STRUCTURAL DESIGN CONCEPT FOR HIGH-RISE PC BUILDINGS- JAPANESE PC PROJECT -

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SUMMARY

The cooperative research project on prestressed concrete (herein after abbreviated as PC) building structures (Japan PC Project) to prepare the design and construction guidelines for high rise PC buildings (less than 60m) started in 1995 under the leadership of the Building Research Institute (BRI), Ministry of Construction Japan. This project will be completed at the end of 1998. The design guidelines for PC structure buildings whose heights are lower than 60m are proposed. The guidelines are characterised by the rational seismic evaluation method reflecting hysteresis characteristics of PC members and structures; i.e., stiffness, strength, and equivalent damping ratio, those are affected by construction methods, members and structures configuration, steel arrangement as well as the prestressed level

INTRODUCTION

In 1998, Japanese Building Codes has been revised to introduce performance based regulation concept into their provisions. The required performances of buildings will be clearly described in their provisions. And the principle of performance evaluation is that the predicted response values should not exceed the estimated limit values. In case of major earthquakes, the maximum response values of strength and displacement of a structure should be smaller than the ultimate capacity for strength and displacement. This principle is also introduced in the report of National R/D project on New Structural Design System in Japan [Ministry of construction, 1998].

Prestressed concrete (herein after abbreviated as PC) structures have many combination of prestressed concrete (PC) members that are precast PC, site cast PC, precast partial PC, site cast partial PC, and site cast reinforced concrete. Adding on these combinations, prestressed level induced into structural members are various from non-crack control to crack width control. Their seismic performance curves are different, equivalent viscous damping ratio is also different depending on members combinations and prestressed level. It is difficult for their many types of PC structures to define the ultimate strength to secure the seismic safety rationally. And a design procedure for high rise building that isn't so common structure because required strength for various PC structures against large earthquake is difficult to be clearly defined.

The cooperative research project on PC building structures (Japan PC Project) to prepare the design and construction guidelines for high rise PC buildings (less than 60m) started in 1995 under the leadership of the Building Research Institute (BRI), Ministry of Construction, Japan. This paper introduces the structural design concept for high rise PC structures proposed in the cooperative research project.

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CONSTRUCTION OF GUIDELINES AND SCOPE

The contents of the guidelines are followings.
1. Scope, in that section target structural performance and its level is also described. 2. Materials, 3. Design for dead and live loads, snow, and wind, 4. Design for earthquake motion, 5. The evaluation methods of members for strength and deformation subjected to earthquake motions. 6. Design for foundation, in this section, foundation and basement should provide enough stiffness and strength in order to avoid the trouble of serviceability, and also should transmit vertical and horizontal load to the soil safely. 7. Design for non-structural members, in that non-structural members should not affect on the seismic performance of main structural members., 8. Details, 9. Specifications in that important issues related to PC structures construction are listed and explained. Design for wind and snow loads are omitted to explain in this paper because these loads do not govern PC building structures in Japan.

The guidelines present design and performance evaluation concept of PC building structures of regular configuration and of height lower than 60 m in basic. Because the response characteristics of irregular configuration structures cannot be clearly understood even by using a non-linear earthquake response analysis of a three-dimensional structure, and reliable strong earthquake motion records are not available at present. And the structural systems in the scope of the guidelines are moment resisting frame with/without shear walls using any PC members induced any prestressed level. PC structure systems that use PC cable outside, or un-bonded PC cable in seismic structural members are out of the scope due to lack of enough research on these issues in this project.

TARGET STRUCTURAL PERFORMANCE AND THESE LEVEL

Three kinds of basic structural performance are provided for, that are safety, reparability, and serviceability, which correspond to the protection of human life, property, and functions and comfort, respectively [Akiyama, Teshigawara, and Fukuyama, 2000]. Since there are many basic structural performance items to evaluate, the items are classified under the five categories; the structural frames, building elements, equipment, furniture, and the ground. Combinations of the five evaluation objects and three kinds of basic structural performance are the performance evaluation items.

