11 WCEE

Copyright © 1996 Elsevier Science Ltd
Paper No. 1144. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

Research on the ultimate strength design method of prestressed concrete structures based on ductile capacity of structure

Kei Fukano, Katsuyoshi Itagaki, Ichizou Kishimoto, Tadashi Nakatsuka, Kazuo Suzuki

Architectural & Engineering Department, Obayashi Corp., 4-33 Kitahama-higashi, Chuo-ku, Osaka, Japan
Dept. of architecture, Faculty of engineering, Univ. of Osaka, 2-1 Yamada-oka Suita, Osaka, Japan

Abstract

Fundamental research for the advanced ultimate strength design method of prestressed concrete (PC) structures was conducted about design base shear coefficients CB for seismic design load especially. At first, trial models of typical PC structure, 1 thru. 12 stories high with factors ; numbers of span, span length, fluctuation of dimensions of column and girder sections, were prepared and transformed into lumped mass systems with elasto-plastic story characteristics for the following analyses. Secondly, first natural period T of PC structures was introduced with structure height H, based on elastic eigen value analysis. Because T is generally accepted as one of fundamental factors of design method and used in this research as a factor to provide CB. And at last, expressions of CB in relation to T for ultimate design specification were obtained as basic proposals, by dynamic elasto-plastic analyses. These analyses were carried out in time history, based on expected standard earthquake waves according to structure life. Proposed CB is due to the maximum response base shear and settled in consideration with elastic and before/after yielding characteristics of stories.

Keywords

PC frame structure; ultimate strength design; natural period;
dynamic response analysis; design shear coefficient

1. Introduction

The current seismic design procedure of prestressed concrete (PC) structures in Japan is divided into two phases due to intensity and occurrence frequency of expected earthquake. The first phase is based on allowable stress design concept with linear elastic analyses and the second on ultimate strength or capacity of structures. The ultimate strength design method is applied to buildings lower than or equal to 31m owing to its practical availability. Problems of the method between theory and practice, however, such as first natural period 'T' and load factor 1.50 of design base shear coefficient 'CB' for seismic load, should be solved urgently, because of the significance in the method and lack of verification compared with recent researches. Objectives of this research, for the advanced ultimate strength design method of PC structure, is to discuss T of PC frame structures and to obtain the relations between T and CB as basic recommendation, because CB for design method is not provided by only analytical results and additional discussion is required in view of the whole design system. Then, the following expressions of 'CB-T' are introduced with the results of response analyses.

2. PC model structures

Trial PC model structures as office buildings, designed on the current ultimate strength design method(ref.1), are 1 thru. 12-story, lower than 45m in height (Fig.1 shows 5-story models). Numbers of span are 1, 2 and equivalent infinite span models are also used, and story-height are 4.5m(1st story) and 3.6m(general story). Models have reinforced concrete (RC) columns with sections designed to satisfy the axial stress below 0.35Fc (Fc;nominal compressive strength of concrete) and shear strength above required one. PC girders have sections with depths determined according to the span-ratio of about 1/17 and widths changed as required. Fluctuations of column and girder section with 10 cm larger in dimension are also used additionally. Two nominal strength of concrete, 27Mpa and 36Mpa, are assumed for column and girder, respectively

3. The first natural period T

The fist natural period T of each structure model was investigated through lumped mass systems, because no expression is authorized for PC structure up to the present(ref.1). Analyzed results about 0.20 thru. 1.30 sec. are shown in Fig.2 and the relation between T and structure height H is indicated approximately linear and intoduced as follows;

$$T = 0.03\ H \quad \cdots\cdots\cdots\cdots\cdots\cdots (A)$$

(T = 0.02 H required in current code as RC, ref.1)

From the scope of models used in this research, eq.(A) is recommended for PC frame structures

