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STATIC AND PSEUDO DYNAMIC TESTS ON PRESTRESSED CONCRETE MODEL FRAMES

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SUMMARY

This paper briefly reviews results from tests on the behaviour of cast-in-place prestressed concrete rigid frame structures. The structures consisted of long span prestressed concrete beams and reinforced concrete columns, and were subjected to simulated earthquake loads. Four 2-story 1/3 scale model frames, two of beam yield type and two of column yield type were tested under pseudo dynamic and static cyclic loadings. The frames exhibited stable hysteretic behaviour up to the story drift angle of 1/30 without significant reduction in load carrying capacity. A hysteretic model for the structures was proposed based on the past experimental studies on prestressed concrete beams and prestressed concrete beams-reinforced concrete columns assemblies. Non-linear dynamic response analyses using the proposed hysteretic model traced the response of the model frames subjected to the pseudo dynamic loading with reasonable accuracy.

INTRODUCTION

Cast-in-place prestressed concrete frames consisted of long span prestressed concrete beams and reinforced concrete columns have been widely used in Japan as building structures. This type of buildings is usually designed in combination with a certain amount of reinforced concrete shear walls to provide sufficient load carrying capacity under earthquake load. To establish more refined ductile frame design procedures for this type of structures based on a weak beam-strong column concept, experimental and analytical studies are needed on the effect of the yielding of the prestressed concrete beams on the dynamic response and displacement capacities of the structures.

This paper is intended to provide structural properties in the ultimate region such as the failure mechanism, displacement capacities and hysteretic characteristics of ductile prestressed concrete frames through static and pseudo dynamic tests on model frames (Ref.1).

EXPERIMENTAL PROGRAM

Test Frames Four 1/3 scale 2-story test frames constructed with 6 meter prestressed concrete beams and reinforced concrete columns were fabricated as shown in Fig.1. Two identical frames of beam yield type, FBY and column yield type, FCY, respectively. The prestressed concrete beams had floor slabs of 1 meter width. The numbers of prestressing cables in the beams and the arrangements of mild steel reinforcements in the columns were varied in accordance with the yield

Table 1 – Mechanical Properties of Materials Used

(a) Concrete

Specimen	Compressive Strength Fc (kg/cm^2)	Strain at Fc ε_c (%)	Modulus of Elasticity (10^5kg/cm^2)
FBY-S,D	338.5	0.246	2.32
FCY-S,D	408.3	0.227	2.56

(b) PC Strand

	ϕ12.4mm Strand SWPR7A
Diameter (mm)	12.41
Area (mm^2)	92.90
Yield Strength (kg/mm^2)	176.5 (150.0)
Actual Ultimate Strength (kg/mm^2)	190.0 (175.0)

(c) Mild Reinforcement

Kind of Reinforcing Bar	SD30		
	D10	D13	D16
Yield Strength (kg/cm^2)	3514	3601	3812
Actual Ultimate Strength (kg/cm^2)	4979	5220	5739
Strain at Rupture (%)	23.6	25.3	25.3

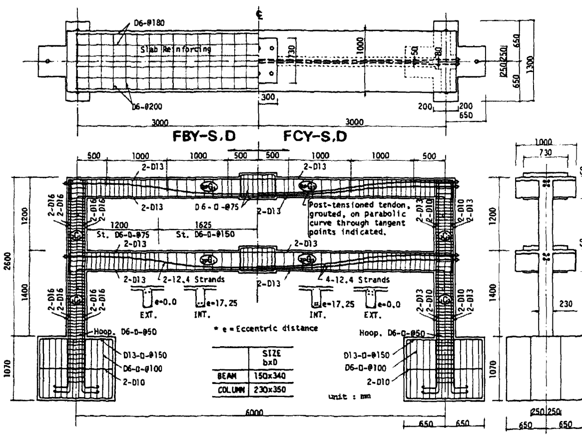


Fig. 1 – Details of Test Specimens

Table 2 – Column Axial Stress of Frames

Specimen		FBY-S,D	FCY-S,D
Dead Load (ton)	2F	2.19	2.19
	1F	2.46	2.46
Live Load (ton)	2F	7.03	14.48
	1F	7.18	12.87
Column Axial Load (ton)	2F	4.61	8.34
	1F	9.43	16.00
Column Section Area (cm^2)		23x35	23x35
Column Axial Stress (kg/cm^2)	2F	5.73	10.35
	1F	11.72	19.88