Reparability is the unique structural performance proposed by [Akiyama, Teshigawara, and Fukuyama, 2000], the purpose of requiring reparability is to secure easy repair of damages caused by external forces to the construction (protection of property). Reparability performance assess whether the degradation of or damage to the structural frames, building materials, equipment, furniture, and the ground is adequately controlled within a predefined range in terms of ease of repair (such as restoration of structural performances, difficulty of repair works, and costs of and economic loss by the repair).

Durability is the performance expressing the degree of deterioration (caused by aging, decay, or termites) up to which other performances of the construction are maintained. In this guideline, durability is a factor for evaluating each basic structural performance. For example, the degradation of structural elements caused by aging, decay, and/or termites is considered in assessing safety. Cracks and other external damages are included in serviceability.

This guidelines select the structural frames and building elements as the main objects of evaluation among the five categories. Building elements are all factors constituting the construction structure other than equipment and furniture, and are structural members and interior and exterior members.

The level of structural performance shows the degrees of safety, reparability, and serviceability, and should be concurrently decided by the owner of the construction and the design engineer with consideration of social restrictions and cultural and economic conditions so to satisfy the wishes of the owner. The Building Standard Law in Japan reflects social restrictions and technological levels, and prescribes the minimum levels of structural performance, below that the structural performance of any construction must never fall.
Performance levels are expressed as combinations of load intensity and the corresponding state (limit state) of the structure. Safety and serviceability of structural frame and building elements against dead load, live load, wind, snow, earthquake are focused on in the guidelines as the performance evaluation items. The other performance evaluation items, especially reparability are evaluated if necessary. Load frequencies caused by regional and environmental conditions should be considered. Load intensity and corresponding state for each event is described in section 4 and 5, respectively.

DESIGN FOR DEAD AND LIVE LOAD

To evaluate the structural performance described at section 3, serviceability for permanent load are evaluated by checking the allowable stress, deflection and crack width. For dead load, live load, and their combinations, ultimate strength design are performed to evaluate structural safety.

Dead loads are calculated as the building design is. The designer should consider the time depending and the space depending change of live load to be designed. For serviceability check by traditional allowable stress, load factors are assumed to be unity. Deformation limit and crack width limit is set on the point of view of serviceability and durability [Architectural Institute of Japan, 1991]. Load due to temperature should be considered if necessary. For safety check by ultimate strength of members, factored load should be considered. Load factors are 1.2 for dead load, 2.0 for live load and 1.7 for both loads. These factors are the same as the current design method for dead and live load of PC structures referring to ultimate strength design method [Architectural Institute of Japan, 1987]. Maximum strength of system is defined as the ultimate strength of members.

DESIGN FOR EARTHQUAKE MOTIONS

Earthquake Motion

The building must satisfy the performance for two intensity levels of earthquake motions. The building should keep function (serviceability) for an earthquake motion that may occur several times in the lifetime of the building, a return period interval of 30-50 years is supposed to cover these events. Structural damage that could threaten the structural safety, durability, and serviceability of the building after event would be also avoided against this event level. Yield of structural members will be checked for this event. And the building should keep safety for an earthquake of largest intensity expected at the construction site. The maximum possible earthquake motion level is determined on the basis of historical earthquake data, recorded strong ground motions in the past, seismic and geologic tectonic structures, active faults, and others. The standard acceleration response spectrum given at the engineering bedrock that is defined as a layer with more than 400 m/s in shear wave velocity is shown in fig.1 (ACC. Spectrum). The evaluation earthquake motion is represented with the acceleration response spectrum in the following formula [Okawa, Dan, and Tohdo, 1999].

$$S_a = ZGS_0 \tag{1}$$

Where, S_a: acceleration response spectrum for evaluation, Z: seismic zoning factor, G: soil amplification factor, and S_0: basic acceleration response spectrum at engineering bedrock.
The basic acceleration response spectra shall be consistent with the design seismic shear force given in the current Building Standard Law of Japan. The relationship between the base shear coefficient and the acceleration response spectrum is given with the earthquake response of the uniform shear beam model. It is reported that in this model the base shear force shall be multiplied by 1.23 for uniform acceleration spectrum, and shall be multiplied by 1.1 for uniform velocity spectrum [Ishiyama, 1987]. In addition to this simplified relationship, we assumed the soil amplification factors 1.5 for acceleration dominated period range, and 2.0 for velocity dominated period range. These factors of 1.5 and 2.0 are based on the nonlinear response computations using simplified models of surface soil layers. With these assumptions, the basic acceleration response spectrum is derived as shown in Fig. 1.

