STUDY FOR SEISMIC CRITERIA BY EQUIVALENT LINEARIZATION

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SUMMARY

Design classifications for prestressed concrete member are a lot of variation from fully prestressed concrete member to partially prestressed concrete member to perform like a reinforced concrete member in the hysteresis characteristics. So, it's very many that the arrangement of the member in prestressed concrete frame building. Therefore, the earthquake performance of prestressed concrete building could not be clarified thoroughly under static load analysis. Thereupon, three simple models to be one column frame was planned to estimate earthquake performance of the prestressed concrete buildings. The equivalent damping factors in three rotational angles (1/240, 1/120 and 1/60 times the radian in 2/3 times height of model frames) was calculated in each steady-state loop by incremental load analysis. So, response displacement in the typical height of model frames was calculated based based on the response acceleration spectrum in "Recommendation for Loads on Building" published by Architectural Institute of Japan. Further, earthquake responses of each model frame are calculated by earthquake response analysis using three typical observed earthquake records and three simulated earthquake motions. From the comparison of the both response results in the model frames, earthquake response in the concrete buildings could be estimated favourably by the equivalent linearization.

INTRODUCTION

This study was carried out by Working Group (chairman : S. Machida) for development of design criteria in Joint Coordinating Committee (chairman : S. Okamoto) on High-rise prestressed concrete building organized by Building Research Institute, Ministry of Construction. The design classification for prestressed concrete member manifolds from fully prestressed concrete member to partially prestressed concrete member to perform like reinforced concrete member in hysteresis behavior. So, the arrangement of prestressed concrete member in the frame building is in various away. Therefore, the earthquake performance of prestresssed concrete buildings could not be clarified well under static analysis. Thereupon, three rises of one column prestressed concrete frames are first planned and designed accordance with "ultimate Strength Design Guideline for Reinforced Concrete buildings" (Japanese PRESSS Guidelines) developed as a part of U.S. - Japanese Coordinated PRESSS (Precast Seismic Structural System) project. The study to estimate the earthquake response for the prestressed concrete buildings was carried out based on the response acceleration spectrum for one mass models shown in "Recommendations for Load on Buildings" Published by Architectural Institute of Japan (AIJ Recommendations). The earthquake response for prestressed concrete buildings was studied due to the next planning.

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1) The response acceleration spectrum (S_a) was calculated by the equivalent period, $T=2\pi/\sqrt{(M/K)}$, and the equivalent damping factor (h_{eq}) in steady-state loop in one mass (M) model. So, from the relation $S_d=S_a/\omega^2$ and $\omega=2\pi/T$, of the response acceleration spectrum (S_a) and the response displacement spectrum (S_d), the response based shear coefficient (C_B) and the response displacement spectrum (S_d) was calculated. The response acceleration spectrum (S_a) by AIJ Recommendations is as follows:

$$S_A(T,h)=\begin{cases}\left(1+\dfrac{f_A-1}{d}\times\dfrac{T}{T_c}\right)F_h\,G_A R_A A_0 & \text{for} \quad 0\le T\le dT_c\\ F_h\,f_A G_A R_A A_0 & \text{for} \quad dT_c\le T\le T_c\\ \dfrac{2\pi\,F_h\,f_V G_V R_V V_0}{T} & \text{for} \quad T_c\le T\end{cases} \tag{1}$$

where, f_A: ratio of S_a (T, 0.05) to $G_A \cdot R_A \cdot A_0$ for the period as $0 \leqq T \leqq dT_c$ (assumed to be 2.5), f_v: ratio of S_a (T, 0.05) $T/2\pi$ to $G_v \cdot R_v \cdot V_0$ in the period as $T_c \leqq T \leqq T$ (assumed to be 2.0), d: ratio of minimum period to maximum period in fixed Sa (T, h) (assumed to be 0.5), T_c:$(2\pi f_v \cdot G_v \cdot R_v \cdot V_0)/(f_A \cdot G_A \cdot R_A \cdot A_0)$ (T_c=0.503), F_h: correction factor for equivalent damping factor [assumed to be 1.5/(1+10h)], A0:maximum basis acceleration of ground motion in standard soil condition (assumed to be 500 cm/sec^2), V_0: maximum basis velocity of ground motion in standard soil condition (assumed to be 50 cm/sec), R_A: correction factor of maximum ground acceleration for return period (R_A=1.0), R_v: correction factor of maximum ground velocity for return period (R_v=1.0), G_A: correction factor of maximum ground acceleration for seismic zone (G_A=1.0), and G_v: correction factor of maximum ground velocity for seismic zone (G_v=1.0).

