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Study on Damage Controlled Precast-Prestressed Concrete Structure with P/C MILD-PRESS-JOINT – Part 1: Overview of P/C Mild-Press-Joint Building Construction and its Practical Applications

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INTRODUCTION

The seismic design of some buildings has been based on new methods aimed at protecting human lives from even large earthquakes by utilizing the structure's plastic deformation capacity. In the Hyogo-ken Nanbu Earthquake, many of these buildings escaped the worst damage including collapse. It was thus considered that they had achieved their safety objective of protecting human lives. However, they suffered cracking and residual deformation, and some that had suffered large damage had to be demolished. In addition, depleting natural resources, global environmental issues, etc., make it desirable to extend building life. Accordingly, it is regarded as important to sustain post-earthquake building usage and to quickly restore building functions. Although security of human lives is of paramount importance, it is also desirable to minimize damage to building structures to enable continued use of buildings and to sustain property values even after the largest level earthquake. It is therefore necessary to establish a design method for building structures in which damage is controlled during a large earthquake. The authors and others have thus proposed a frame using a PC Mild-Press-Joint method [1]. With this method, members are press-bound by prestressing strands in columns and beams of PCa with an initial tension set to 0.5 Py / strand (Py: nominal yield strength) that is lower than in a conventional PC structure. This method allows a rocking between the column and beam press-binding interfaces during a large earthquake. This is aimed at controlling damage to members and minimizing residual deformations. The following sections outline the PC Mild-Press-Joint method and describe application examples.

Keywords: P/C MILD-PRESS-JOINT structure, damage control, corbel, elastic rotation

DAMAGE CONTROLLED CONCRETE-BASE STRUCTURES

In conventional RC structures, earthquake energy is absorbed by all structural members, resulting in a lot of cracks. Furthermore, reinforcing bars yield under large earthquake load. This results in spindle-shaped hysteresis characteristics, as shown in Fig. 1(a), and large residual deformations. In PC structures, cracking is suppressed by the compressive stress introduced into the concrete. Even large deformations are restored after an earthquake by the internally introduced prestress force. Therefore, origin-oriented hysteresis characteristics, as shown in Fig. 1(b), are indicated. The authors have utilized these characteristics of PC structures to develop a P/C Mild-Press-Joint method that realizes damage control. Precast-concrete frames using unbonded post-tension are being studied in the U.S.A. in the area of concrete-based structures utilizing the characteristics of crack-resistance, origin-oriented hysteresis, and so on. These studies are typically found in the PRESS research program [2], [3].

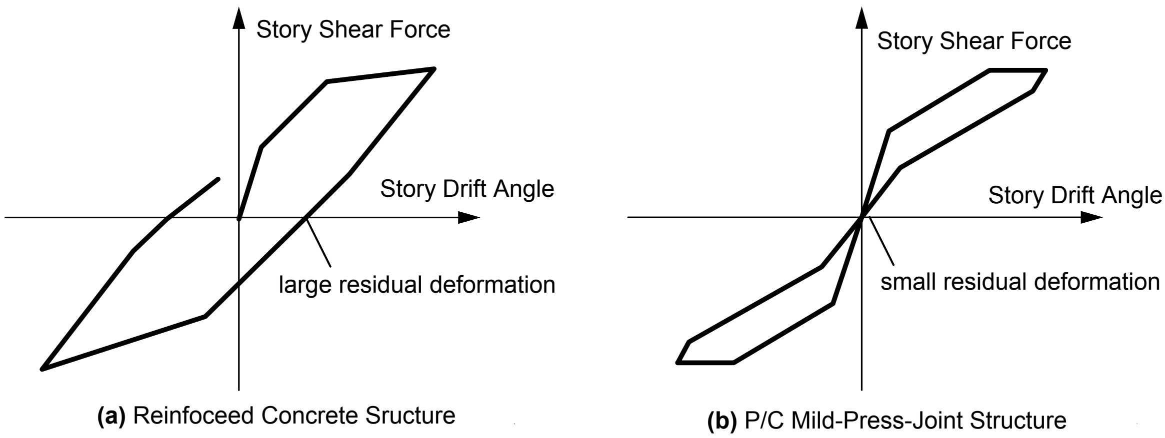


Fig. 1. Compare Reinforced Concrete Structure with P/C Mild-Press-Joint Structure

OVERVIEW OF P/C MILD-PRESS-JOINT SYSTEM

Principal features of the proposed new structural system are as follows.

