

## **APPLICATION OF HIGH-RISE PRECAST PRESTRESSED CONCRETE BUILDINGS IN HIGH-SEISMICITY REGIONS**

**Satoru FUKAI<sup>1</sup>**

### **SUMMARY**

The possibility of application of precast prestressed concrete system to buildings up to 60m high in high-seismicity regions is discussed. Three typical types of precast prestressed high-rise buildings are chosen as an object of structural design trial. The buildings are designed according to the guideline coded in a research project entitled "Research and Development of Structural Design and Construction Guideline for Precast Prestressed Concrete Structures", organized in Japan Association for Building Research Promotion. This guideline is based on capacity spectrum method which predicts dynamic response using capacity spectrum and demand spectrum. The results of the structural design revealed that precast prestressed concrete system are successfully applied to high-rise buildings even in high-seismicity regions, and that those buildings are comparable to equivalent steel-encased reinforced concrete buildings in terms of structural and economic performance.

### **INTRODUCTION**

A project entitled "Research and Development of Structural Design and Construction Guideline for Precast Prestressed Concrete Structures" was carried out in Japan. This project aimed at providing a seismic design guideline for high-rise precast prestressed concrete buildings up to 60m. The project is organized by Building Research Institute of Ministry of Construction, cooperated with construction companies, design firms, research institutes and universities. Buildings designed according to this guideline are expected to be superior to buildings designed in other structural systems in terms of structural and economic performance. This paper describes a structural design trial carried out on typical types of high-rise precast prestressed concrete buildings designed according to this guideline, and the merits of these buildings.

### **STRUCTURAL DESIGN TRIAL**

Three typical types of precast prestressed concrete buildings are chosen; Type-1: office building with a core at its center, Type-2: office building with cores at both sides, and Type-3: condominium with a open space at its center. The buildings were designed by "Structural Design and Construction Guideline for Precast Prestressed Concrete Structures". This guideline is a displacement-based design in which displacement response to earthquake motions is predicted by capacity spectrum method. In the capacity spectrum method response is obtained as an intersection of the capacity spectrum with the demand spectrum. The capacity spectrum was calculated as a relation between story shear force at the first floor and horizontal displacement at the centroid of a design seismic load distributing along the height in push-over analysis. The demand spectrum usually given with 5% damping factor consists of two parts: constant acceleration ( $S_a=1176\text{cm}/\text{sec}^2$ ) range for high frequency range, and constant displacement ( $S_d=160\text{cm}$ ) for low frequency range. The following equation is used for obtaining demand spectrum with other damping factor than 5%:  $D_h=1.5/(1+10h)$ . The outline and structural performance of these buildings are discussed in the following sections.

<sup>1</sup> Structural Engineering Dept., Nikken Sekkei 2-1-2 Koraku, Bunkyo-ku, Tokyo 112, Japan E-mail:fukai@nikken.co.jp

**Type-1(Office building with a structural core at its center)**

Type-1 building is a 10-story office building with a structural core at its center. A perspective drawing is shown in Fig. 1. An inside view is illustrated in Fig. 2. The longest beam span is 15m. The average story height is 4m. The structural framing isometric drawing is shown in Fig. 3. The typical floor plan and structural elevation are indicated in Fig. 4 and 5, respectively. The typical member sections are shown in Fig. 6. Earthquake resisting system is moment-resisting frames without structural walls. The moment-resisting frames are designed by weak-beam strong-column concept. The beams are partially prestressed concrete members, and composite members with precast and cast-in-place concrete. The columns are ordinary reinforced concrete. The maximum design compressive strength of concrete is about 60MPa.



