RESPONSE PREDICTION OF PRESTRESSED CONCRETE BUILDINGS AGAINST EARTHQUAKE EXCITATIONS BY CAPACITY SPECTRUM METHOD

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SUMMARY

Non-linear time-history analyses on single-degree-of-freedom systems with load-displacement relations of prestressed and conventional reinforced concrete are reported. The analytical results are used for investigating response characteristics of prestressed concrete systems and deriving substitute damping. Energy time-history of prestressed concrete system is compared with that of reinforced concrete. The substitute damping obtained is compared with equivalent viscous damping derived directly from load-displacement relationship of the systems. Referring to the substitute damping from the dynamic response analyses and the equivalent viscous damping from stationary load-displacement curves, equivalent damping for the capacity spectrum method is proposed.

INTRODUCTION

Hysteresis energy dissipation of prestressed concrete systems is smaller than that of conventional reinforced concrete. This should be reflected in seismic design of prestressed concrete systems. For example, NZS4203:1992 specifies larger seismic design load for prestressed concrete moment-resisting frames than for conventional reinforced concrete depending on their vibration period. The larger seismic design load is intended for reducing seismic response of prestressed concrete frames to almost the same level as reinforced concrete frames. However, as displacement-based design has been popular and has already been implemented in several code practices, what should be evaluated is displacement response by which structural performance is discussed.

In a project, which finished early 1999, to establish a design guideline for high-rise precast prestressed concrete buildings, prediction of displacement by the capacity spectrum method with equivalent damping has been implemented. Because the design guideline is performance-based, response prediction of structures to earthquake excitations is the key for the design guideline. Among several methods proposed for response prediction capacity spectrum method may be the most straightforward and visual.

In the 11th WCEE the author presented numerical equations giving substitute damping for single-degree-of-freedom systems with load-displacement hysteresis loops of prestressed and conventional reinforced concrete [Nishiyama, 1996]. Also shown was that displacement responses obtained by non-linear time-history analysis were well estimated by the equivalent linearization method with the substitute damping

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Substitute damping may be able to be used in capacity spectrum method as a structural damping. However, for practical design of building structures, it is difficult to assign substitute damping for each member. Equivalent viscous damping derived easily from stationary load-displacement relationship of the member may be used referring to the substitute damping.

In this paper non-linear time-history analyses on single-degree-of-freedom systems with load-displacement relations of prestressed or conventional reinforced concrete are reported. The analytical results are used for investigating response characteristics of prestressed concrete systems and deriving substitute damping. The substitute damping obtained is compared with equivalent viscous damping derived directly from load-displacement relationship of the systems. Referring to the substitute damping from the dynamic response analyses and the equivalent viscous damping from stationary load-displacement curve, equivalent damping for the capacity spectrum method is proposed.

ANALYSES OF SDOF SYSTEMS

Response prediction by substitute damping proposed by Shibata and Sozen [Shibata, 1976] can be a powerful tool for displacement-based design. However, substitute damping is calculated based on results of non-linear time-history analyses using recorded or artificial earthquake wave data. It is supposed to depend on the characteristics of earthquake waves used in the analyses. When we have a new system whose load-deformation hysteresis loops are different from what we have had in the past, there is some sort of difficulties to get substitute damping. On the other hand, equivalent viscous damping can be easily derived if we have a stationary load-displacement curve of the new system. The load-displacement curve can be obtained by some experiment if possible or applying load-displacement curve idealizations proposed in the past. However, equivalent viscous damping does not include dynamic effect and response to earthquake waves is by nature non-stationary. It is felt that equivalent viscous damping based on stationary load-displacement curve would overestimate the damping that should be used for response prediction.

The relation between substitute damping and equivalent viscous damping is of great interest for implementing response prediction to design procedures. To compare substitute damping with equivalent viscous damping non-linear time-history analyses using recorded and artificial earthquake wave data were carried out on single-degree-of-freedom systems with load-displacement relations of prestressed and conventional reinforced concrete. The analyses were also used for studying energy response of prestressed concrete systems in detail.