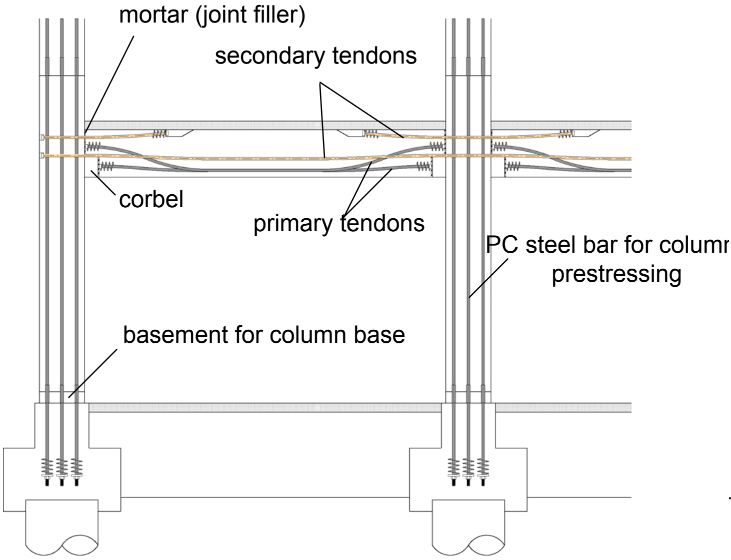
1) Structural members, beams and columns are precast-prestressed components. Structural frames are realized by connecting the beam and the column using prestressing tendons. Table1 shows structure design criteria for P/C Mild-Press-Joint system. The frames behave as full-prestressing structures under design vertical load and under Level 1 earthquake load provided for by the Japanese Building Code. Level 1 earthquake corresponds to moderate earthquakes, which are being expected to occur in Japan approximately every 50 years. Under Level 1 earthquake load, connections among beams and columns behave as rigid joints and interfaces among them remain in compressive state. Under Level 2 earthquake load (recurrent period of 500 years) and Level 3 earthquake load (recurrent period of 1000 years), the connections rotate elastically to prevent damage to beams and columns. Seismic energy dissipation devices, such as damper and damping wall, are installed as needed.

Tab. 1. Structural Design Criteria

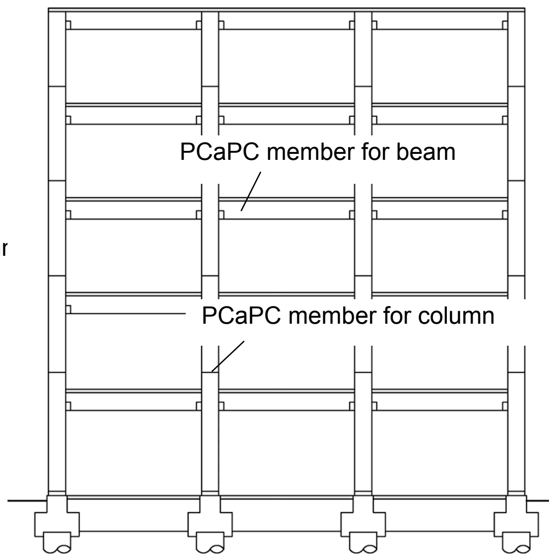
	Behavior of beam-column interface	Rotation angle of member	Storey drift angle (residual story drift angle)	Damage of general member of framework	Damage of beam-column interface
Vertical loading	Compressive stress remeins at beam-column interface	Rigid	-	None	None
Level 1 (moderate earthquake)	Compressive stress remeins at beam-column interface	Rigid	-	None	None
Level 2 (severe earthquake)	·Member of framework rotate elastically ·Secondary EC strands does not yield	<1/50	<1/75 (<1/500)	None	Beam end concrete & mortar (joint filler)
Level 3 (very severe earthquake)	·Member of framework rotate elastically. ·Secondary EC strands does not yield	<1/33	<1/50 (<1/400)	None	Beam end concrete & mortar (joint filler)

2) Fig.2 shows example of P/C Mild-Press-Joint structure prestressing tendons are classified into primary tendons and secondary tendons. The primary tendons are stretched up to 85% of nominal yielding strength, and then are anchored at the end surface of each component. They never are placed through adjacent

components. The secondary tendons are playing the role to connect beams and columns or columns and foundations. The effective prestressing force of the secondary tendons is limited to 50% of nominal yielding strength. It is because the secondary tendons should not be entered in plastic range under Level 2 or Level 3 design earthquake loads that initial stretching force is controlled to low level.