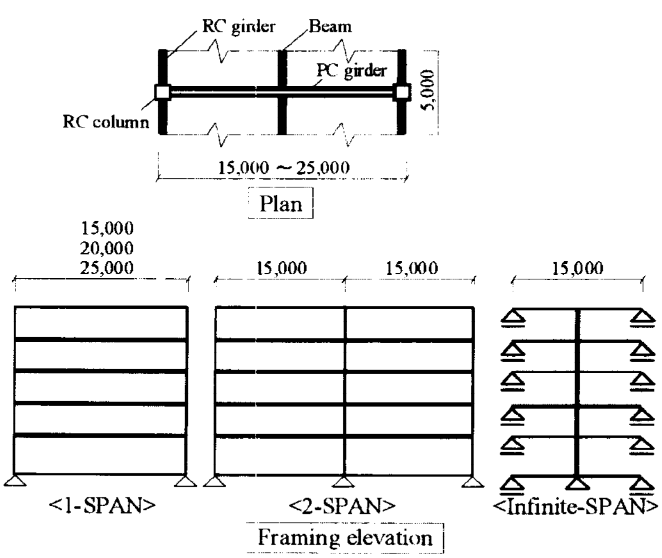

Fig.1 PC structure models (unit; mm)

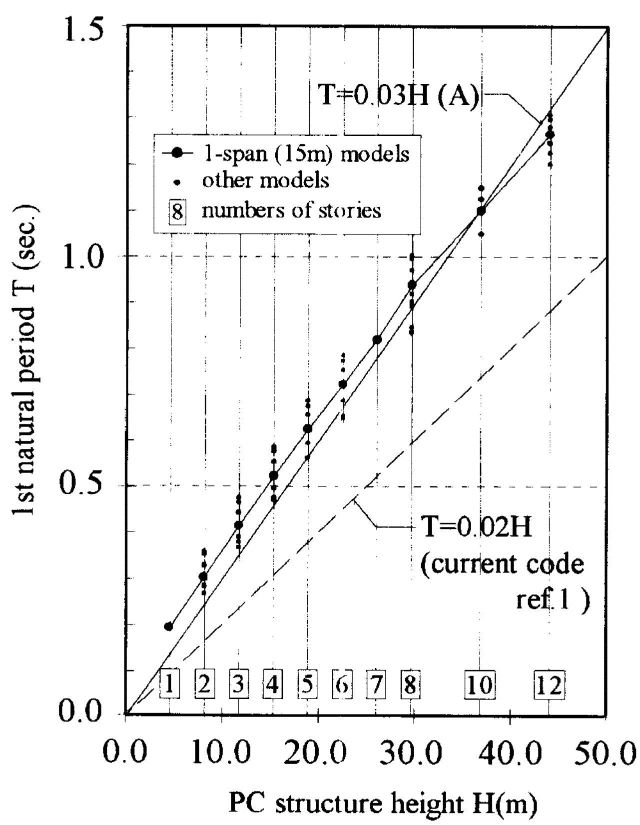

Fig.2 1st natural period T and height H

lower than 45m in height. Fig.2 also shows that T of 1-span (15m) models denotes average values and represent this research, then, these models are used in chapter 4 and 5. for dynamic analyses as standard models.

4. Elasto-plastic characteristics of model structure

For dynamic response analyses, elasto-plastic force-displacement relations of stories were assumed for all standard models above(Fig.3,4). Tri-linear type skeleton curves in this research consist of three story stiffnesses, that is, first(k1), second(k2) and 3rd(k3) gradients, as shown in Fig.3. k1 is linear gradient based on initial elastic stiffness of story and k3 is assumed as 1/1000 of k1. For the second gradient k2 degraded by cracking(Q1), two types, A and D, are assumed as follows. In type-A, second gradient ratio 'α' to k1 is directly settled to 0.30 thru. 0.50 on author's recent investigations, and in type-D, k2 is assumed considering yielding interstory drift angle(atQ2) as 1/150. This value is also settled in consideration with the elastic limit 1/200 of ref.1 and one of the design response limit 1/100 of ref.4. Shear forces at story yielding(Q2), elastic limit, are main factors of this research and decided using CB=0.20 thru.0.60 (Fig.3) with distribution factor Ai and design dead and live loads Wi(ref.1) for each story in all models.