Idealization of load-displacement hysteresis loops of prestressed concrete

Load-displacement hysteresis curves for prestressed concrete used in the analyses was originally proposed by Thompson and Park [Thompson, 1980] and later modified by Nishiyama [Nishiyama, 1993]. The idealization simulates less hysteretic energy dissipation of prestressed concrete than that of ordinary reinforced concrete as shown in Fig.1. For ordinary reinforced concrete Takeda model was used.

The skeleton curve consists of three segments as shown in Fig.2. The first segment represents elastic portion, the second one for after-cracking but before-yielding. The last represents after-yielding. Two connections between the two of the three segments characterize cracking and yielding. Yield strength is specified as 20% and 30% the system weight. Cracking strength is 1/3 the yield strength. The stiffness at yielding is 30% the elastic stiffness. The stiffness after yielding is 1/250 the elastic stiffness. Unloading stiffness factor γ for Takeda model is 0.5. The damping factor of 3% proportional to the stiffness at yielding was used.

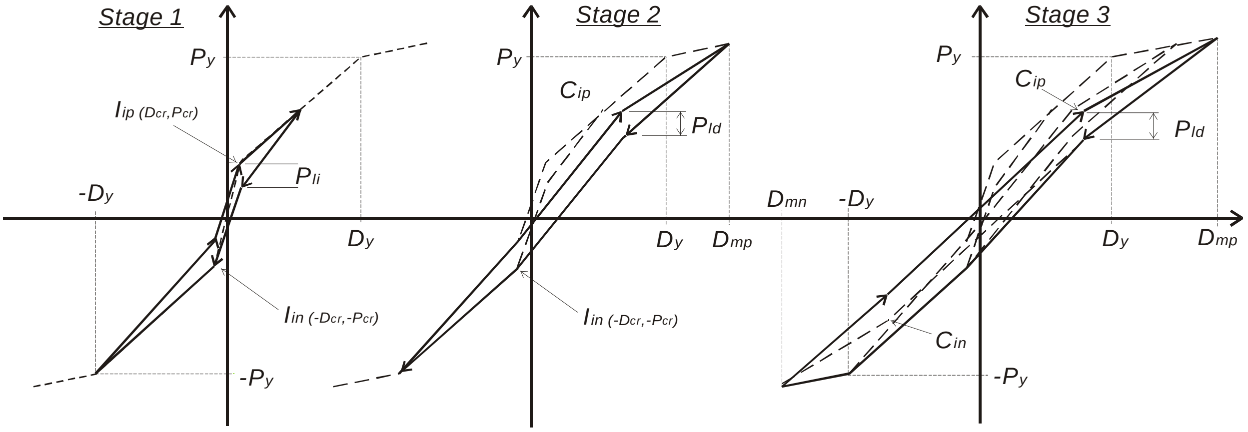

Fig.1 Modified Thompson and Park model

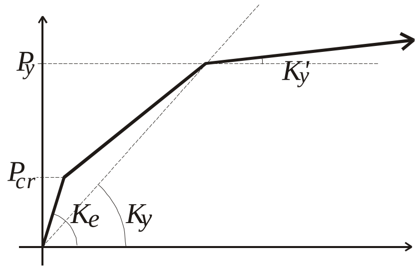

Fig.2 Skeleton curve

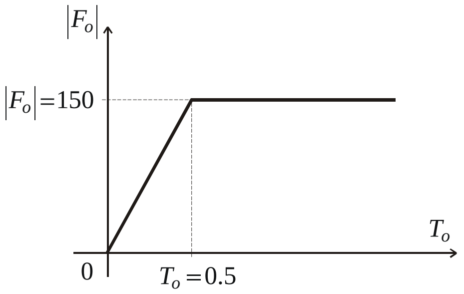

Fig.3 Fourier amplitude spectrum

Earthquake waves

Four earthquake waves were used: JMA (Japan Maritime Meteorological Agency) record during the 1995 Hygoken Nanbu earthquake, El Centro 1940 NS and two artificial waves. JMA record and one of the artificial wave (*New2*) are considered to be near-field earthquakes while El Centro NS and the other artificial wave (*New4*) are considered to represent far-field earthquakes. The artificial waves were generated based on the Fourier amplitude spectrum (h=0) shown in Fig.3. The difference between two artificial