Fig.1 Outside view

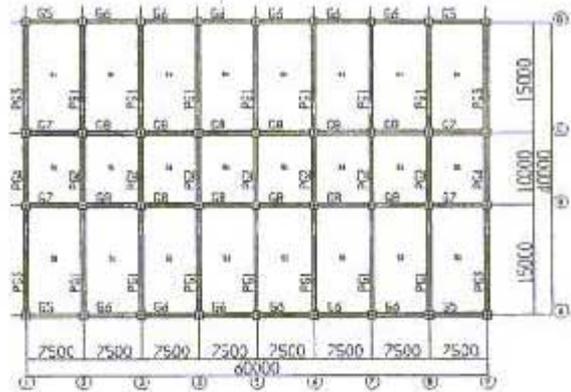


Fig.4 Typical floor plan

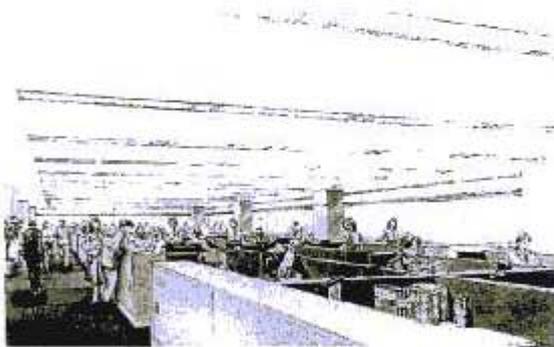


Fig.2 Inside view

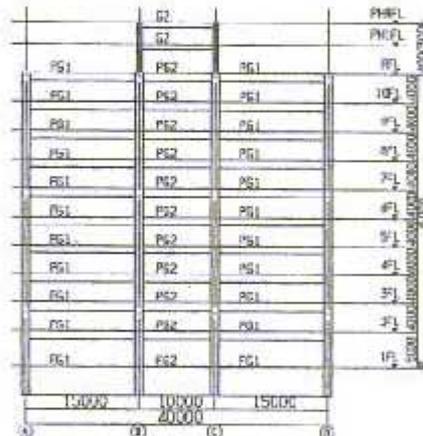


Fig.5 Structural elevation



Fig.3 Structural framing

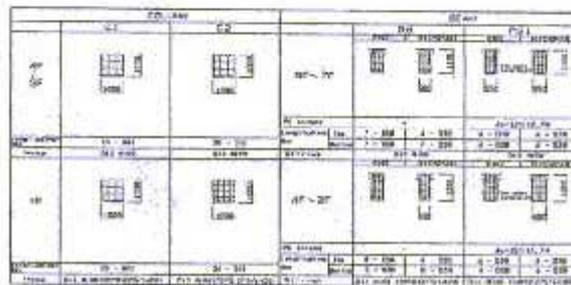


Fig.6 Typical member sections

The story shear-drift relation obtained by a push-over analysis is shown in Fig. 7. The capacity spectrum and the demand spectra are shown in Fig. 8. The demand spectrum with 10% equivalent damping is adopted because the beams are partially prestressed. The base shear coefficient at the maximum inter-story drift of 1/50 is about 0.32 in X direction, and 0.33 in Y direction. In X direction, the spectral displacement of performance point is about 40 cm (1/74), and the spectral acceleration is about 370 cm/sec<sup>2</sup>. In Y direction, the spectral displacement is about 38 cm (1/76), the spectral acceleration is about 380 cm/sec<sup>2</sup>. The plastic hinge formations at the maximum inter-story drift of 1/50 are shown in Fig.9. The plastic hinges formed only at the bottom ends of the first floor columns besides at the beam ends. The results assured the possibility of application of precast prestressed concrete system to this type of buildings.