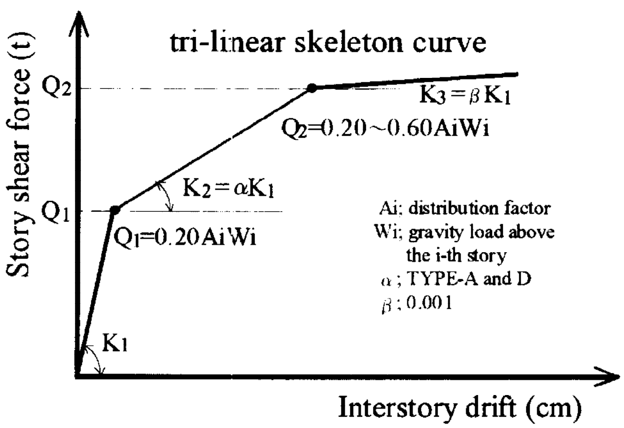

Fig.3 Story shear force-interstory drift relationship

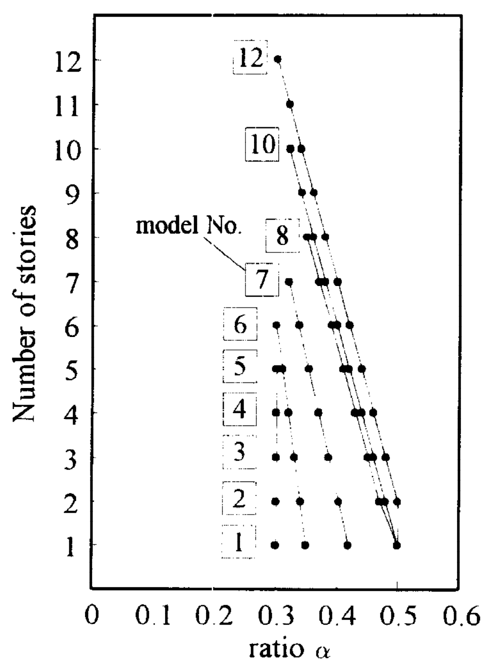

Fig.4 2nd gradient ration α (TYPE-A)

Though hysteresis loop of PC frame structure is not so clearly studied even now, the following three loop characteristics are observed in general. Before yielding in stories, ① loops with small hysteretic damping due to high restoration of PC girders, and After yielding, ② loops with a little larger hysteretic damping than the former due to remaining high restoration of PC girders and inelastic behavior of columns,③ loops similar to RC structures subjected to elasto-plastic behavior of RC columns. By reference to above characteristics and past experimental results (ref.3), a new rule of hysteresis loop 'PRC loop' for dynamic response analysis was proposed(Fig.5), in consideration with continuous relationship between RC and PC. In this loop, an unloading curve from a point on second branch is directed to the previous maximum point on opposite side, and a curve from a point of the third branch is

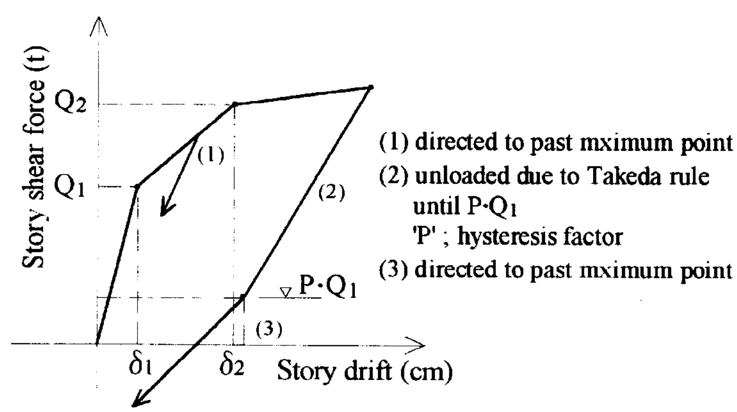

Fig.5 Hysteresis rule of PRC loop

based on the degrading type rule proposed by TAKEDA (Fig.6) for RC. Hysteresis factor 'p' is considered, which is to estimate the effect of degradation of high restoration of PC girders(Fig.5). Fig.6 shows TAKEDA loop and PRC loop for comparison. The equivalent viscous damping factor (heq) of PRC loop is given theoretically as follows ;

$$heq={}_{T}heq\left\{1-\frac{pQ_c}{Q_y}\cdot\frac{1}{1+\beta\mu-\beta}\right\} \cdots\cdots (B)$$

$$_{T}heq=\frac{1}{\pi}\left\{1-\frac{1+(\delta_c/\delta_y)}{1+(Q_c/Q_y)}\cdot\mu^{\alpha}\cdot\frac{1+\beta\mu-\beta}{\mu}\right\}$$