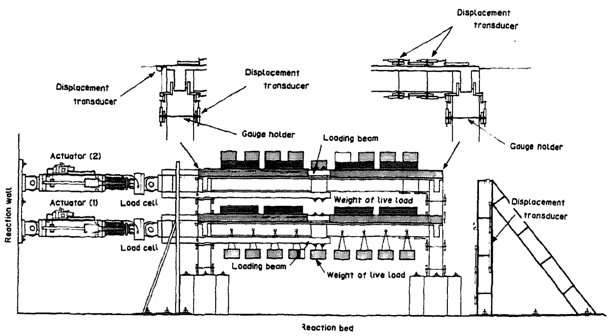


Fig. 2 – Test Set-Up

type so that the supposed yield type would be easily realized. Two and four strands of ϕ12.4mm were used for the beams of FBY and FCY, respectively with additional mild steel reinforcement. The average initial prestress in the beams was 49kgf/cm^2 for FBY and 98kgf/cm^2 for FCY, respectively. The design strength of concrete was 350kgf/cm^2. Table 1 show the mechanical properties of the materials used. The effective prestress in the beams at the age of loading was 95% of the initial prestress.

Loading Arrangement and Instrumentation Fig.2 shows the loading arrangement and test rig. Two servo actuators were used to apply horizontal loads to the test frames through steel loading beams connected to the loading stubs formed at the mid span of the prestressed concrete beams. Superimposed dead loads were also applied to the beams by steel weight to simulate the axial stress of columns in the 2-story prototype frame building having 18 meter long prestressed concrete beams at an interval of 6 meters. Table 2 shows the axial stress of the columns of test frames. The rotations of the beams and columns at expected plastic hinge locations adjacent to columns and beams, respectively were measured by pairs of displacement transducers with a gauge length equal to 75% of the depth of beams or equal to the depth of columns. As a feedback signal for the control of the servo actuators, the output voltage of inductance type displacement transducers (±10V/±200mm) were used. Horizontal displacements at the each floor level and the axial strain of longitudinal mild steel reinforcing bars around the expected plastic hinge locations were also measured.

Static Loading Test One of the two identical test frames prepared for each yield type, FBY-S or FCY-S, was subjected to horizontal static cyclic loading by alternating the direction of the load at the center of the beam. The combination of forces at second and roof floor levels was determined by the inverted triangular load distribution along the height of the test frame.

Pseudo-Dynamic Loading Test (PDL Test) The other two identical frames, FBY-D or FCY-D, were subjected to the pseudo-dynamic loading as a two-degree-of-freedom-system. The first 6 second of the N-S component of the Tohoku University record, the 1978 Miyagiken-oki earthquake, was used as the input ground motion of the PDL test. Taking into account of the scale reduction of the models, the maximum acceleration amplitude of the Tohoku University record was chosen to be three times the original record, that is 258.2×3=774.6gal. The central difference method was used for the numerical integration with the time interval of 0.01/3 second and zero damping. More detailed procedures of the PDL test are reported elsewhere (Ref.2). Prior to the PDL test, small horizontal force was applied to each floor level of the model independently (referred to as FLL test) to obtain a flexibility matrix of the models in the elastic region.

TEST RESULTS AND DISCUSSIONS

The relationship between the base shear, Q_1, and overall drift angle, R_r, defined as the ratio of roof level displacement to the total height of the test frame is shown in Fig.3, where the same relationship resulted from the static loading test after the completion of the PDL test is shown by the broken line. The maximum values for the base shear forces, roof-level displacements and corresponding drift angles are summarized in Table 3. Fig.4 shows the crack development at a specific drift angle.