waves is an envelope curve of the acceleration time-history. The envelope proposed by Osaki [Osaki, 1994], which is assumed to follow normal distribution was used. The standard deviation assigned for near-field and far-field earthquakes were 0.06 and 0.20, respectively. The maximum velocity of the waves was transformed to 50cm/s and 75cm/s. The artificial waves generated are shown in Fig.4.

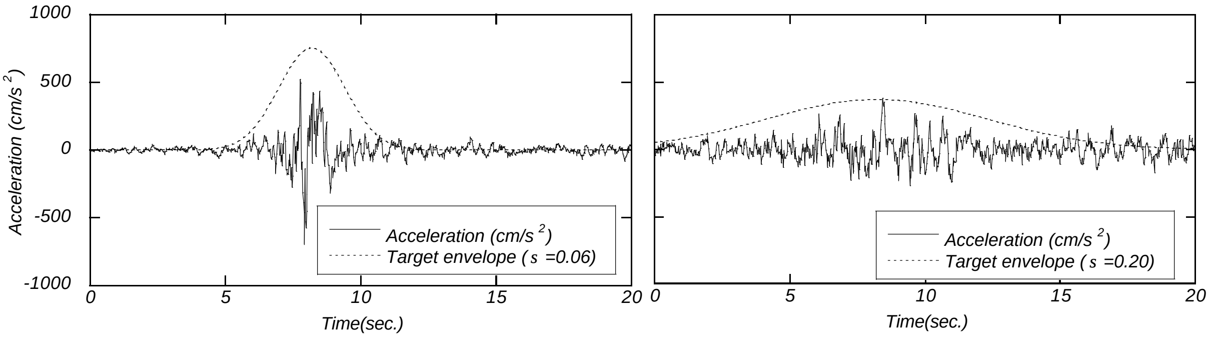

Fig.4 Acceleration-time history of artificial waves (*New2* and *New4*)

Energy time history

Equation for energy from $t=0$ to $t=t_0$ was derived by integration of equation of motion as follows,

$$\int_0^{t_0} m\ddot{x}\dot{x}dt + c\int_0^{t_0} \dot{x}^2 dt + \int_0^{t_0} Q(x)\dot{x}dt = -\int_0^{t_0} m\ddot{y}_0\dot{x}dt \quad (1)$$

where, m: mass of the system, x: relative displacement, c: coefficient of viscous damping, $Q(x)$: restoring force at x, y_0: ground acceleration. The above equation can be simplified as follows,

$$E_k + E_d + E_h = E_g \quad (2)$$

where, E_k: kinematic energy, E_d: damping energy, E_h: hysteretic energy, E_g: energy of ground motion.

Fig.5 shows energy time history for the artificial near-field earthquake *New2* with maximum velocity of 75cm/s. The total amount of energy from the ground motion in both cases are almost the same. Looking at the figure with focusing on a half cycle, that is, from Point *A* to Point *B* where E_k=0 as shown in Figs.6 and 7 reveals that the fluctuation in E_h of the prestressed concrete system is much larger than that of the reinforced concrete system. This is because residual displacement of prestressed concrete is smaller and energy released in the path from Point *A* to *C* is much larger than that of reinforced concrete. Therefore, kinematic energy and damping energy of prestressed concrete are larger than those of reinforced concrete.