2) Three rises (five, ten, and fifteen stories) of one column prestressed concrete model frames was designed accordance with Ultimate Strength Design Guidelines for Reinforced Concrete Buildings. Each rise frame are classified to five design classification representing to vary hysteresis model. The equivalent damping factors of the model frames in three rotational angles (1/240, 1/120, and 1/60 times the radian in 2/3 times the height of frames) was calculated in each steady-state loop by incremental load analysis. This defined each rotational angles (1/240, 1/120 and 1/60) in 2/3 height of model frames were estimated to be 1/200, 1/100 and 1/50 times the radian in maximum story drift angle. Also, typical height (2/3 times the overall height) was supposed to be 1.0 of participation vector in elastic first mode of model frames.

3) The response base shear coefficient (C_B) and the response displacement spectrum (S_d) was calculated using the equivalent damping factor (h) and equivalent period (T) in each rotational angle of model frame. The relation of lateral load (Q_B) and displacement (D) in the typical height of model frames by incremental load analysis was plotted in the calculated the response base shear coefficient (C_B) and the response displacement spectrum (S_d). The response base shear coefficient (C_B) and displacement (S_d) by equivalent linearization was estimated by a intersection point of the response C_B-S_d spectrum, and the relation of Q_B-D in the typical height of model frames by incremental load analysis.

4) Earthquake response analysis of each model frame are carried out using three typical earthquake records amplified to the maximum ground velocity to 50 cm/sec and three modulated records. So, the earthquake response lateral shear force and displacement was analyzed in the model frames.

The earthquake response and the response spectrum in the model frames was compared to examine the deviation in the both response. From the comparison of the both response results, earthquake response in the concrete buildings could be estimated favorably by the equivalent linearization. The design criteria by equivalent linearization are discussed

2. DESIGN FOR MODEL FRAMES

Three prestressed concrete model frames (Fig.1) to be one column of 5-story (height: 21m), 10-story (height: 41m) and 15-story (height: 61m) are planned. Seismic design for model frames was carried out accordance with Japanese PRESSS Guidelines (Ref. 1). Five design classifications of model frames representing to vary hysteresis rule of member are a) precast prestressed concrete model (PCaPC), b) cast-in-situ prestressed concrete model (PC), c) precast partially prestressed concrete model (PCaPPC), d) cast-in-situ partially prestressed concrete model (PPC), and e)cast-in-situ reinforced concrete model (RC). Each design classification are shown in Table 1.

Materials: Compressive strength of precast and cast-in-situ concrete is 60 N/mm^2. Yield strength of PC (prestressing) bar in columns is 1,080N/mm^2, and PC 7-strands in girders is 1,580N/mm^2. High strength deformed PC bar of yield strength equal to 1,275N/mm^2 is used as lateral reinforcement in columns and girders.

Gravity weights: Each story weight of earthquake inertia force are 100 tonf on the upper story, 90 tonf on the typical story and 95 tonf on the first story.

Lateral load resisting capacities at maximum story drift angle of 0.01 radian by incremental load analysis are 0.3 for 5-story model, 0.292 for 10-story model and 0.236 for 15 story model in terms of a base shear coefficient.