Behaviour of Test Frames in Static Loading Tests First half cycle of static loading tests on FBY-S and FCY-S was carried out monotonically up to the development of the sufficient numbers of yield hinges to form the collapse mechanism. Formation of the collapse mechanism was attained at the overall drift angle of 1/60 for FBY-S and 1/87 for FCY-S, respectively. Fig.5 shows the sequence of the development of yield hinges observed in the tests comparing with the results obtained from elasto-plastic frame analysis. The stresses of the prestressing cables in the beams were still less than 80% of their nominal yield strength at the yielding of mild steel reinforcement by which the development of yield hinges was checked. Because of the considerable increase in the moment resisting capacity of the prestressed concrete beam members after the yielding of mild steel reinforcement due to the increase in the stresses

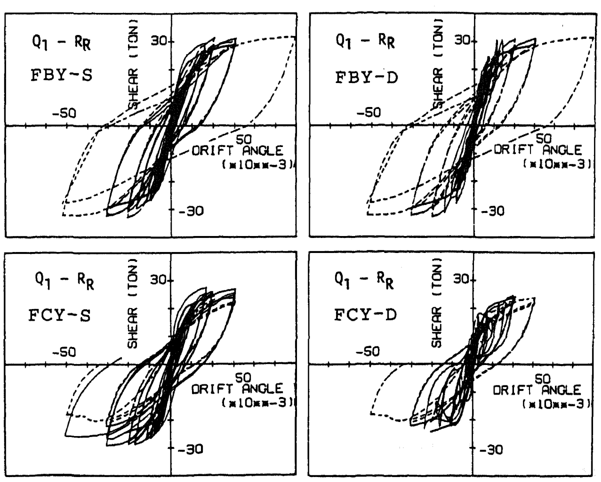


Fig. 3 - Base Shear Force-Roof Drift Angle Relationships

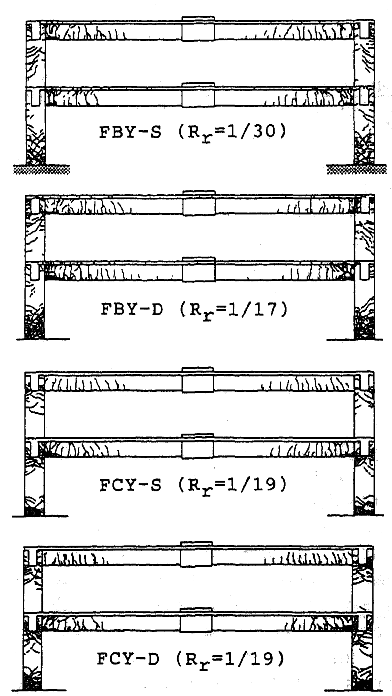
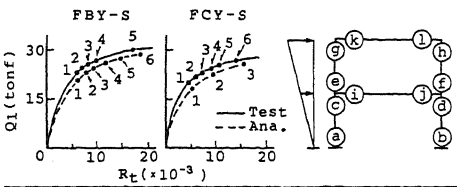


Fig. 4 - Crack Patterns



		1	2	3	4	5	6
FBY-S	Test	a, i•	b	j•	k•	h	
	Ana.	i•	b	a	j•	k•	h, l•
FCY-S	Test	i•	b	k•	a	j•	h
	Ana.	a, b	d, h, i•	c, g			

•: Beam

Fig. 5 – Comparison of Test and Analytical Results for Yield Hinge Developments

Table 3 – Summary of Static and Pseudo-Dynamic Loading Test Results

Specimen			Qu (ton) +	Qu (ton) −	δ_{max} (mm) +	δ_{max} (mm) −	R($\times 10^{-3}$) +	R($\times 10^{-3}$) −
FBY-S		RF			79.89	80.25	30.73	30.87
		2F	19.17	19.00	25.96	34.57	21.63	28.81
		1F	30.77	31.83	53.93	46.29	38.52	33.06
FBY-D	PDL	RF			37.27	37.61	14.33	14.47
		2F	19.54	19.64	15.38	16.97	12.82	14.14
		1F	30.92	31.55	22.62	20.88	16.16	14.91
	STATIC	RF			154.8	135.3	59.54	52.04
		2F	19.10	20.91	61.13	61.56	50.94	51.30
		1F	31.58	32.82	93.63	76.82	66.88	54.87
FCY-S		RF			80.26	132.0	30.87	50.77
		2F	18.49	19.68	24.86	34.08	20.72	28.40
		1F	27.53	29.23	55.40	97.94	39.57	69.96
FCY-D	PDL	RF			51.56	61.55	19.83	23.67
		2F	15.49	17.22	16.24	26.75	13.53	22.29
		1F	25.04	23.32	35.44	35.41	25.31	25.29
	STATIC	RF			80.02	130.2	30.78	50.07
		2F	15.19	13.80	24.63	51.90	20.53	43.25
		1F	23.96	22.15	56.62	78.29	40.44	55.92