Previous experimental results in Fig.7 denotes that p of 0.40 is seemed to be available because heq by eq.(B) with p of 0.40 estimates the experimental results on the average and p of 0.40 is recommended generally in the range of interstory drift angle, 1/25 thru. 1/100.

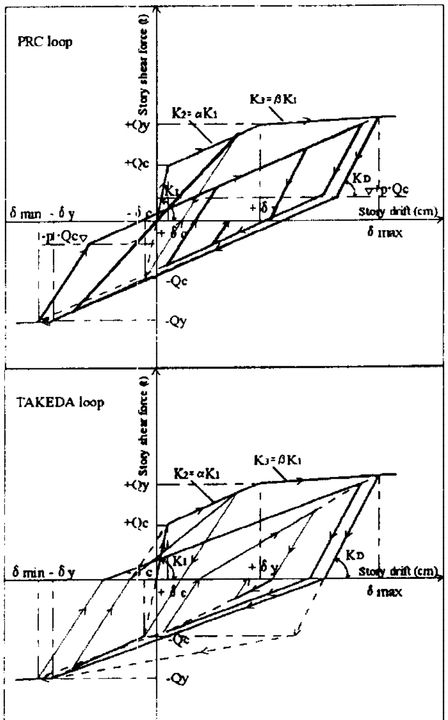

Fig.6 PRC and TAKEDA loop

Table 1 Earthquake wave

ID	Earthquake wave	Maximum acceleration (cm/s²)		Symbol
		Level-1	Level-2	
1	EL-CENTRO 1940 NS	255.4	510.8	□
2	TAFT 1952 EW	248.4	496.8	○
3	HACHINOHE 1968 NS	165.1	330.1	△
4	TOKYO 101 1956 NS	242.5	484.9	◇
5	OSAKA 205 1963 EW	123.0	246.1	▽