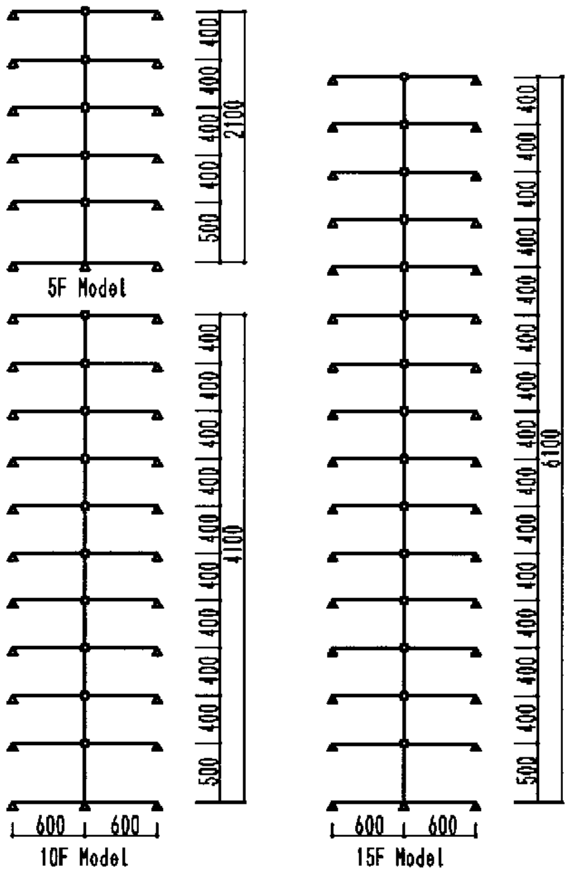

Fig.1 Model Frames

3. INCREMENTAL LOAD ANALYSIS

To calculate equivalent damping factor of each model frame in steady-state loop are carried out incremental load analysis. Lateral load distribution factor was used as Ai mode (Building Standard Enforcement Regulation by Ministry of Construction, Japan).

3.1 Analytical Model

Each member in frame is represented by a lineal element at the centroid of the section. Nonlinear rotational springs are inserted at the end of a member to represent inelastic deformation within the member. The stiffness of a member was varied at two loading levels corresponding to flexural cracking of concrete and yielding of tensile reinforcements and PC tendons. The stiffness after yielding was 1/1000 times the initial elastic stiffness. The equations of initial stiffness K_E of a member, relation factor α_y at yielding, flexural cracking moment M_c and ultimate moment M_y used in the analysis are as follows:

Table 1 The Design Classification

Frame Name		Design Classification	Column	Beam	Joint Method
a	PCaPC	Precast PC	PCaPC	PCaPC	Precast
b	PC	Cast in Situ of PC	RC	PC	Cast in Situ
c	PCaPPC	Precast PPC	PCaPC	PCaPPC	Precast
d	PPC	Cast in Situ of PPC	RC	PPC	Cast in Situ
e	RC	RC	RC	RC	Cast in Situ

PC : Prestessed Concrete
PPC : Partial Prestressed Concrete
PCa : Precast

$$K_E = L / \left\{ L^2 / (3 E_c I_c) + k / (G_c A_c) \right\} \quad (2)$$

$$\alpha_y = (0.043 + 1.67 n\, p_t + 0.043 a / D + 0.33 \eta)(d / D)^2 \quad (3)$$