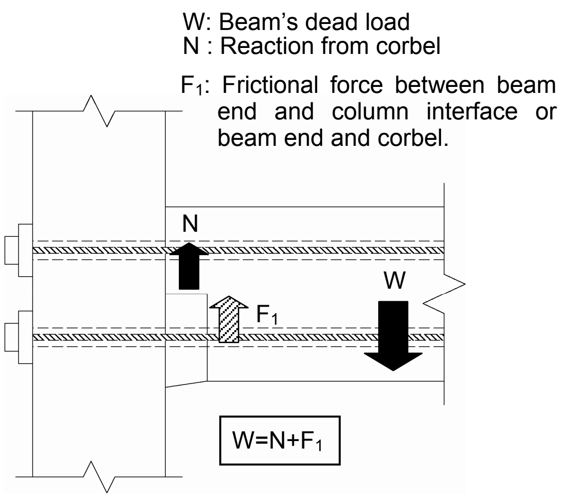
(a) Wiring Plan of P/C Mild-Press-Joint Structure



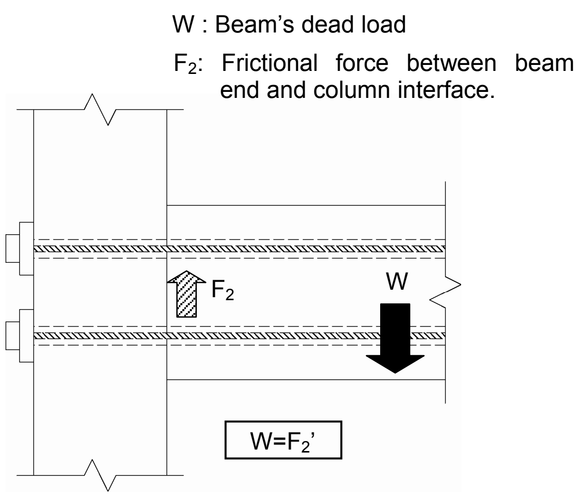
(b) Outline of P/C Mild-Press-Joint Structure

Fig. 2. Example of P/C Mild-Press-Joint Structure

3) Frictional force produced between beam end and column interface by prestressing strand has to transmit shearing stress to column in traditional P/C anchoring method. The problem which it can't resist beam's dead load, if prestress forces introduced into the PC steel members strand are not set some level. But, in P/C Mild-Press-Joint system, column has corbel shown in Fig.3. This makes corbel transmit beam's dead load. So, it is easy to construct stable structure, even if prestress forces introduced into the PC steel members strand are set at 50% of the nominal yield strength of the prestressing strands.



(a) Structure with Corbel



(b) Structure without Corbel

Fig. 3. Difference between with Corbel and without Corbel

Characteristics of P/C Mild-Press-Joint Method

1) High durability
Damage conditions of the joint used in the PC Mild-Press-Joint method are shown in Fig. 4. Using the high quality industrial products (concrete strength Fc: 50N/mm^2) for main members, column and beam members are press-bound by the tensile forces of the prestressing strands. Prestress prevents cracks from occurring. Elastic rotation is generated at the joints in a secondary design level earthquake and above, and closes after the earthquake. Therefore, if the joints are inspected and repaired after the earthquake, the structure's life is maintained.