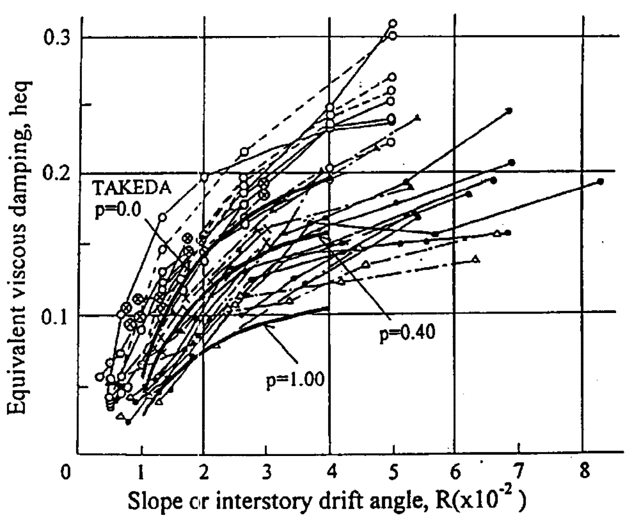

Fig.7 Equivalent viscous damping, heq

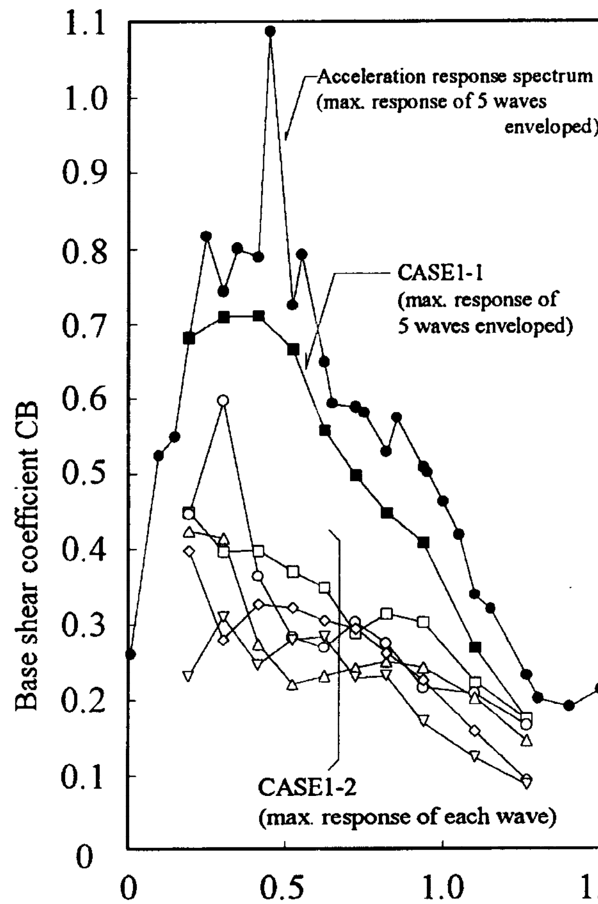

Fig.8 CB-T relation (Level-1)

5. Dynamic response analysis

Dynamic response analyses were carried out using five standard earthquake wave records listed in Table-1. The intensity levels of waves, the maximum acceleration, were determined based on the maximum velocity, 25 cm/s for the middle scale seismic load expected several times during structure life (level-1), and 50 cm/s to large scale earthquake expected at least once (level-2), respectively. These two levels were provided as current design specifications in Japan(ref.3,4).

The objective of the analyses for level-1 is to investigate the behavior of PC structure in elastic-state and that for level-2 in specified inelastic-state. Cases of analyses are divided into the following, on the basis of skeleton curves adopted. Analysis cases for level-1 are elastic analyses using skeleton curve having only first branch(case 1-1) and having both first and second branches(case 1-2). Analyses for level-2 include following two cases, that is, the same elastic analysis as case 1-2(case 2-1) and elasto-plastic analyses according to proposed tri-linear skeleton curves(case 2-2). Analysis time interval used was 0.005 sec. and assumed internal viscous damping factor h1 was 3% in all cases.

6. Base shear coefficients

Base shear coefficients CB for PC structures in elastic-state under level-1 earthquake, and in elastic or limited inelastic-state under level-2 earthquake were investigated in this research. The limited inelastic-state herein was defined by limited interstory drift angle of 1/100.

Fig.8 presents analytical results for level-1 earthquake. The relation between the maximum response CB and T in Fig.8 shows that equivalent acceleration response spectrum is larger than CB in the case 1-1 in terms of

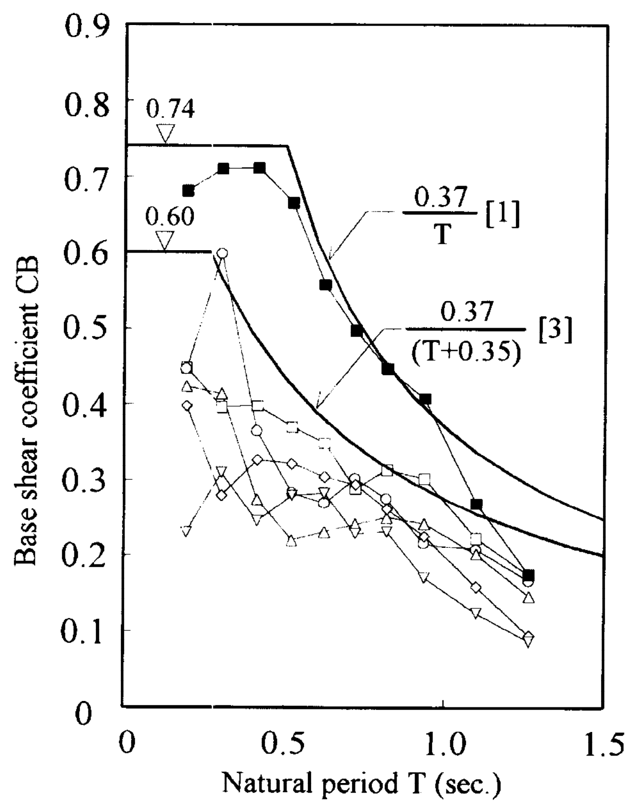

Fig.9 Formulation of CB-T due to max. response (Level-1)