Table 4 – Maximum Base Shear Force of Test Frames (tonf)

		FBY-S	FBY-D	FCY-S	FCY-D
Test	2F	19.17	20.91	19.68	17.22
	1F	31.83	32.82	29.23	25.04
Q_{c1}	2F	17.19		17.02	
	1F	26.13		25.87	
$\frac{Test}{Q_{c1}}$	2F	1.12	1.22	1.16	1.01
	1F	1.22	1.26	1.13	0.97
Q_{c2}	2F	17.83		16.52	
	1F	27.97		25.45	
$\frac{Test}{Q_{c2}}$	2F	1.08	1.17	1.19	1.04
	1F	1.14	1.17	1.15	0.98

Test : obtained form experiment
Q_{c1} : by the virtual work method
Q_{c2} : by elasto-plastic frame analysis

of the cables, stable load-displacement relationships were observed until the overall drift angle reached 1/33 for FBY-S and 1/30 for FCY-S, respectively even after the formation of collapse mechanism. The crush of concrete in the compression zone of the beams occurred at the roof level drift angle, R_r, in the range 1/50 to 1/30. No distress in the compression zone of the base columns was observed at R_r=1/30 for the FBY-S frame. On the contrary, the crush of concrete in the compression zone of the base column was observed at R_r=1/75 for the FCY-S frame, and significant reduction in load carrying capacity occurred beyond R_r=1/30.

Behaviour of Test Frames in PDL Tests

1) FBY-D : During the PDL test, the drift angle and base shear reached 1/70 and 95% of the maximum resisting base shear, respectively. The fundamental natural period obtained through a free vibration test by means of the PDL test method was found to be 0.26 sec., which was 1.5 times longer than the elastic natural period (0.125 sec.) calculated from the flexibility matrix obtained by FLL tests. The maximum overall drift angle reached 1/17 in the positive direction and 1/19 in the negative direction without significant reduction in the base shear in the static loading carried out after the completion of the PDL test.

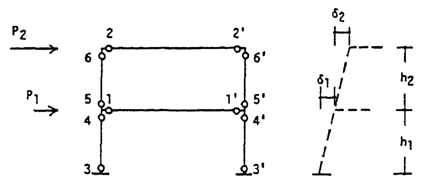
2) FCY-D : During the PDL test, the overall drift angle reached 1/50 in the positive direction and 1/42 in the negative direction, respectively. In the static loading test carried out after the completion of the PDL tests, the main reinforcing bars at the base of columns were fractured at R_r=1/19 and then 10% reduction in the base shear capacity followed.

Base Shear Capacities of Test Frames The maximum base shear carried by the test frames are summarized in Table 4 with the calculated values. Calculated base shears, Q_{c1} and Q_{c2} are obtained by applying the virtual work method to an assumed hinge mechanism under the inverted triangular load distribution and by elasto-plastic frame analysis, respectively. The experimental values are 10 to 20% greater than calculated value excepted for FCY-S.

End Rotation of Beams Table 5 summarized the end rotations of the frame members measured at typical loading stages. For the beam yield type test frame, the end rotations of the second and roof floor beams were almost equal and two-thirds of the overall drift angle, respectively. For the column yield type test frame, those were almost equal to one half and less than one-third of the overall drift angle.