$$M_c = \left(1.8\sqrt{F_c} + P_e / A_c\right) Z_e + N D / 6 \quad (4)$$

$$M_y = 0.9 \sigma_y a_t d + (f_{py} a_p)(1 - 0.5 q) d \quad (5)$$

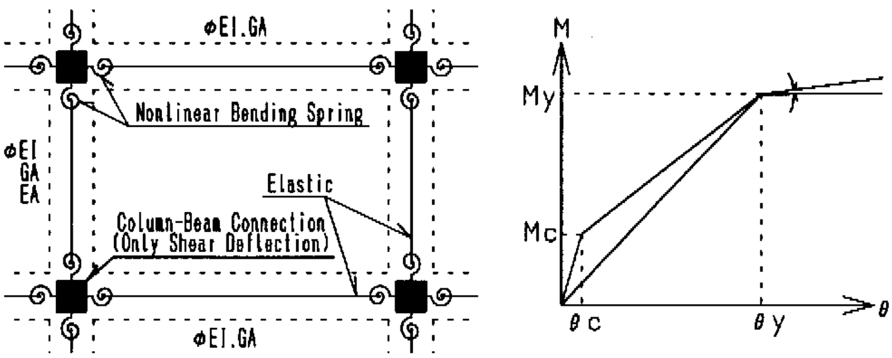

Fig.2 Analytical Model

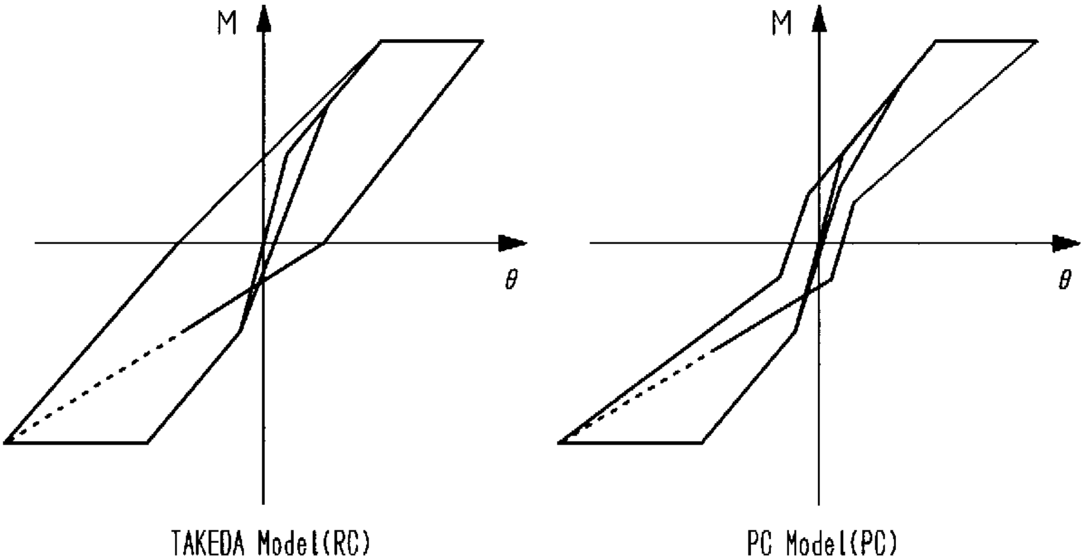

Fig.3 Hysteresis Model

where, L: length of face to the inflection point of a member, E_c and G_c: elastic and shear moduli of concrete, Ic and G_c: moment inertia and modulus of a member considering the effect of reinforcement, Ac: area of concrete section, k: shape factor for shear (1.2 for columns and 1.0 for beams), n: modular ratio of steel to concrete, p_t: tensile reinforcement ratio including the effect of PC tendon, a: shear span, d and D: effective and overall member depth, $\eta =(N+P_e)/(b \cdot D \cdot F_c)$, b: member width, at and a_p: area of tensile reinforcement and PC tendon, F_c: compressive strength of concrete, σ_y:1.1 times the nominal yield strength of reinforcement, f_{py}: yield strength of PC tendon, and $q=(f_{py} \cdot a_p)/(b \cdot D \cdot F_c)$. Analytical and nonlinear models for member are shown in Fig.2. Hysteresis model for incremental load analysis was used as TAKEDA model for reinforced concrete member and PC model for fully and partially prestressed concrete member. Hysteresis models used are shown in Fig. 3 [Takeda, 1970], [Hayashi, 1995].

3.2 Result by Incremental Load Analysis

The steady-state loop in the typical height (2/3 times the total height of model frames) was calculated at the three rotational angles (1/240, 1/120 and 1/60 times the radian) by incremental load analysis. The equivalent damping factor (h_{eq}) of each model frame calculating by the steady-state loop and displacement by response spectrum are shown in Tables 2 and 3. The displacement in the typical height by incremental load analysis and response spectrum of each model frame is shown in Fig.4 [Ichisawa, 1998], [Chiba, 1998], [Fu, 1998].