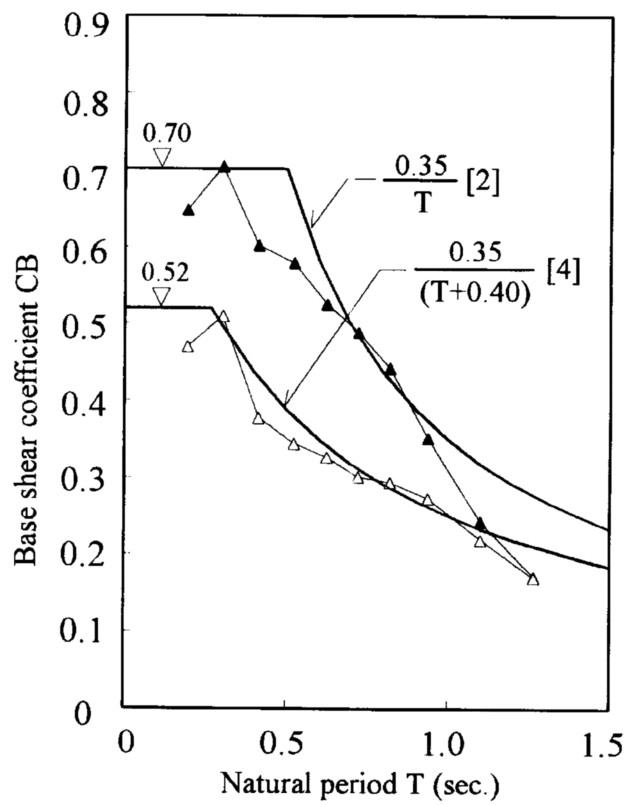

Fig.10 Formulation of CB-T due to ave.+1 σ (Level-1)

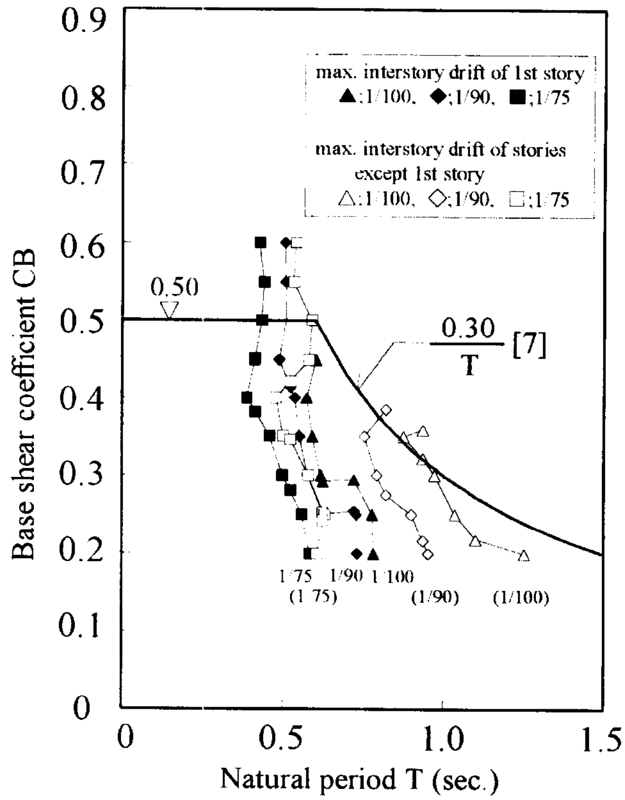

Fig.11 Formulation of CB-T due to max. response (Level-2, case 2-2)