Table 5 - End Rotation at Typical Loading Stages

	Shear Force (ton)		Story Drift (10^{-3})			Rotation (10^{-3})											
						Beam Left		Beam Right		Column Left				Column Right			
	Q_1	Q_2	R_1	R_2	R_T	1	2	1'	2'	3	4	5	6	3'	4'	5'	6'
FBY-S	13.78	8.41	2.49	2.51	2.5	1.22	0.44	1.23	0.64	1.65	0.09	0.01	0.17	2.30	0.34	0.63	0.90
	22.15	13.19	6.16	5.15	5.69	3.39	1.57	3.60	1.82	4.56	0.05	0.03	0.84	5.01	0.60	1.13	2.24
	25.11	14.90	8.42	9.83	7.85	5.98	2.36	4.75	2.69	6.13	0.16	0.47	1.28	7.07	0.54	1.68	2.99
	26.65	16.44	10.79	9.02	9.97	8.51	3.19	5.77	3.49	8.28	0.06	0.43	1.93	9.82	0.98	1.78	3.53
	29.37	19.14	17.67	14.32	16.12	19.24	7.79	8.98	5.50	14.18	0.17	0.79	2.24	16.73	1.67	2.62	4.83
	30.77	18.34	38.44	21.54	30.64	29.66	22.97	20.54	7.10	28.76	0.06	1.12	3.69	34.26	1.43	0.83	12.07
FCY-S	15.03	10.06	2.06	2.71	2.36	0.78	0.72	1.22	0.73	1.60	0.49	0.09	0.66	1.99	0.63	0.58	1.33
	21.08	14.22	6.16	5.36	5.79	2.85	1.88	3.49	0.66	9.84	1.09	0.46	0.84	5.54	1.78	1.09	5.91
	23.26	15.54	8.42	6.89	7.72	4.07	2.65	4.17	0.66	8.14	1.40	0.46	0.46	6.89	2.63	1.31	8.11
	24.70	16.54	10.69	8.51	9.68	4.97	3.23	5.03	0.78	10.60	2.00	0.72	2.06	8.64	3.23	1.72	10.08
	27.52	18.49	20.55	12.78	16.97	11.17	5.45	9.70	0.92	20.49	4.81	1.46	4.12	18.64	8.10	1.95	16.73
	26.96	18.02	39.58	20.72	30.87	20.55	8.16	19.86	1.16	41.58	12.02	19.52	12.90	47.21	18.06	0.62	27.29



$Q_1 = P_1 + P_2$ $\quad$ $R_1 = \delta_1 / h_1$

$Q_2 = P_2$ $\quad$ $R_2 = \delta_2 / h_2$

$R_T = (\delta_1 + \delta_2)/(h_1 + h_2)$

Equivalent Viscous Damping Factor, h_{eq}

In Fig.6 are plotted the experimentally determined equivalent viscous damping factor from the hysteretic loops in the static and PDL loading tests against the overall drift angle. In Fig.6 are also plotted the values obtained from the static loading tests on the prestressed concrete beams and prestressed concrete beams-reinforced concrete columns assemblies. The values of h_{eq} for the reinforced concrete column yield type frames which were on the lower bound of the values obtained from the loading tests on prestressed concrete beams with the prestressing steel ratio, λ_p given by Eq.1 in the range of 0.32 to 0.61 were 25% higher than those for the prestressed concrete yield type frames which on the upper bound of the values obtained from the same tests on beams with λ_p in the range of 0.71 to 0.83. To simulate the experimentally determined relationship between h_{eq} and ductility a hysteretic model of prestressed concrete frame structures was proposed as shown in Fig.7.

$$\lambda_p = A_p \cdot f_{py} / (A_p \cdot f_{py} + A_r \cdot f_{ry}) \qquad (1)$$

in which A_p, A_r = the sectional area of prestressing cables and mild steel reinforcements, respectively. And f_{py}, f_{ry}= the yield strength of prestressing c ..les and mild steel reinforcements, respectively.