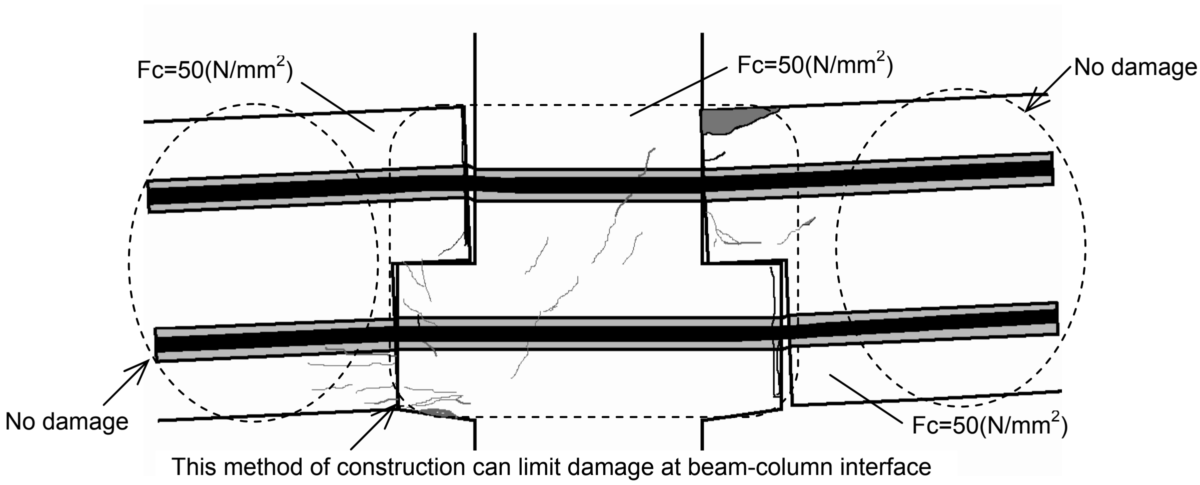
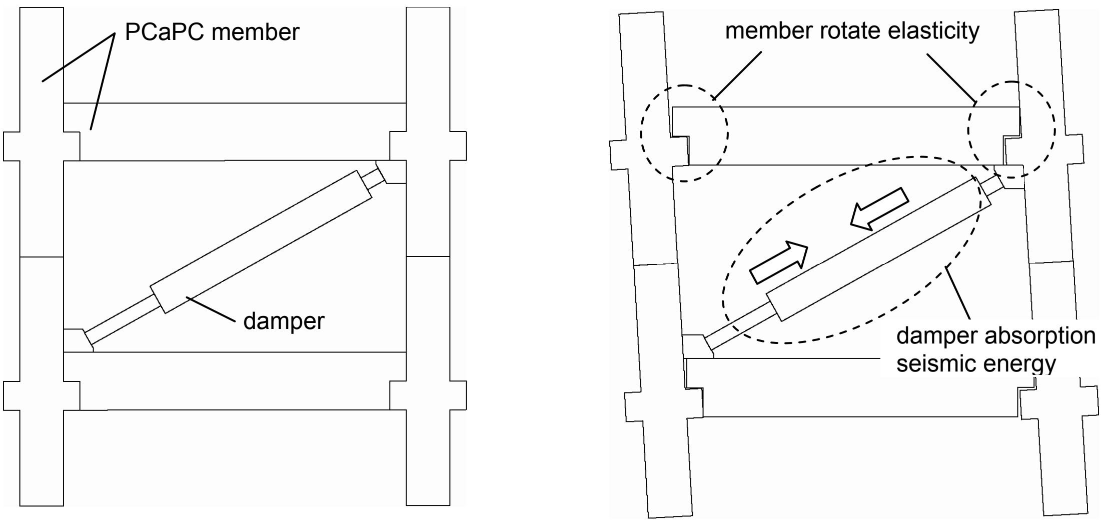


Fig. 4. Ultimate State (P/C Mild-Press-Joint)

2) High seismic energy adsorption capacity
The mechanism in which the P/C Mild-Press-Joint structure absorbs seismic energy is shown in Fig. 5. Capacity to absorb an earthquake's input energy is lower in prestressed concrete structures than in reinforced concrete structures and steel structures. This method allows joint rotation during the earthquake and thus improves this capacity. It can also efficiently absorb energy by co-using damping members.