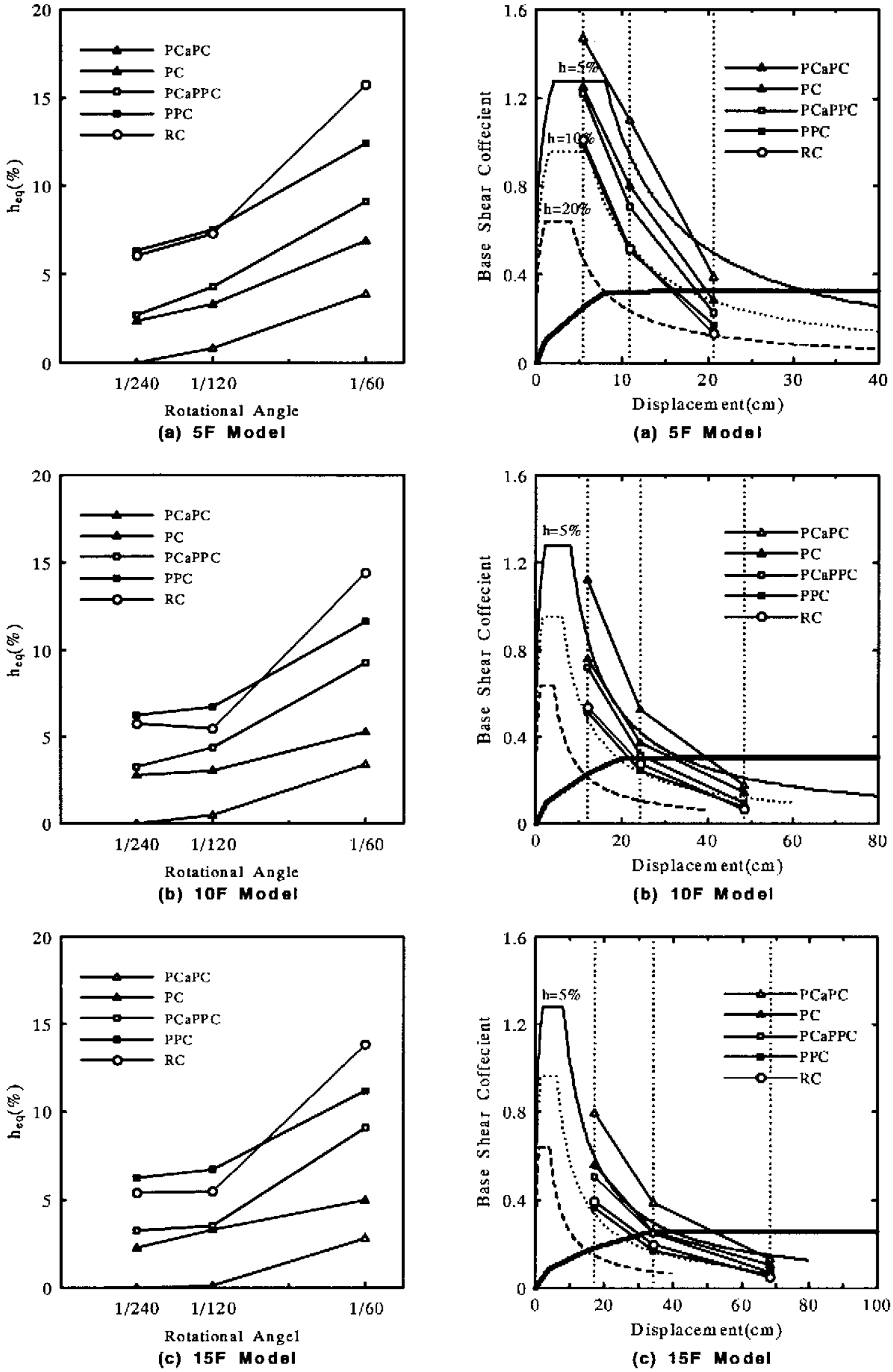

Fig.4 Equivalent Damping Factors and Results from Equivalent Linearization

Table 2 Equivalent Damping Factor

Frame Name	heq of 5F Model(%)			heq of 10F Model(%)			heq of 15F Model(%)		
	1/240	1/120	1/60	1/240	1/120	1/60	1/240	1/120	eq
PCaPC	0.00	0.86	3.88	0.00	0.47	3.36	0.00	0.15	2.82
PC	2.32	3.31	6.89	2.79	3.04	5.26	2.50	3.31	4.95
PCaPPC	2.70	4.33	9.10	3.27	4.33	9.27	3.26	3.51	9.11
PPC	6.34	7.48	12.50	6.23	6.74	11.60	6.21	6.71	11.20
RC	6.02	7.31	15.70	5.74	5.47	14.50	5.42	5.46	13.80