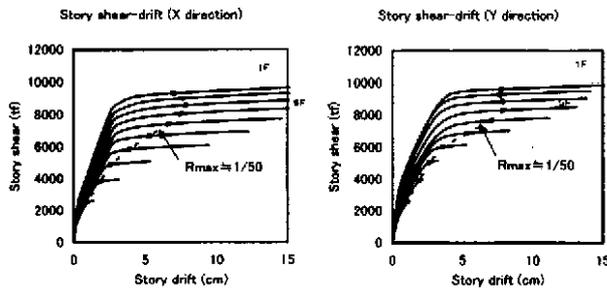


Fig.7 Story shear-drift relation obtained by push-over analysis

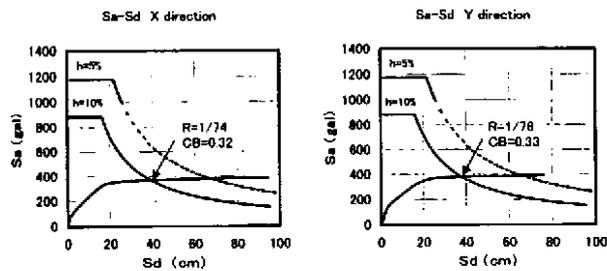


Fig.8 Capacity spectrum and demand spectra

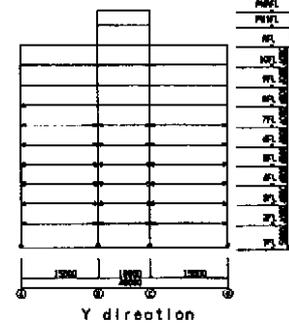
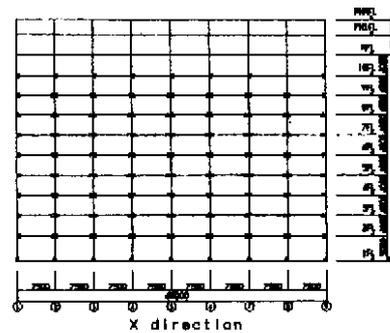


Fig.9 Plastic hinge formation at the maximum inter-story drift of 1/50

The structural performance of the building is compared with that of an equivalent composite building consisted of steel-encased reinforced concrete columns and steel beams. The typical member sections are shown in Fig. 10. The results of the push-over analysis are illustrated in Fig. 11. The base shear coefficient at the maximum inter-story drift of 1/50 is about 0.32 in X direction, and 0.33 in Y direction. The results show no difference in structural performance and dimension of the section between the prestressed concrete and the equivalent composite buildings. Structural cost of composite buildings is usually less expensive than prestressed concrete in Japan. Once other cost is included, however, such as fireproofing materials and ceilings, the difference is very little.

	COLUMN		BEAM			
	CF	CF	SG5	SG5	SG5	SG5
4F						
h direction	400-200-200-200	400-200-200-200	400-200-200-200	400-200-200-200	400-200-200-200	400-200-200-200
b direction	400-200-200-200	400-200-200-200	400-200-200-200	400-200-200-200	400-200-200-200	400-200-200-200
Longitudinal bar	12 - 020	12 - 020	12 - 020	12 - 020	12 - 020	12 - 020
Mesh	S11 8100					
1F						
h direction	400-200-200-200	400-200-200-200	400-200-200-200	400-200-200-200	400-200-200-200	400-200-200-200
b direction	400-200-200-200	400-200-200-200	400-200-200-200	400-200-200-200	400-200-200-200	400-200-200-200
Longitudinal bar	12 - 020	12 - 020	12 - 020	12 - 020	12 - 020	12 - 020
Mesh	S11 8100					

Fig.10 Typical member section

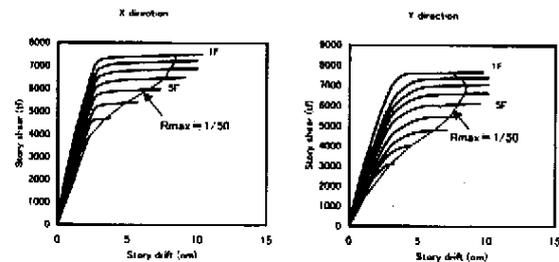


Fig.11 Story shear-drift relation obtained by push-over analysis

**Type-2(Office building with structural cores at both sides of the plan)**

Type-2 building is an 11-story office building with structural cores at both sides of the plan. An outside view is shown in Fig. 12. The perspective drawing of the lobby space is shown in Fig. 13. The longest precast prestressed concrete beam of 18m consists of three segments prefabricated at a factory and assembled at the site. The average story height is 4m. The structural framing is shown in Fig. 14. The typical floor plan and structural elevations are indicated in Fig. 15 and 16, respectively. The typical member sections are shown in Fig. 17. Most of the design seismic load is attributed to the structural cores. The floor system is precast concrete panels connected each other by cast-in-situ concrete on their top. The columns and walls are cast-in-place concrete members. The earthquake resisting system is moment-resisting frames and structural walls. The maximum design compressive strength of concrete is about 50MPa.