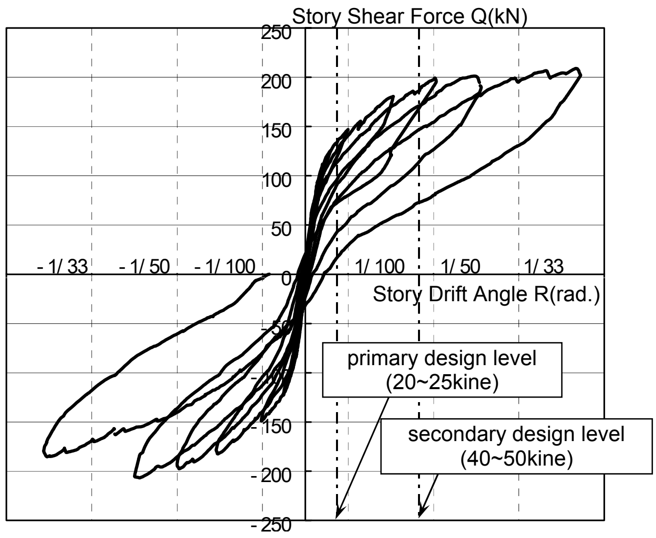


(a) Bofore applying horizontal loading **(b)** Under horizontal loading

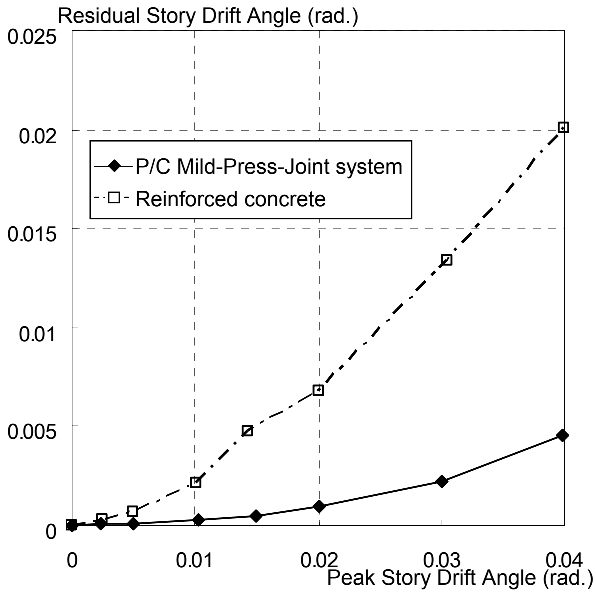
Fig. 5. Example of Energy Absorption in P/C Mild-Press-Joint Structure

3) Small residual deformation

Cracks do not occur in general parts of members even under an earthquake force of secondary design level. Furthermore, primary PC steel members and secondary PC steel members do not yield. Therefore, deformation is restored after the earthquake and the prestress minimizes residual deformation. Local damage due to concrete collapse occurs at beam-column joints. This is caused by joint rotation. However, the Influence on residual story deformation angle is small. The typical hysteresis loop of the Mild-Press-Joint system is shown in Fig. 6(a). The relationship between the peak story deformation angle and the residual deformation angle is shown in Fig. 6(b). It is found that neither primary nor secondary PC members yield even when they suffer a secondary design level seismic force and above. Thus, deformation is restored by the prestress effects after the earthquake finishes, while showing hysteresis where residual deformation is very small.



(a) Hysteresis Loop

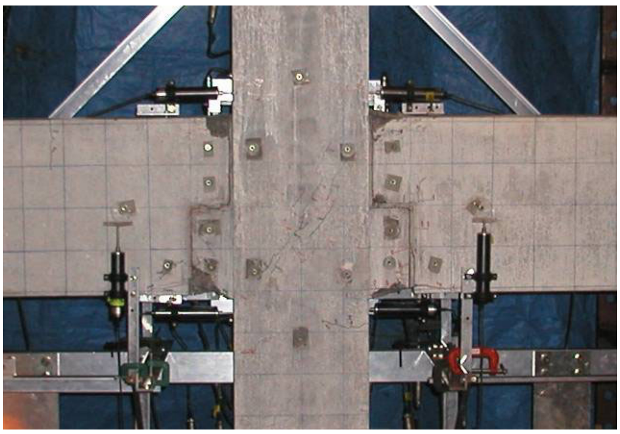


(b) Residual Story Drift Angle- Peak Story Drift Angle Relationship

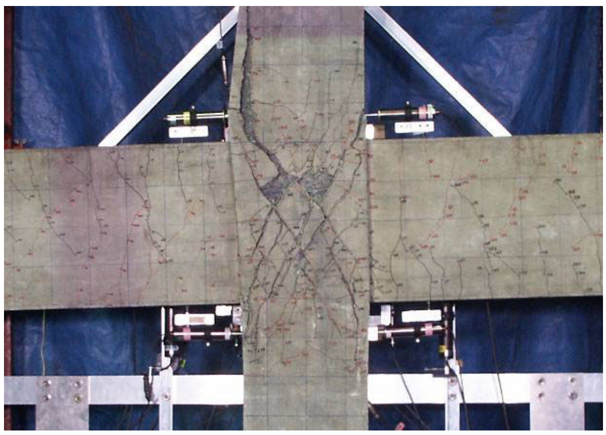
Fig. 6. Deformation Property of P/C Mild-Press-Joint

4) Easy assessment of post-earthquake damage

Photos of experiments on frame beam-column joints conducted in 2003 (story deformation angle R= 1/25 rad. at the final stage) are shown in Fig. 7. Earthquake damage was localized to binding parts and damping members. This shows that repair cost and executors can be estimated and located with high accuracy in the design stage.