Evaluation Procedure

Overall these criteria are verified by the response drift, and then design assumption should be confirmed up to the specified response drift. The response drift is evaluated based on a series of nonlinear static analysis under monotonically increasing lateral forces and equivalent linear response method using acceleration and displacement response spectrum that utilizes the structural characteristics of PC structures; i.e., residual displacement after damage is small and hysteresis damping is almost constant until relatively large deformation.

The proposed seismic evaluation procedure applies the equivalent single-degree-of-freedom (ESDOF) system and the response spectrum method. A flow of this procedure is illustrated in Fig. 2. There are indeed various analytical methods for predicting the response of structures subjected to earthquake excitations. The one that is shown here is based on the equivalent single degree of freedom (ESDOF) system and the response spectrum method [ATC-40, 1996: Freeman, 1978: Shibata, and Sozen, 1976].

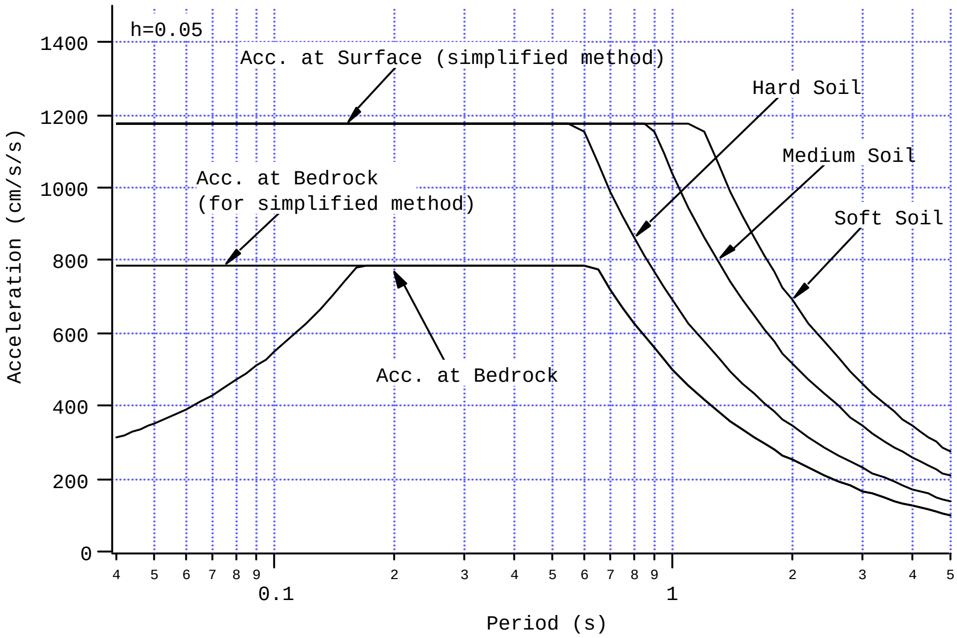


Fig.1 Acceleration response spectrum at engineering bed rock and surface

Determination of the response spectra to be used in the evaluation procedure (Step I)

i) For a given basic design spectrum at the engineering bedrock level, draw up the free-field site-dependent acceleration (Sa) and displacement response spectra (Sd), for different damping levels.
ii) In the estimation of free-field site-dependent acceleration and displacement response (step i) above), consider the strain-dependent soil deposit characteristics.
iii) In case of need, present graphically the relation of Sa-Sd, for different damping levels.