Table 3 Displacement of Each model

Frame Name	5F Model cm(Radian)	10F Model cm(Radian)	15F Model cm(Radian)
PCaPC	22(1/60)	40(1/70)	51(1/80)
PC	20(1/65)	20(1/65)	39(1/105)
PCaPPC	18(1/70)	26(1/110)	34(1/120)
PPC	17(1/75)	22(1/130)	27(1/150)
RC	16(1/80)	23(1/125)	30(1/135)

Table 4 Earthquake Motions Used in Analyses

Earthquake Name	Max. Acceleration (cm/sec^2)	Max. Velocity (cm/sec)	Max. Acceleration (50cm/sec)	Duration (sec.)
EL CENTRO 1940 NS	342	33	511	20
TAFT 1952 EW	176	18	497	20
HACHINOHE 1968 EW	225	34	330	20
NEW-RC 3 WAVES (EQ-1,2,3)				50

New-RC 3 waves : Simulated Earthquake Motions

4. EARTHQUAKE RESPONSE ANALYSIS

Earthquake response analysis of each model frame was carried out using three typical earthquake records and modulated records (New-RC motions) developed by New-RC Project organized by Building Research Institute, Ministry of Construction. Analytical model and hysteresis model was same as incremental load analysis.
Damping matrix was assumed to be proportional to the instantaneous stiffness matrix. A first mode damping factor at the initial elastic stage was assumed to be 5%, and that for higher modes are assumed to be proportional to model frequencies at the initial elastic stage. Earthquake records name used, the maximum acceleration and velocity, and duration are shown in Table 4.

4.1 Comparison of Response Results

Earthquake response and response spectrum was compared to examine the equivalent liearization. From the comparison of the both results, the maximum response displacement in the typical height by three typical earthquake records is less than the response spectrum. The response deviation was about 20%. However, the maximum response by three New-RC records coincides with the response spectrum by equivalent linearization favorably. The comparison of the both results in each model frame is shown in Tables 5, 6 and 7.

Table 5 Maximum Response Displacements
From Earthquake Response Analysis and Equivalent Linerization (5F Model)

Frame Name	Typical Records EL CENTRO NS		Simulated Motions (EQ-1,23)		Disp. at Typical Height From Equivalent Linearization	Ratio of Disp. Response Analysis to Equivalent Linerization
	Drift Angle (Radian)	Diplacement Typical Height (cm)	Drift Angle (Radian)	Diplacement at Typical Height (cm)		
PCaPC	1/65(3F)	17.61(1/74)	1/57(EQ-2)	22.45(EQ-1)	22(1/60)	0.80(1.02)
PC	1/74(3F)	16.24(1/80)	1/58(EQ-2)	19.82(EQ-2)	20(1/65)	0.81(0.99)
PCaPPC	1/70(2F)	14.88(1/87)	1/65(EQ-2)	17.85(EQ-3)	18(1/70)	0.83(0.99)
PPC	1/85(2F)	13.60(1/96)	1/77(EQ-2)	13.76(EQ-2)	17(1/75)	0.80(0.81)
RC	1/86(2F)	13.21(1/98)	1/75(EQ-2)	14.42(EQ-3)	16(1/80)	0.83(0.90)

Table 6 Maximum Response Displacements
From Earthquake Response Analysis and Equivalent Linerization (10F Model)