(a) P/C Mild-Press-Joint



(b) Reinfoceed Concrete

Fig. 7. Ultimate Stage (story drift angle R= 1/25 rad.)

DESIGN DETAILS

P/C Mild-Press-Joint detail is shown in Fig. 8. Two kinds of PC steel members, primary and secondary, are employed in this joint method. Both members are placed in a pipe sheath, into which grout is injected to integrate them. Primary tendons, which are stretched to 80 % of nominal yielding strength, are anchored at the end surface of beams. Those members are aimed at making the beam members PC members. The members were designed for full prestress under long-term load. Secondary tendons coated with epoxy resin of suitable adhesion capacity are employed for the beam-column press-binding. The prestressing strands are anchored in the column and beam members. Prestress forces introduced into the PC steel members strand by strand are set at 50% of the nominal yield strength of the prestressing strands. As a result, although the tensile forces in the prestressing strands increase with rotation during the earthquake, the strand will stay within the elastic range. Thus, the frame is restored to its original location after the earthquake and residual deformation becomes very small. To show why the prestress force is set to 50%, conceptual skeleton curves of the frame are presented in Fig. 9 for prestress forces of 25%, 50% and 75%. As shown, for an introduced prestress force of 75%, yield is reached before the target story deformation angle is reached. For an introduced prestress force of 25%, large deformation is needed to utilize the strand's full strength. An introduced prestress force of 50% maintains the prestressing strand within the elastic range over the angle up to the targeted secondary design level (R=1/75rad.). This does not cause excess deformation at maximum strength and does not to lose prestress force under repeated deformation. Mortar is inserted between column face and beam end. Because it is difficult to undertake construction in the case that clearance that is between clearance of column and beam's span is zero.

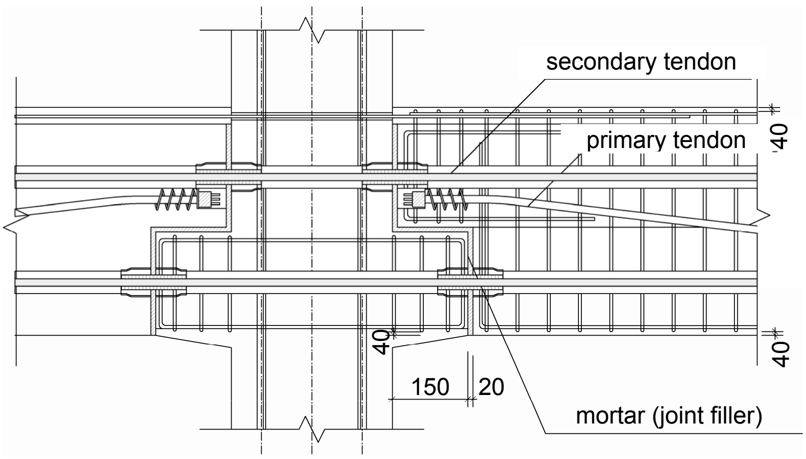


Fig. 8. Detail of Beam-Column Connection

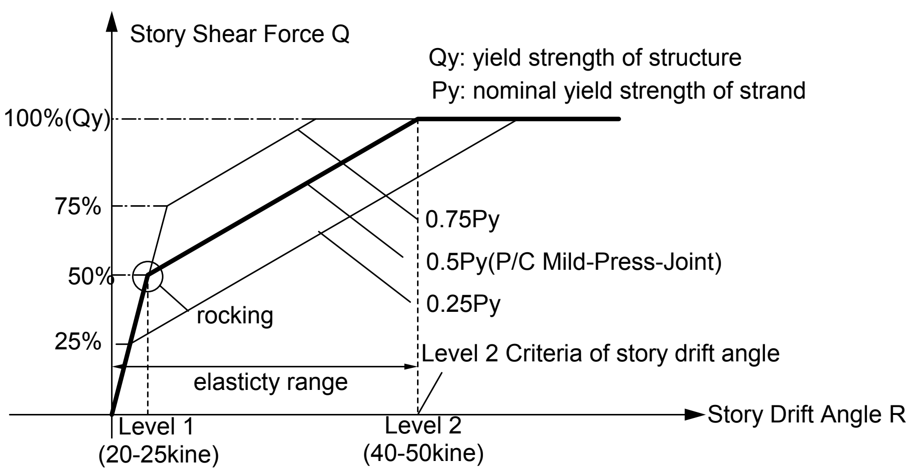


Fig. 9. Conceptual Skeleton Curve of the Frame for Various Levels of Prestress Forces