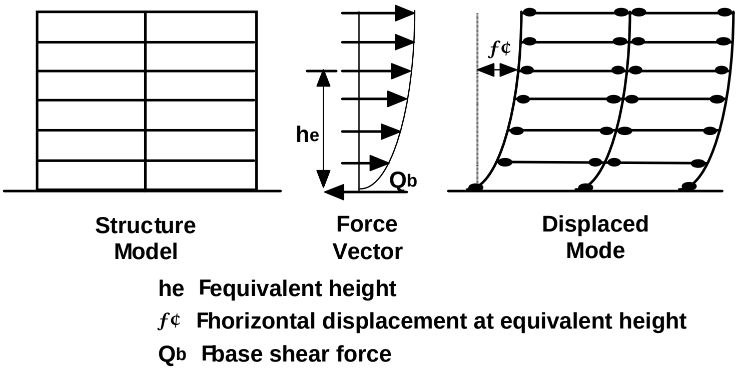
Determination of the hysteretic characteristic, equivalent stiffness and equivalent damping ratio of the structure (Step II)

i) Model the structure as a simplified ESDOF system and establish its force-displacement relationship (see Fig. 2a).
ii) Determine the limit strength and displacement of the structure corresponding to the ESDOF system mentioned above.
iii) The soil-structure interaction effects should basically be considered.
iv) In case of need, determine the equivalent stiffness in accordance with the limit values.
v) Determine the equivalent damping ratio on the basis of viscous damping ratio, hysteretic dissipation energy and elastic strain energy of the structure (see Fig. 2b).
vi) In case that the torsional vibration effects are predominant in the structure, these effects should be considered when establishing the force-displacement relationship of the ESDOF system.

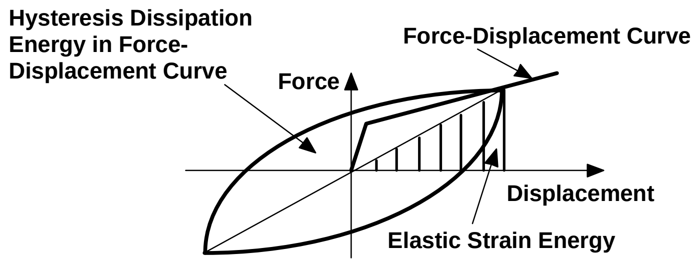
Examination of the safety of the structure (Step III)

In this final step, it is verified whether the response values predicted on the basis of the response spectra determined according to the step I satisfy the condition of being smaller than the limit values estimated on the basis of step II (see Fig. 2c).

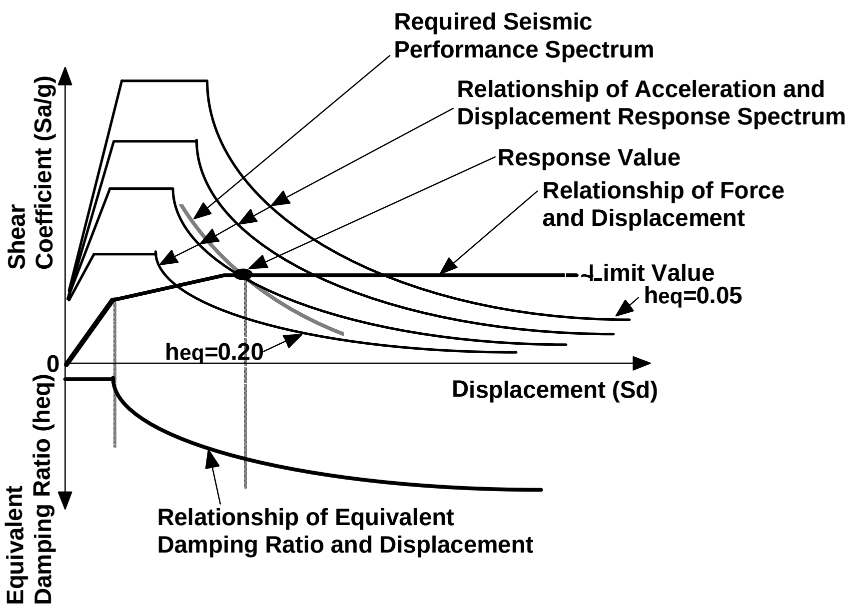
In order to determine the limit strength and displacement of the structure, a specific displaced mode is necessary to be assumed in advance for its inelastic response (see Fig. 2a). Basically, any predominant or possible to be experienced displaced mode of the structure subjected to earthquake motions can be applied. The predominant or possible to be experienced displaced mode implies any of the failure modes observed during the major earthquakes such as beam failure mode, story failure mode or any other definite failure mode.