Fig.12 Outside view

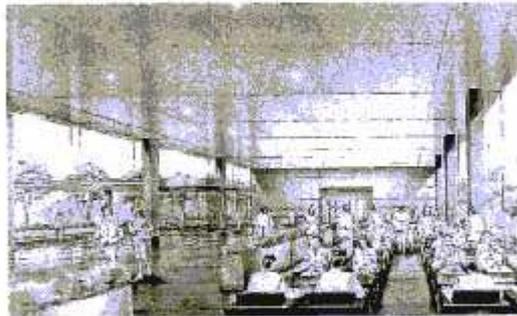


Fig.13 Inside view

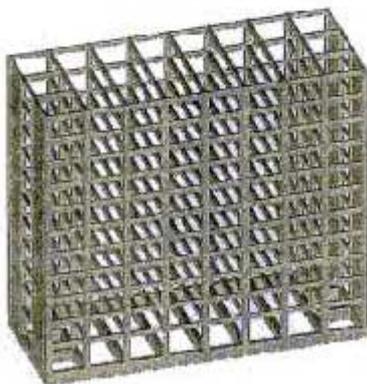


Fig.14 Structural framing

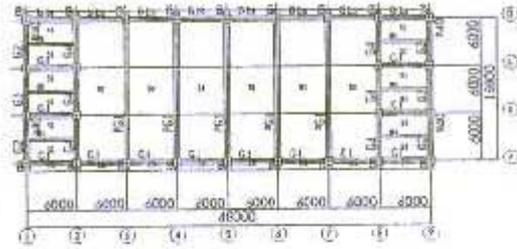


Fig.15 Typical floor plan

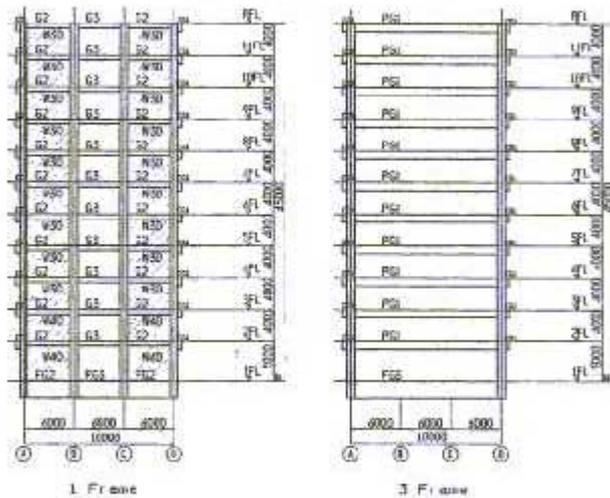


Fig.16 Structural elevation

Member	C1		C2		C3		C4	
	Section	Detail	Section	Detail	Section	Detail	Section	Detail
Column	300x300	300x300	400x400	400x400	500x500	500x500	600x600	600x600
Beam	300x300	300x300	400x400	400x400	500x500	500x500	600x600	600x600
Wall	200x200	200x200	300x300	300x300	400x400	400x400	500x500	500x500
Slab	100x100	100x100	150x150	150x150	200x200	200x200	250x250	250x250

Fig.17 Typical member section

The story shear-drift relation obtained by a push-over analysis is shown in Fig. 18. The capacity spectrum and demand spectra are shown in fig.19. The demand spectrum with 10% equivalent damping is adopted because the main earthquake resisting system is the structural cores designed in ordinary reinforced concrete. The base shear

coefficient at the maximum inter-story drift of 1/60 is about 0.26 in X direction, and 0.33 in Y direction. In X direction, the spectral displacement of performance point is about 46cm (1/63), the spectral acceleration is about 300 cm/sec<sup>2</sup>. In Y direction, the spectral displacement of performance point is about 38cm (1/77), the spectral acceleration is about 390 cm/sec<sup>2</sup>. The plastic hinge formations at the maximum inter-story drift of 1/60 are shown in Fig.20. The plastic hinges formed only at the beams besides at the bottom ends of the first floor columns and the columns with axial tensile force. The wall contribution to the story shear force at the stage is shown fig.21. That value ranged from 50 to 70%. The results of a time-history response analysis using a multi-mass shear system is shown in Fig. 11. These results of the analyses confirmed the possibility of application of prestressed concrete to this type of buildings.