EXAMPLE OF P/C MILD-PRESS-JOINT METHOD APPLICATION

Katsura Campus of Kyoto University

Buildings where the PC Mild-Press-Joint method was actually applied are introduced below. Photos1 (a), (b) and Fig. 10 show the Katsura Campus of Kyoto University, Japan. The building is of four stories, about 20m high and 45m long in the ridge direction, showing a delicate line at the façade.

(a) Outside View (1)

(b) Outside View (2)

Phot. 1. Outside View of Katsura Campus of Kyoto University

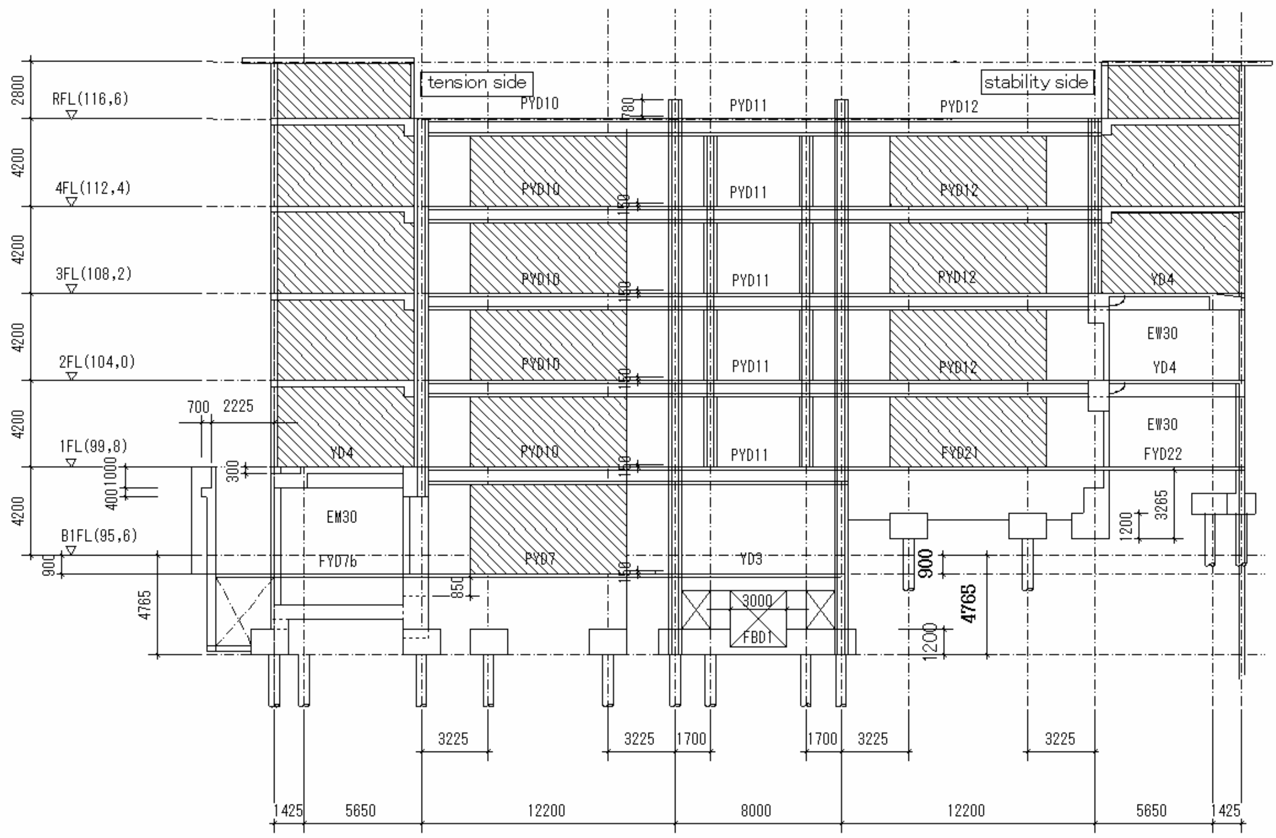
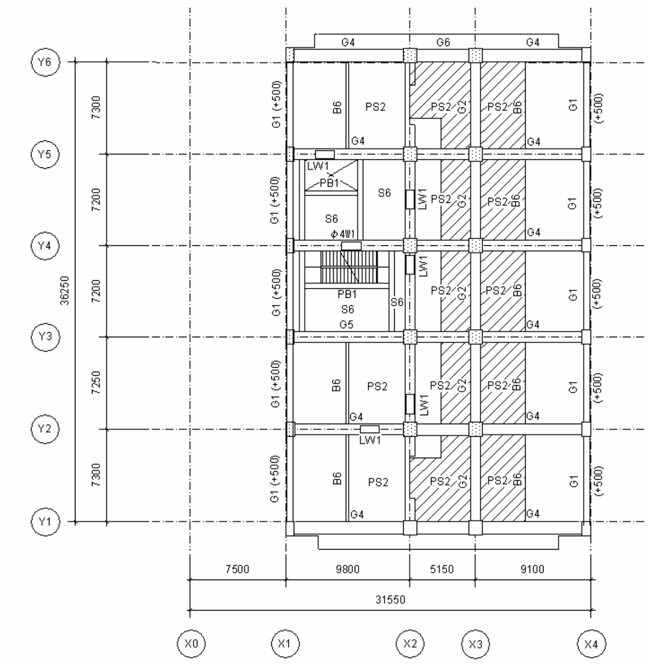