(a) Structure Model and Inelastic Response



(b) Energy for Equivalent Damping Ratio



(b) Comparison of Expected Response Values and Estimated Limit Values

Fig. 2 Illustration of Proposed Evaluation Procedure for Major Seismic Events

Damping

Damping ratio of several types of PC members to be used at the estimation of response is as listed in equation (2).

$$hs = \left(0.06 + 0.14\sqrt{\alpha}\right)\cdot\left(1 - 1/\sqrt{\mu}\right) + \left(0.02 + 0.03\sqrt{\alpha}\right) \quad (2)$$

In the equation (2), μ: ductility factor, α: contribution factor of re-bars to bending strength, when α equals to zero, that presents a damping of full PC member,

$$hs^{PC} = 0.06\left(1 - 1/\sqrt{\mu}\right) + 0.02 \quad (3)$$

and when α equals to 1, that presents a damping of RC member.

$$hs^{RC} = 0.2\left(1 - 1/\sqrt{\mu}\right) + 0.05 \quad (4)$$

These are derived using Takeda hysteresis model for RC members [Takeda, Sozen and Nielsen, 1970], Modified Thompson & Park Model for PC members [Nishiyama,1993], assuming that the total hysteresis energy absorbed by members during earthquake is equal to viscous damping energy with equivalent stiffness at maximum response displacement, that is formulated by equation (5) [Shibata, and Sozen, 1976].

$$hs = -\int_0^t \ddot{y}_0 \cdot \dot{y} \cdot dt \Big/ \left(2\omega e \cdot \int_0^t \dot{y} \cdot dt\right) \quad (5)$$

Here, $\ddot{y}_0$: input earthquake acceleration, $\dot{y}$: response velocity, ωe: equivalent frequency at maximum response displacement.

The relationship between equivalent damping ratio (heq) obtained from hysteresis model of RC and PC members and substitute damping ratio defined by Eq. (3) and (4) is shown in fig. 3. In this comparison, response velocities in eq. (5) are obtained by SDOF dynamic response using artificial earthquake motions with far source (New2) and near source (New4) and several recorded earthquake motions.

