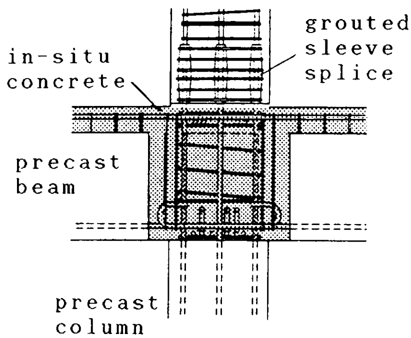
(a) U-shaped bar anchorage
in interior joint



(b) 180° hook anchorage
in exterior joint

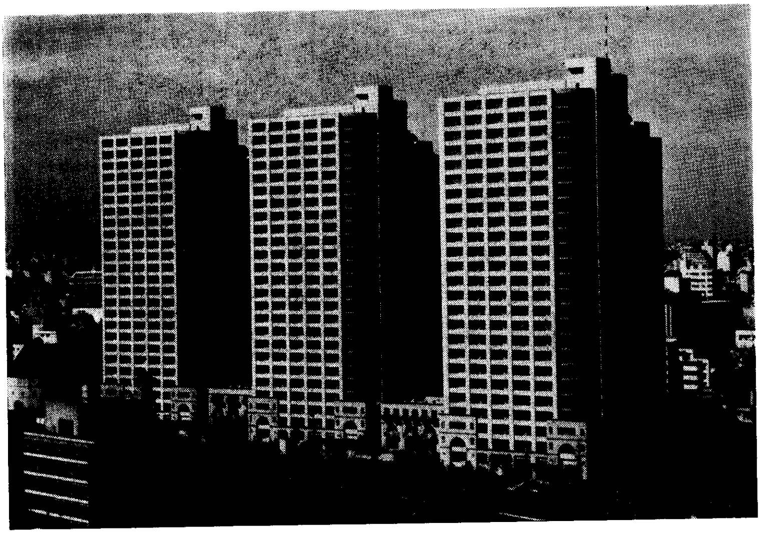


(c) Precast beam-joint unit

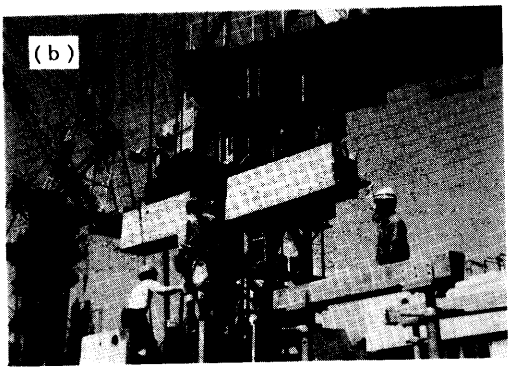


(d) Joint between precast
beams and columns

Fig. 11--Various details of beam-column joints

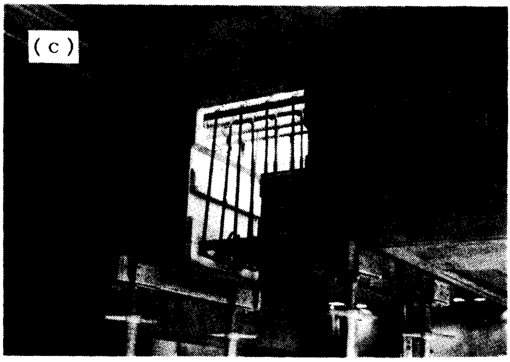


(a) Perspective view

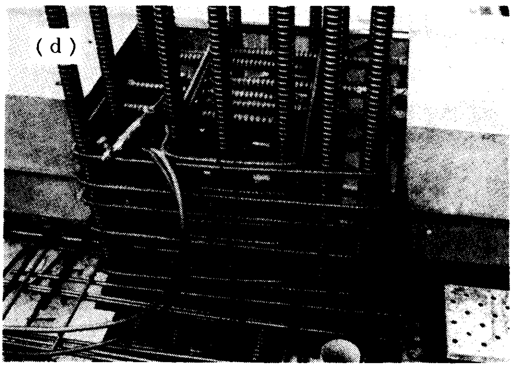


(b) Precast concrete beam

Fig. 12--Construction of 25-story buildings using precast concrete systems

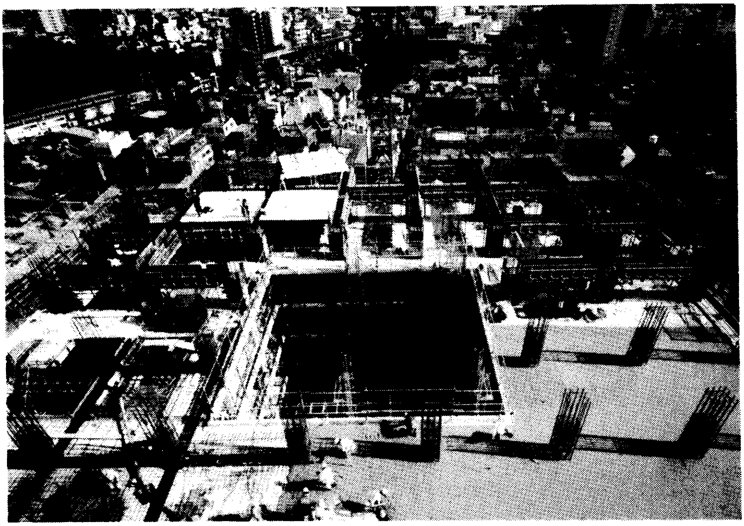


(c) Beam-beam joint

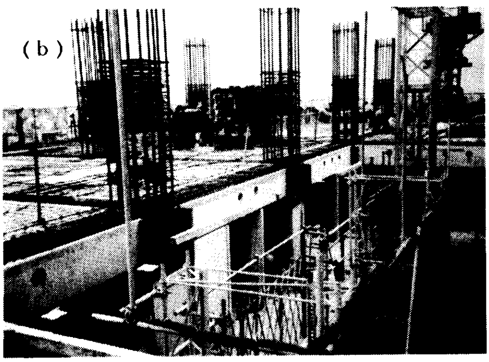


(d) Beam-column joint

Fig. 12 cont.--Construction of 25-story buildings using precast concrete systems

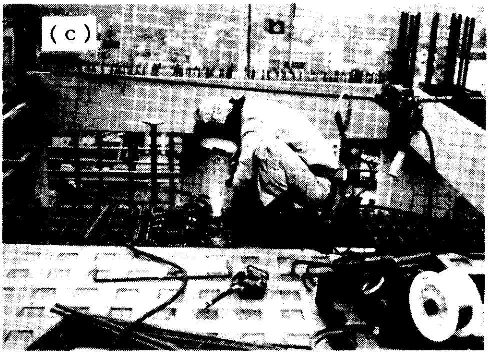


(a) Construction site

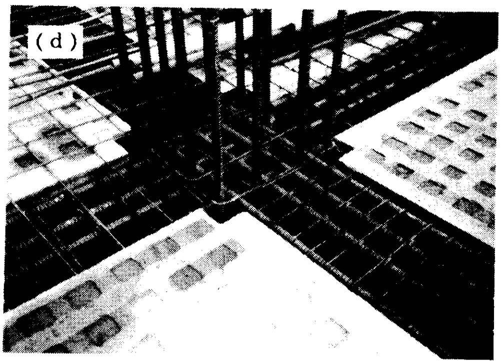


(b) Precast concrete beams

Fig. 13--Construction of 30-story building using precast concrete systems



(c) Beam bar splice
(enclosed welding)



(d) Beam-column joint

Fig. 13 cont.--Construction of 30-story building using precast concrete systems