Fig. 10. Framing Elevation

LUXIA

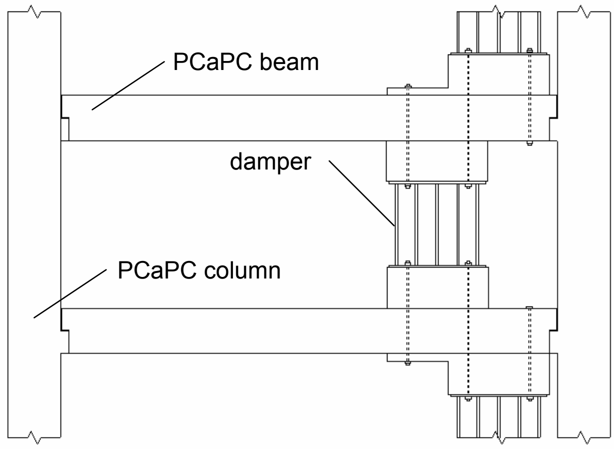
A 22-story high-rise condominium named "LUXIA", 72.3m high, built in Shinagawa, Tokyo is shown in Fig. 11. To increase its seismic-energy absorption capacity, steel dampers with low-yield steel are employed in each story. Damper layout is showed in Fig.12. This increases earthquake resistant capacity. It is used damper of NK=LY100, NK-LY160, NK-LY225, in "LUXIA". Mechanical properties of damper showed in Table 2.

(a) Outside View



(b) Ground Plan

Fig. 11. Outside View and Ground Plan of "LUXIA"



(a) Y2 Sectional View of "LUXIA"

(b) Steel Damper Used in "LUXIA"

Fig. 12. Damper Layout in "LUXIA"

Tab. 2. Mechanical Properties of Damper

damper	mechanical property					
	yield strength σ_y	tensile strength σ_{max}	σ_y / σ_{max}	stretch		Charpy absorption energy
	[N/mm2]	[N/mm2]	[%]	test piece	[%]	[J]
NK-LY100	100±20	200-300	<60	No.5	50<	27<
NK-LY160	160±20	220-320	<80	No.5	45<	
NK-LY225	225±20	300-400	<80	No.5	40<	

CONCLUSIONS

1) It is possible to build a high-tenacity frame by using corbels and by press-binding the beam and column while controlling the introduced prestress force at 50%.
2) It is easy to assess post-earthquake damage, since the damaged areas are localized.

REFERENCES

1. Kiyoshi Nakano et al., Damage Controlled Seismic Design by Precast Prestressed *Summaries of technical papers of annual meeting, Architectural Institute of Japan (Kanto)*, September 2001, pp893-894 (in Japanese)
2. M.T. EL-Sheikh, R. Sause, S. Pessiki, L. Lu, Seismic Behavior and Design of Unbonded Post-tensioned Precast Concrete Frames, *PCI Journal, Vol. 44, No.3, pp.54-71*, May-June 1999
3. M.J.N. Priestley, The PRESS Program – Current Status and Plans for Phase III, *PCI Journal, Vol41, No.2, , pp.22-40*, March-April 1996