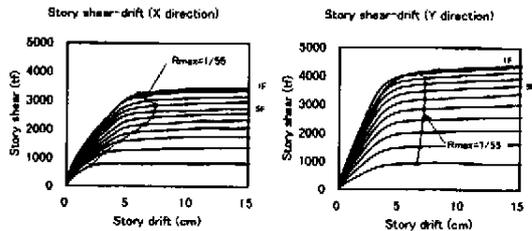


Fig.18 Story shear-drift relation by push-over analysis

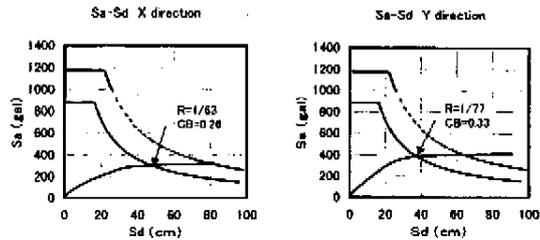


Fig.19 Capacity spectrum and demand spectra

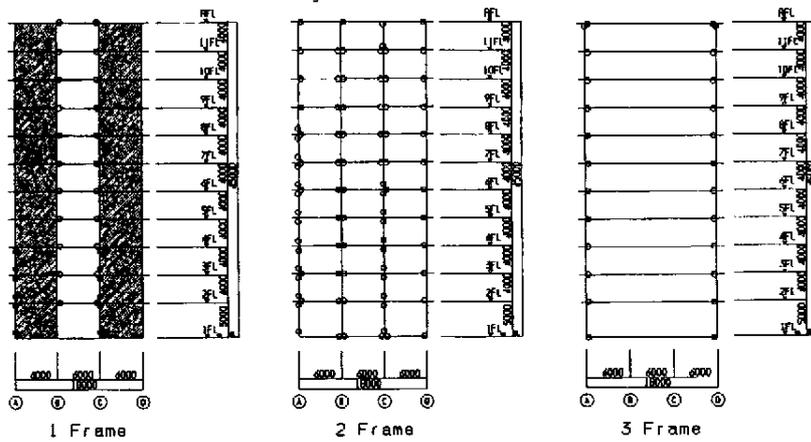


Fig.20 Plastic hinge formations at the inter-story drift of 1/60

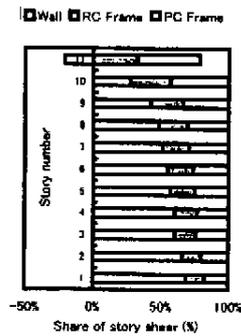


Fig.21 Wall contribution to the story shear force

The structural performance of the building is compared with that of an equivalent composite building consisted of steel-encased reinforced concrete columns, beams and steel beams. The typical member sections of the composite structure are shown in Fig. 22. The results of the push-over analysis in Y direction are illustrated in Fig. 23. The base shear coefficient at the maximum inter-story drift of 1/60 is about 0.41. The results show no difference in structural performance and dimension of the section between the prestressed concrete and the equivalent composite buildings. As indicated in the type-1 building, the difference is very little.