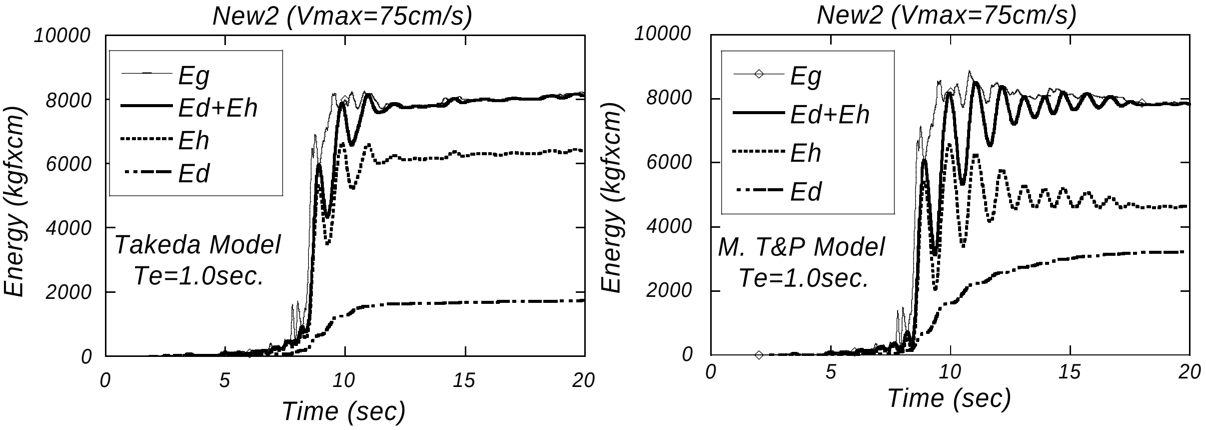

Fig.5 Energy time history

Ductility design which is implemented in modern seismic design codes worldwide relies on energy dissipation by members' plastic deformation, that is, damage to members. As shown in this paper prestressed concrete dissipates less hysteretic energy than conventional reinforced concrete. This means that it has less damage and less residual deformation. Energy which should be absorbed during earthquake is dissipated kinematically and by viscous damping due to higher acceleration and velocity. This may be another way of resisting earthquake which does not leave damage to buildings after earthquake. Of course higher acceleration and velocity may be harmful to the contents of the structures and must be considered.

Required Capacity Spectra

Fig.8 shows required capacity spectra in which period is based on the elastic stiffness of the systems. The target ductilities are 2 and 4. Required capacity for prestressed concrete systems is larger than that for reinforced concrete systems in all four earthquake waves. This fact certifies that larger seismic design load should be assigned to prestressed concrete systems. It is revealed by close observation to a half cycle path that the larger difference in released energy was found especially in the far-field earthquakes, the larger difference in required capacity was observed. On the contrary, in case of the near-field earthquakes the difference in released energy is smaller and the difference in required capacity is also smaller.