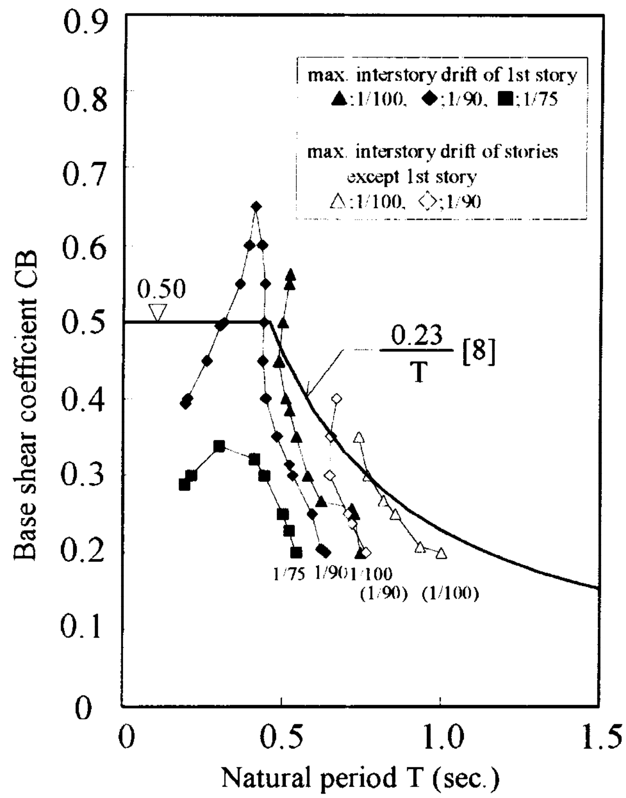

Fig.12 Formulation of CB-T due to ave. +1 σ (Level-2, case 2-2)

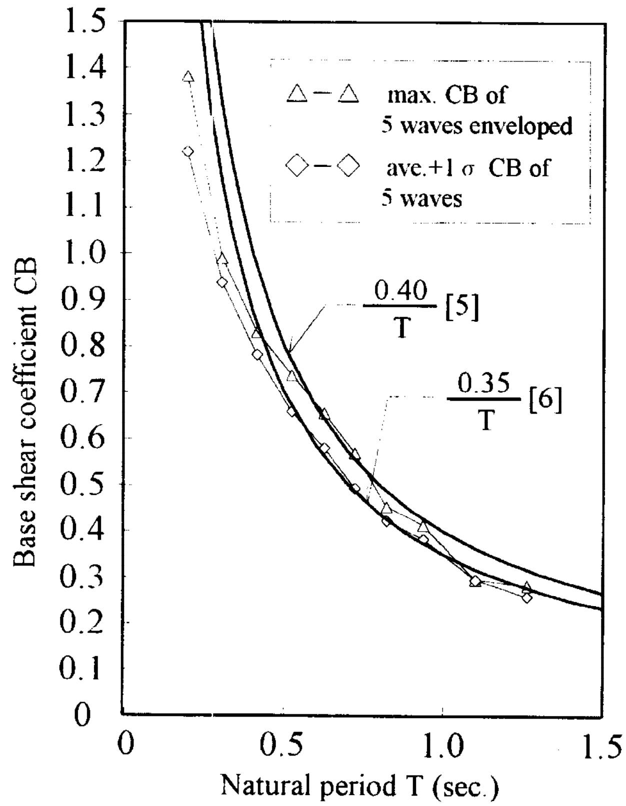

Fig.13 Formulation of CB-T (Level-2, case 2-1)