	COLLUMN		BEAM			
	C.1	C.2	G1	G2	G3	G4
4F						
2F						
1F						
Detail	See 408/200/19/20	See 408/200/19/20	Steel	See 408/200/19/20	See 408/200/19/20	See 408/200/19/20
Detail	See 408/200/19/20	See 408/200/19/20	Bar	See 408/200/19/20	See 408/200/19/20	See 408/200/19/20
Detail	See 408/200/19/20	See 408/200/19/20	Reinforcement	See 408/200/19/20	See 408/200/19/20	See 408/200/19/20
Detail	See 408/200/19/20	See 408/200/19/20	Detail	See 408/200/19/20	See 408/200/19/20	See 408/200/19/20

Fig.22 Typical member section

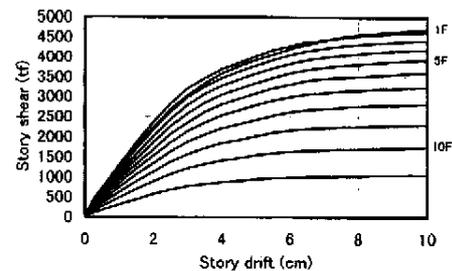


Fig.23 Story shear-drift relation obtained by push-over analysis

**Type-3 (Condominium with an open space at its center of the plan)**

Type-3 building is a condominium with an open space at its center of the plan. An outside view is shown in Fig. 24. The perspective drawing of the dwelling unit is shown in Fig. 25. The 20-story condominium has a plan consisted of 6m x 6m grids. The longest beam span is 12m. The structural framing is shown in Fig.26. The typical floor plan and structural elevation are indicated in Fig.27 and 28, respectively. The typical member sections are shown in Fig. 29. The primary seismic resisting system is a moment-resisting frame. Since the main purpose of this trial is to introduce as many precast members as possible, the columns are also assembled by post-tensioning. The maximum design compressive strength of concrete is about 60MPa.



Fig. 24 Outside view

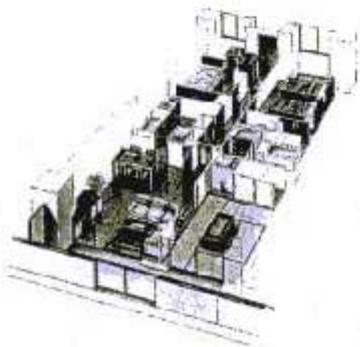


Fig. 25 Inside view

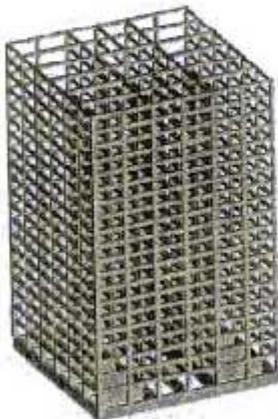


Fig. 26 Structural framing



Fig. 27 Typical floor plan

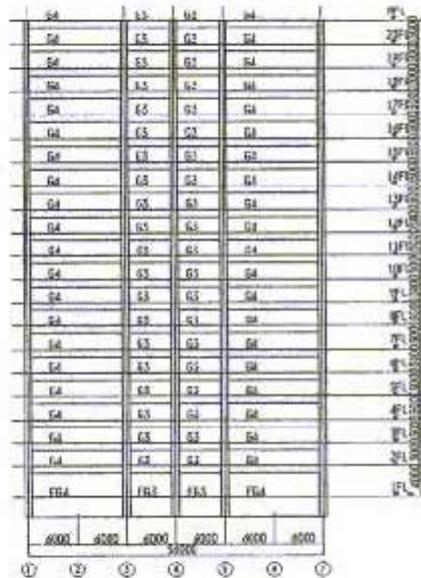


Fig. 28 Structural elevation

FLOOR	COLUMN		BEAM	
	C1	C2	B1	B2
20F				
19F				
18F				
17F				
16F				
15F				
14F				
13F				
12F				
11F				
10F				
9F				
8F				
7F				
6F				
5F				
4F				
3F				
2F				
1F				
Basement				

Fig. 29 Typical member sections

The story shear-drift relation obtained by a push-over analysis is shown in Fig. 30. The capacity spectrum and the demand spectra are shown in Fig. 31. The demand spectrum with 5% equivalent damping is adopted because both beams and columns are precast prestressed concrete members and assembled by post-tensioning. The base shear coefficient at the maximum inter-story drift of 1/50 is about 0.31 in X direction, and 0.32 in Y direction. In X direction, the spectral displacement of performance point is about 66 cm (1/60), and the spectral acceleration is about 390 cm/sec<sup>2</sup>. In Y direction, the spectral displacement is about 62 cm (1/62), the spectral acceleration is about 400 cm/sec<sup>2</sup>. The plastic hinge formations at the inter-story drift of 1/50 are shown in Fig.32. The plastic hinges formed only at the beams besides at the bottom ends of the first floor columns. The results assured the possibility of application of precast prestressed concrete system to this type of buildings.