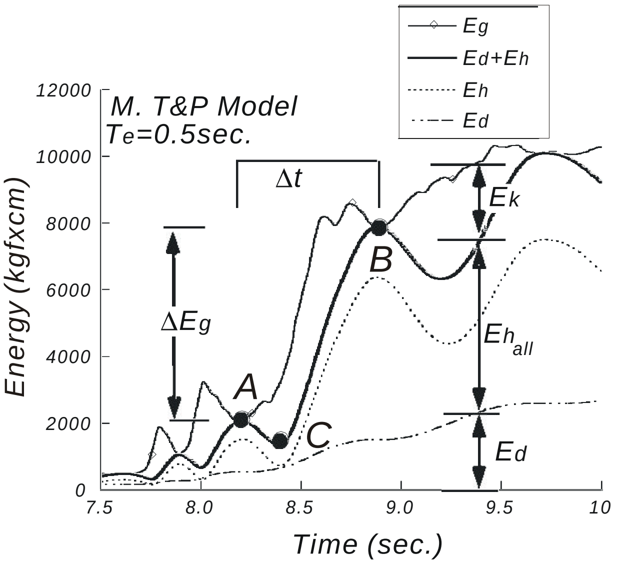

Fig.6 Energy time history

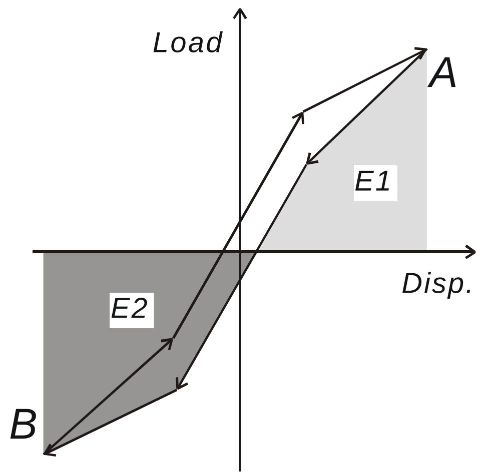

Fig.7 Stationary hysteresis loop of Modified Thompson and Park model

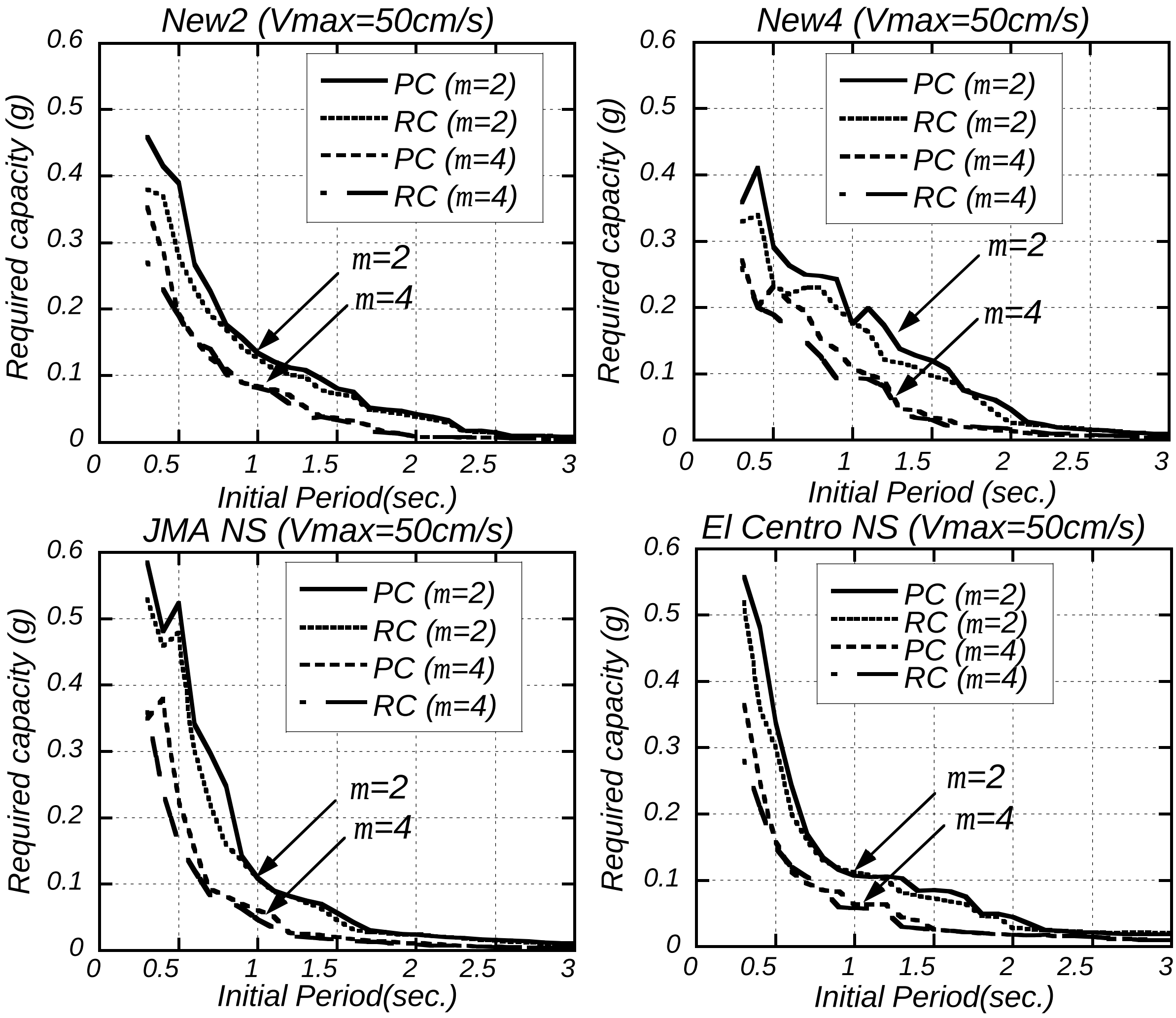

Fig.8 Required capacity spectra

Damping factor

In Fig.9 substitute damping h_s calculated from the analytical results are plotted against ductility factor, m by white circles (*New2*), white square (*New4*), black circles (JMA) and black squares (El Centro NS). Also shown in this figure are the equations,

$$h_s = a\left(1-1/\sqrt{m}\right)+0.05 \qquad \text{for Takeda model} \qquad (3)$$

$$h_s = a\left(1-1/\sqrt{m}\right)+0.02 \qquad \text{for modified Thompson and Park model} \qquad (4)$$

a ranges 1/5, 1/4 and 1/*p* for Takeda model, and 1/15 and 1/10 for modified Thompson and Park model. Equivalent viscous damping h_{eq} obtained from a stationary load-displacement curve of the model is also plotted by a solid line. As shown in the figure h_{eq} is regarded as an average of the plotted substitute dampings. Equivalent viscous damping is considered to be larger than substitute damping because it is obtained from a stationary response and may overestimate hysteretic energy dissipation. However, due to the following reasons there are some cases in which substitute damping is larger than equivalent viscous damping:

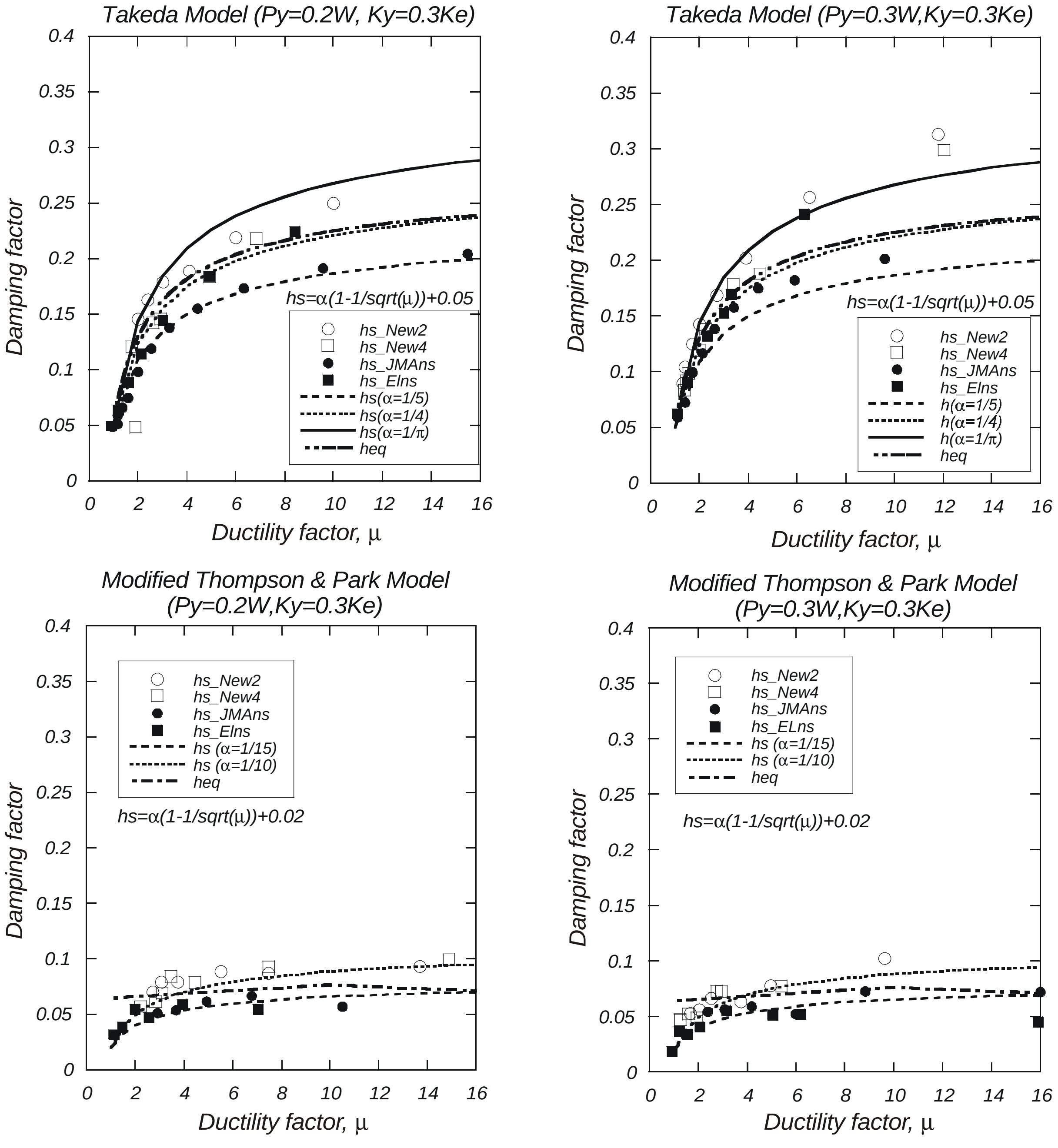

Fig.9 Damping factors

(1) substitute damping includes viscous damping which is assigned in dynamic response analyses,
(2) h_s includes hysteretic energy dissipated before yielding, and
(3) virgin loop dissipated much larger hysteresis energy than successive stationary loops.

As far as the analyses in this paper are concerned suitable values for a are 0.02 for Takeda model and 0.06 for Modified Thompson and Park model. It should be noted that the equations are lower bound and response prediction using them would overestimate a real response.

RESPONSE PREDICTION BY CAPACITY SPECTRUM METHOD

Response prediction by capacity spectrum method as illustrated in Fig.10 consists of the following steps:

1. Assume a maximum displacement.
2. Equivalent period of vibration and equivalent damping are calculated using the assumed maximum displacement.
3. Modify a demand spectrum by the equivalent damping.
4. Obtain an intersection between the demand spectrum and the line by which the equivalent linearized system can be expressed.
5. Several cases are calculated on the basis of assumed maximum displacements.
6. By connecting the intersections obtained above a target response spectrum is drawn on the *Sa* - *Sd* plane.
7. Response can be obtained as an intersection between the target response spectrum and the capacity spectrum based on the load-displacement curve of the system.

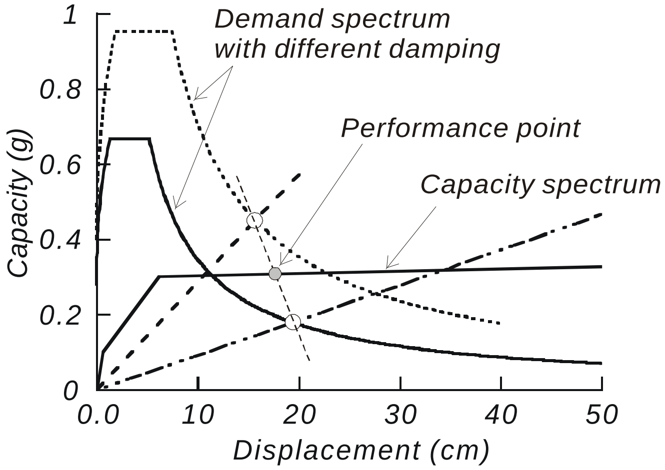

Fig.10 Capacity spectrum method

In practical design the above procedure may be troublesome. Therefore, in the seismic design specified in the design code for the project on high-rise precast prestressed concrete buildings response prediction may be completed when the first intersection is obtained (Step 4) and confirmed to be smaller than the maximum displacement assumed in Step 1.