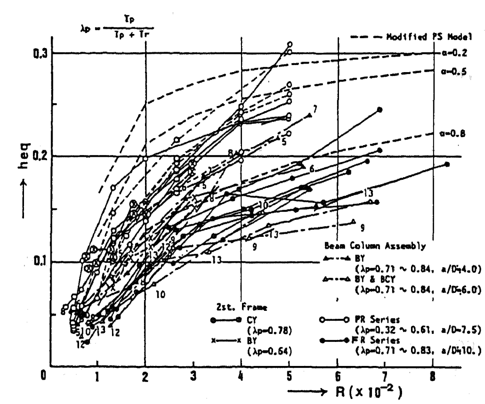


Fig. 6 - Equivalent Viscous Damping Factors

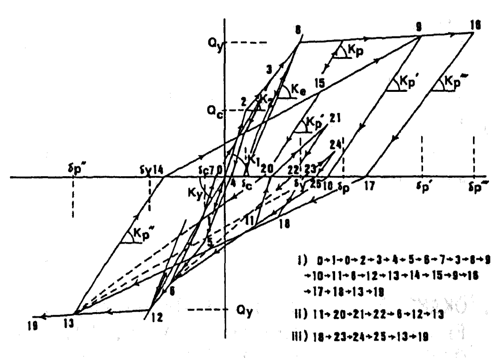


Fig. 7 - Hysteretic Model

Earthquake Response Analysis

Time histories of the roof-level displacement and shear forces vs. overall drift angle are shown in Fig.8 and Fig.9, respectively comparing the responses obtained from the PDL tests with those obtained from inelastic response analysis carried out on a lumped mass shear model having the proposed hysteretic model in Fig.7. The value of α in the hysteretic model was assumed to be 0.8 for the FBY and 0.6 for FCY. The time history curves obtained by the analyses reasonably traced the experimental curves.

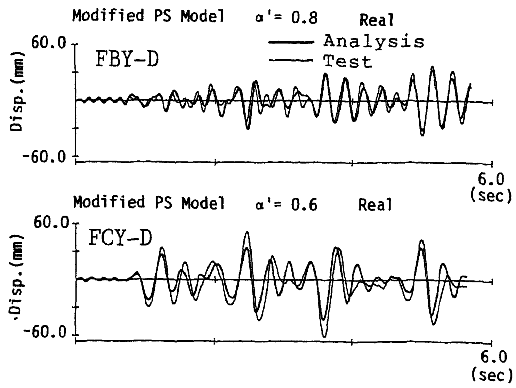


Fig. 8 - Comparison in Displacement Time History Between Tests and Analysis

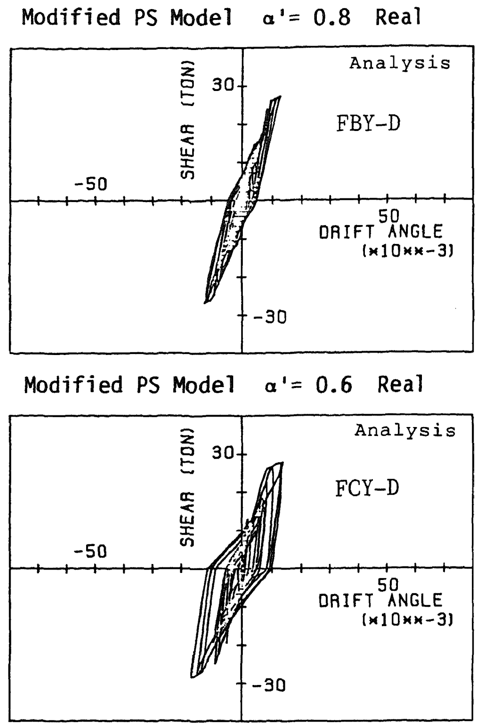


Fig. 9 - Shear Force and Roof Drift Angle Relationships

CONCLUSIONS

Test programs on model frames under static cyclic and pseudo-dynamic loading were carried out in order to investigate the seismic characteristics of the frame structures consisted of long span prestressed concrete beams and reinforced concrete columns. Major findings are summarized as follows.

1) The model frames exhibit stable hysteretic behaviour up to the overall drift angle of 1/30 without significant reduction of load carrying capacity. Though the beam yield frames show ductile behaviour up to the drift angle of 1/20, significant reduction of load carrying capacity was recognized in the column yield type frame beyond the overall drift angle of 1/30.
2) A hysteretic model was proposed to simulate the change of the relationship between equivalent viscous damping factor and drift angles according to the yield type or prestressing steel ratio.
3) The non-linear dynamic response analyses using the proposed hysteretic model trace the response of the model frames subjected to the pseudo dynamic loading with reasonable accuracy.

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