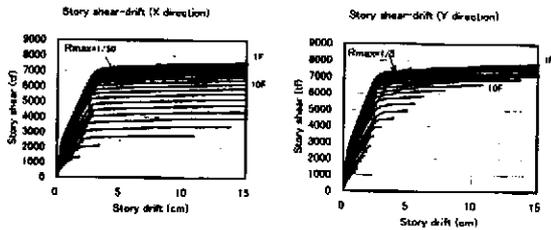


Fig.30 story shear-drift relation by push-over analysis

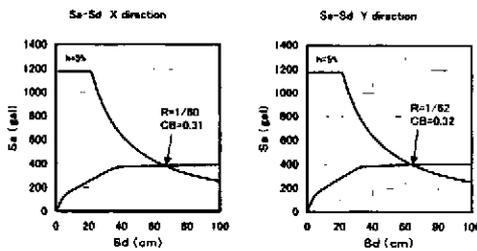


Fig.31 Capacity spectrum and demand spectra

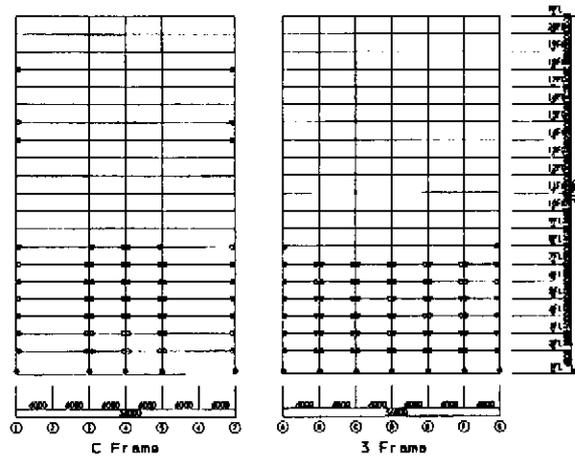


Fig.32 Plastic hinge formations at the inter-story drift of 1/50

The structural performance is compared with that of an equivalent reinforced concrete building. The typical member sections of the reinforced concrete structure are shown in Fig. 33. The results of the push-over analysis in X direction is shown in Fig. 34. The base shear coefficient at the maximum inter-story drift of 1/50 is about 0.27 in X direction. The result shows no difference in structural performance and dimension of the section between the prestressed concrete and the equivalent building. Structural cost of reinforced concrete buildings are usually more inexpensive than prestressed concrete in Japan. However, construction term of precast prestressed concrete buildings is shorter than that in reinforced concrete buildings. This merit is very important as much as cost.

	COLUMN		BEAM			
	C1	C2	1F	2F	3F	4F
5F						
2F						
1F						
Notes	1. 03H 013 040					

Fig.33 Typical member sections

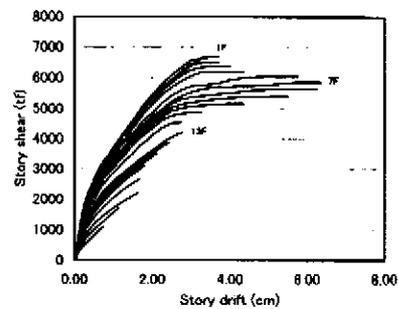


Fig.34 Results of push-over analysis

## CONCLUSION

The results of the structural design trial revealed that precast prestressed concrete systems are successfully applied to high-rise buildings even in high-seismicity regions, and that those buildings are comparable to equivalent steel-encased reinforced concrete buildings in terms of structural and economical performance.

## ACKNOWLEDGMENT

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