Examples

Demand Spectra used here were derived from a design spectrum proposed in “Recommendations for Loads on Buildings” [AIJ, 1993] published by Architectural Institute of Japan. Acceleration response spectrum is given by a set of equations in the recommendations.

For response prediction in this paper the following numerical values were used:

A_o =200 cm/s^2, V_o =13.33 cm/s, G_A =1.2, G_V =2.0 (for medium subsoil), f_A =2.5, f_V =2.0, d=0.5, F_h =1.0(h=0.05)

Two return periods of 200 and 400 years were chosen for comparison. Acceleration response spectra for return period of 200 and 400 years are given by the following sets of equations, respectively.

$$S_A(T,h)=\begin{cases}349\left(1+\dfrac{3T}{0.56}\right) & 0\le T\le 0.28\\ 872.5 & 0.28\le T\le 0.56\\ \dfrac{488.6}{T} & 0.56\le T\end{cases}\qquad S_A(T,h)=\begin{cases}507\left(1+\dfrac{3T}{0.56}\right) & 0\le T\le 0.28\\ 1267.5 & 0.28\le T\le 0.56\\ \dfrac{709.8}{T} & 0.56\le T\end{cases}\tag{5}$$

Fig.12 schematically shows the prediction procedure.

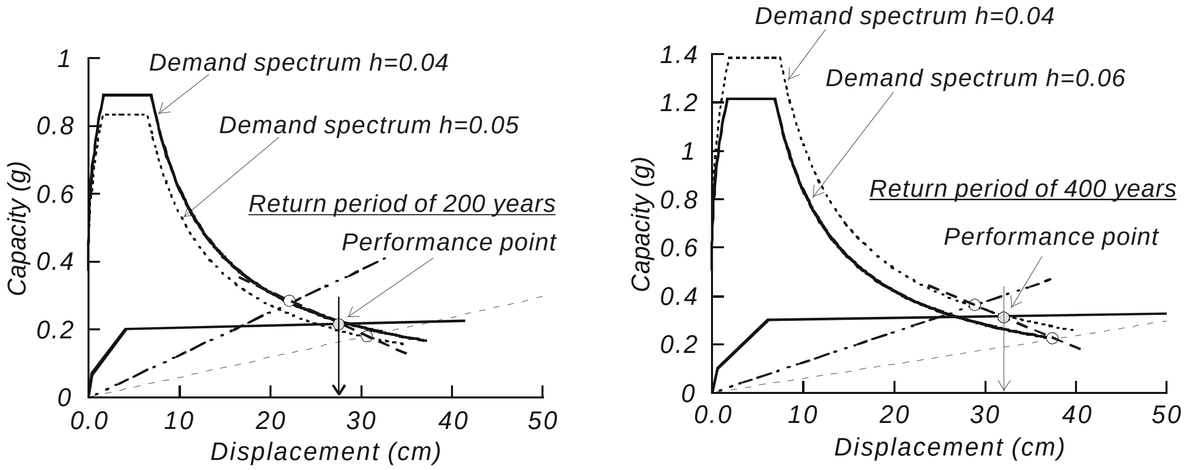

Fig.11 Response prediction by capacity spectrum method for Modified Thompson and Park model

CONCLUSIONS

1. Equivalent damping was proposed for prestressed concrete and conventional reinforced concrete systems.
2. Energy response of prestressed concrete system was investigated and compared with that of conventional reinforced concrete. The reason why the response of prestressed concrete is larger than that of reinforced concrete is that released energy on unloading path is larger than that of reinforced concrete.
3. Response prediction by capacity spectrum method was demonstrated.

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