Frame Name	Typical Records EL CENTRO NS		Simulated Motions (EQ-1,23)		Disp. at Typical Height From Equivalent Linearization	Ratio of Disp. Response Analysis to Equivalent Linerization
	Drift Angle (Radian)	Diplacement Typical Height (cm)	Drift Angle (Radian)	Diplacement at Typical Height (cm)		
PCaPC	1/68(2F)	33.04(1/88)	1/46(EQ-2)	40.44(EQ-3)	40(1/70)	0.83(1.01)
PC	1/131(7F)	18.44(1/157)	1/79(EQ-2)	30.03(EQ-3)	32(1/90)	0.58(0.94)
PCaPPC	1/132(2F)	17.46(1/66)	1/89(EQ-2)	27.76(EQ-3)	26(1/110)	0.67(1.07)
PPC	1/151(2F)	16.55(1/175)	1/109(EQ-2)	20.45(EQ-3)	22(1/130)	0.75(0.93)
RC	1/156(2F)	15.81(1/183)	1/112(EQ-2)	21.17(EQ-3)	23(1/125)	0.69(0.92)

Table 7 Maximum Response Displacements
From Earthquake Response Analysis and Equivalent Linerization (15F Model)

Frame Name	Typical Records EL CENTRO NS		Simulated Motions (EQ-1,23)		Disp. at Typical Height From Equivalent Linearization	Ratio of Disp. Response Analysis to Equivalent Linerization
	Drift Angle (Radian)	Diplacement Typical Height (cm)	Drift Angle (Radian)	Diplacement at Typical Height (cm)		
PCaPC	1/93(4F)	36.58(1/112)	1/83(EQ-1)	39.11(EQ-1)	51(1/80)	0.72(0.77)
PC	1/113(7F)	30.49(1/134)	1/72(EQ-3)	34.98(EQ-3)	39(1/105)	0.78(0.90)
PCaPPC	1/127(2F)	29.82(1/137)	1/90(EQ-3)	34.61(EQ-3)	34(1/120)	0.88(1.02)
PPC	1/146(2F)	20.70(1/198)	1/125(EQ-3)	20.05(EQ-3)	27(1/135)	0.77(0.75)
RC	1/137(2F)	23.08(1/177)	1/134(EQ-2)	26.12(EQ-3)	30(1/150)	0.77(0.87)

4 .2 Response Deviation by Design Classification

Response characteristics in the five design classification (RC, PPC, PCaPPC, PC and PCaPC) was examined by varying hysteresis model of member. Response of precast prestressed concrete model frames was shown to be the maximum response in the five design classification, also the minimum response was cast-in-situ reinforced concrete or cast-in-situ partially prestressed concrete model frames. The response deviations of the minimum to the maximum response by spectrum was shown to be about 1.33 in 5-story, 1.85 in 10-story and 1.87 in 15-story models. The response deviations by earthquake response analysis using three typical records was 1.32 in 5-story, 2.07 in 10-story and 1.58 in 15-story models, also that by three New-RC records was 1.31 in 5-story, 2.43 in 10-story and 1.61 in 15-story models. This response deviation was shown favorably as the relation of the equivalent damping factor and earthquake response in the model frames.

5. CONCLUSIONS

To examine equivalent linearization, three height of 5, 10 and 15 story model frames to be one column was planed and designed accordance with Japanese PRESSS Guidelines. Five design classifications were represented to vary the hysteresis models in the model frames. Steady-state loop in the typical height at three rotational angle levels was analyzed to calculate the equivalent damping factors. Response spectrum of each model frame was calculated using the equivalent damping factors accounted by the steady-state loop. Further, to verify the response spectrum by equivalent linearization, earthquake response analysis of the model frames was carried out using three typical earthquake records and three modulated records developed by New-RC Project. From the both results of equivalent linearization and earthquake response analysis, following conclusions may be drawn:

1) Ratio of maximum story drift angle to rotational angle in 2/3 times the overall height of model frames was shown to be 1.1 favorably.

2) In the comparison of response displacement by spectrum and earthquake response displacement analyzed, the maximum response by three typical earthquake records was about 0.8 times the response by spectrum. Also, the maximum response by three New-RC records coincides with the response by spectrum favorably.

3) Earthquake response in the concrete frames could be estimated by equivalent linearization favorably.

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