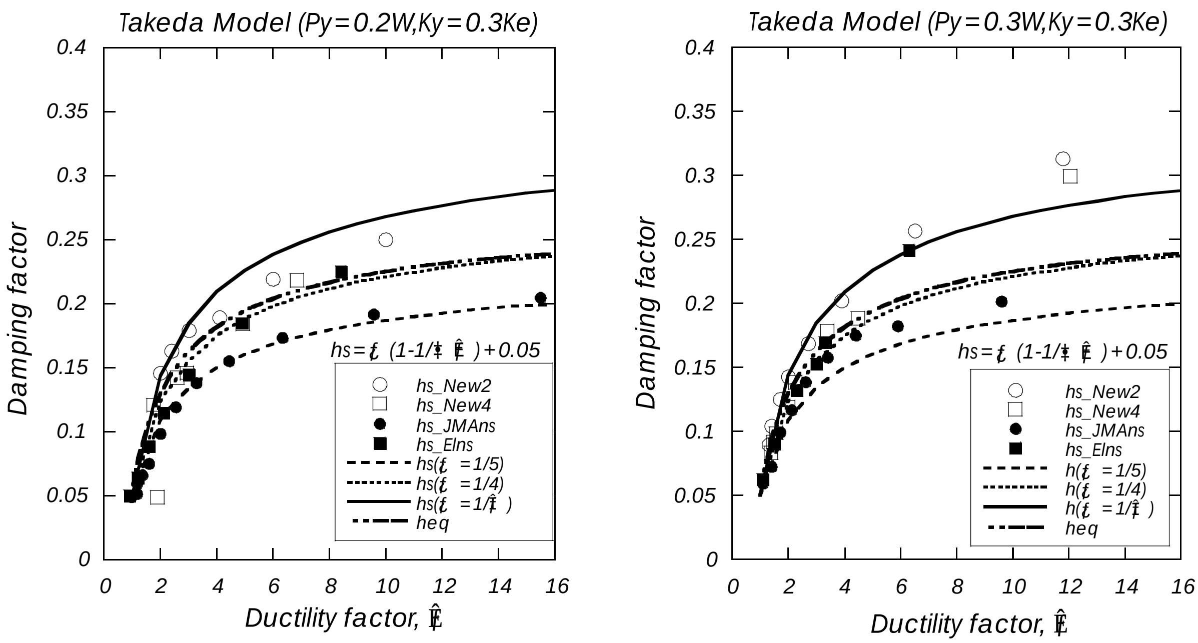


Fig. 3 (a) Damping factor for RC members

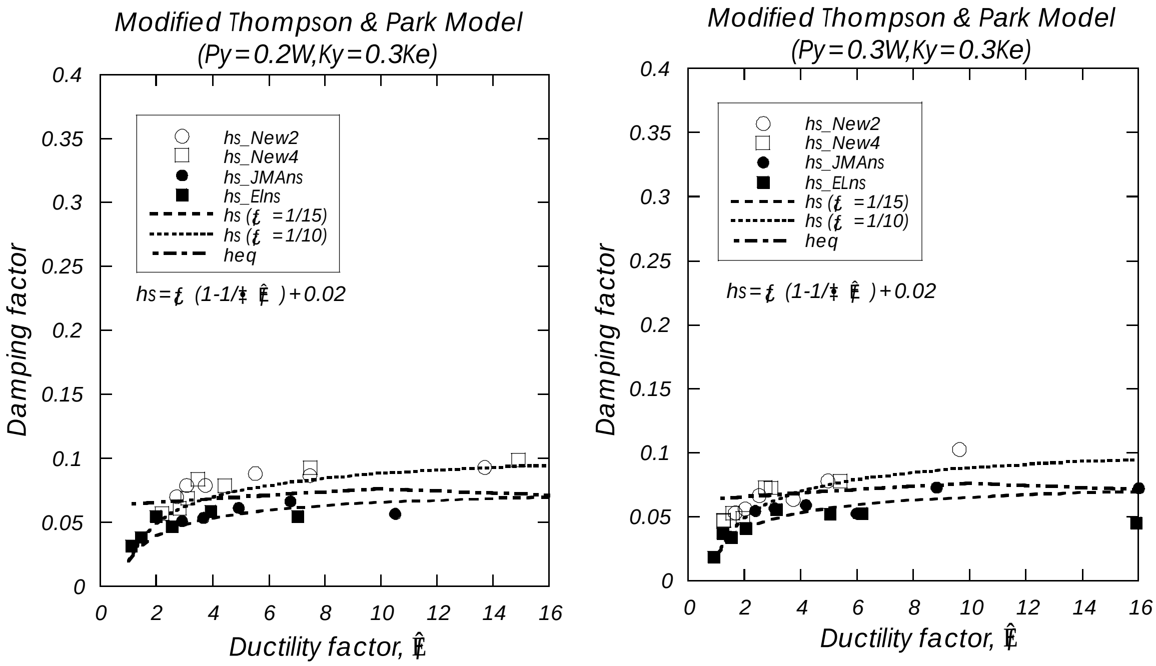


Fig. 3 (b) Damping factor for PC members

Damping ratio for total structure system is calculated based on equivalent damping of constituting members defined by equations (2) and (6).

$$hs^{system} = \sum_{1}^{n} \left(hs,i \cdot Wi\right) / \left(\sum_{1}^{n} Wi\right) + hv \qquad (6)$$

Here, Wi : potential energy of each member constituting of system, hv : viscous damping.

Design of Structural Member

Design deformation and design strength of structural members could be calculated from the factored response value of ESDOF. The reason why response value of ESDOF would be enlarged would be that there might be many unexpected factors such as characteristics of earthquake motions, structural modeling etc. Here, deformation capacity of every structural member should be confirmed more than response value of ESDOF or the corresponding response value with 1.5 times potential energy of response value of ESDOF. Load incremental non-linear structural analysis is the analysis tool that is preparing for general use.

CONCLUSIONS

The design guidelines for PC structure buildings whose heights are lower than 60m are proposed. The guidelines are characterized by the rational seismic evaluation method reflecting hysteresis characteristics of PC members and structures; i.e., stiffness, strength, and equivalent damping ratio, those are affected by construction methods, members and structures configuration, steel arrangement as well as the prestressed level.

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