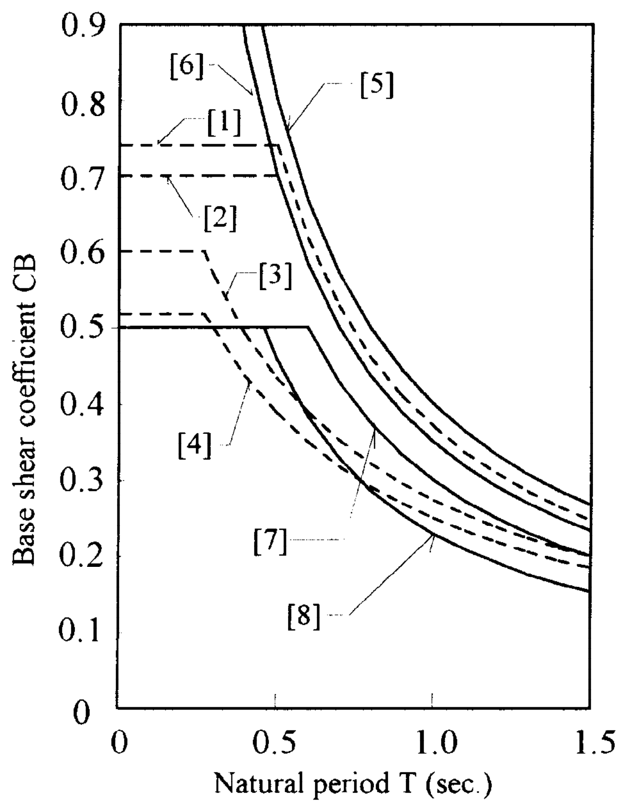

Fig.14 Comparison of eqs. 1 thru. 8

Table 2 Expressions for CB-T

Level	CASE	Enveloped data	CB expressions due to T			Eq.No.
			T<Tc	Tc	Tc<T	
1 25 (cm/s)	1-1	maximum	0.74	0.50	0.37/T	1
		ave. +1 σ	0.70	0.50	0.35/T	2
	1-2	maximum	0.60	0.27	0.37/(T+0.35)	3
		ave. +1 σ	0.52	0.27	0.35/(T+0.40)	4
2 50 (cm/s)	2-1	maximum	———	———	0.40/T	5
		ave. +1 σ	———	———	0.35/T	6
	2-2	maximum	0.50	0.60	0.30/T	7
		ave. +1 σ	0.50	0.46	0.23/T	8

T owing to higher mode effects, and similar tendency is observed in the case 1-2 due to gradient reduction of the second branch. This trend means that, even before yielding in level-1, CB should not be determined without appropriate consideration on gradient reduction, in contrast with Japanese code(ref.1)
based on the accelaration spectrum and elastic analyses.
In Fig.9, CB-T relations enveloping results of the maximum response by the five waves in case 1-1 and 1-2 are shown and approximate curves (eq.(1) and (3)) are expressed. Fig.10 illustrates CB-T relations enveloping the results on average values plus a standard deviation 'σ' of the maximum responses for each wave and corresponding approximate curves expressed by eq. (2) and (4).
Fig.11 presents the results of CB-T in case 2-2 on condition that the maximum interstory drift angles are below about 1/100 and the approximate curves (eq.(7)) enveloping the results of CB. In Fig.12, the similar curves (eq.(8)), which envelope data of average value plus a standard deviation 'σ' of the CB above mentioned, is shown. Fig.13 illustrates CB-T relations which is necessary to ensure stories elastic-state under level-2 earthquake. All CB-T relations are summarized in Fig.14. and Table-2. The CB-T relation for ultimate strength design for PC structures should be determined in consideration of the CB-T relations under both level-1 and 2 earthquake, and the consideration of case 1-2 to case 2-2 seems to be very important especially.

7. Conclusions

1. The available equation (A) about the first natural period T(sec.), derived from the examination for typical PC frame structures lower than 45 m in height, was proposed in terms of height H (m).
2. Relation between base shear coefficients CB and T for ultimate strength design method of PC structures were obtained in consideration of two levels of earthquake. The CB-T relations were examined to ensure the structures in initial elastic state for level-1 earthquake and to ensure the structures in second elastic state after cracking and in state of interstory drift angle below about 1/100 for level-2 earthquake, respectively.

8. Reference

1. The Building Standard Law Of Japan, 1994
2. "The Standard for Structural Design and Construction of Prestressed Concrete Structures," Architectural Institute of Japan, 1987.
3. "Ultimate Strength and Deformation Capacity of Buildings in Seismic Design," Architectural Institute of Japan, 1990.
4. "Design Guidelines for Earthquake Resistant Reinforced Concrete Buildings Based on the Ultimate Strength Concept" Architectural Institute of Japan, 1990.