Prediction of Response of Prestressed Concrete Buildings to Earthquake Excitation Using Capacity Spectrum Method

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Abstract

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

1. Introduction

Hysteresis energy dissipation of prestressed concrete buildings is considered smaller than that of conventional reinforced concrete (Nishiyama 1993). This has been reflected in the seismic design of prestressed concrete buildings. For example, NZS4203:1992 (SNZ 1992) specifies a 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 the seismic response of prestressed concrete frames to almost the same level as reinforced concrete frames (Nishiyama 1990). However, as displacement-based design has being getting popular and has already been implemented in several code practices, what should be evaluated is the displacement response by which structural performance is discussed.

In a research project, completed in early 1999, to establish a design guideline for high-rise precast prestressed concrete buildings (Japan Association for Building Research Promotion 1999), prediction of displacement using the capacity spectrum method with an equivalent structural damping was implemented following the proposed guideline. Because the design guideline is performance-based, prediction of the response of structures to earthquake excitation is the key for a successful use of the design procedure. Among the several methods proposed for response prediction, the capacity spectrum method may be the most straightforward and visual.

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

For practical design of building structures, it is difficult to assign substitute dampings for constituent members and to accumulate them to obtain an equivalent structural damping of the whole structure for use of the capacity spectrum method. This paper reports the results of non-linear time-history analyses on single-degree-of-freedom systems with load-displacement relations of prestressed and conventional reinforced concrete buildings. The analytical results are used for investigating the response characteristics of prestressed concrete buildings and deriving a substitute damping. The substitute damping obtained is compared with an equivalent viscous damping derived directly from the load-displacement relationship of the systems. Based on the comparison of the substitute damping from the dynamic response analyses and the equivalent viscous damping from stationary load-displacement curve, an equivalent structural damping for the capacity spectrum method is proposed.

Three kinds of dampings are used in this paper, as follows. Substitute damping, which was originally proposed by Shibata and Sozen (1976), is a damping derived from dynamic response analyses using Equation (6), equivalent viscous damping, which is a hysteretic damping derived from load-displacement hysteresis loops of a member or a subassembly obtained by pseudo-static loading tests, and equivalent structural damping, which represents a structural damping of a building, which is used for the capacity spectrum method to obtain the displacement response.

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2. Analyses of SDOF systems

The response prediction by substitute damping proposed by Shibata and Sozen (1976) can be a powerful tool for displacement-based design. However, substitute damping is calculated based on the 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. In the case of a new system whose load-deformation hysteresis loops are different from what we have had in the past, some difficulty is involved in obtaining the substitute damping. On the other hand, an equivalent viscous damping can be easily derived if the stationary load-displacement curve of the new system is known. The load-displacement curve can be obtained through quasi-static loading experiments if such can be carried out or else load-displacement curve idealizations proposed in the past can be modified and employed. However, the equivalent viscous damping does not include the dynamic effect and response to earthquake waves is by nature non-stationary. It is therefore felt that the equivalent viscous damping based on stationary load-displacement curve, if it is used in the capacity spectrum method, would overestimate the damping that should be used for response prediction, as discussed in Section 2.5.

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

2.1 Idealization of load-displacement hysteresis loops of prestressed concrete

The load-displacement hysteresis curves for prestressed concrete used in the analyses were originally proposed by Thompson and Park (1980) and later modified by Nishiyama (1993). The idealization simulates less hysteretic energy dissipation of prestressed concrete than that of ordinary reinforced concrete as shown in Fig. 1. The idealization is able to cover load-displacement hysteresis curves from fully prestressed concrete to ordinary reinforced concrete using the ratio of non-prestressed mild-steel contribution to the total moment capacity of the member section as parameter $\eta$. Although the idealization can be used for ordinary reinforced concrete systems by setting the ratio to unity, the Takeda model was used for ordinary reinforced concrete systems as a benchmark.

The prestressed, partially prestressed and reinforced concrete idealizations are expressed by the same functions, in which the loop widths $P_{ii}$ and $P_{id}$ at coordinates $I_p$, $I_m$, $C_p$ and $C_m$ vary depending on parameter $\eta$.

\[
P_{ii} / P_{cr} = (0.2 + 0.8\sqrt{\eta})D_i / D_m \quad (1)
\]

\[
P_{ma} / P_{my} = (0.3 + 0.6\sqrt{\eta})D_y / D_m \quad (2)
\]

$D_i$ and $D_m$ are the displacement at unloading from the envelope curve and the current value of the maximum imposed displacement, respectively.

Equivalent viscous damping $h_{eq}^p$ obtained from the idealization above is expressed by the following equation.

\[
h_{eq}^p = \frac{1}{2\pi} (1.3 + 0.05\mu)(1.3 + 0.6\sqrt{\eta})
\]

It should be noted that $h_{eq}^p$ is given by a linear equation of the square root of $\eta$.

The idealization was originally derived from the loading test results on partially prestressed concrete members and their assemblages. In this paper, the idealizations are assumed to represent the structural behavior of a building that can be modeled as a sin-
gle-degree-of-freedom system.

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

2.2 Earthquake waves

Four earthquake waves were used: The JMMA (Japan Maritime Meteorological Agency) record during the 1995 Hyogo-ken Nanbu earthquake (JMA), El Centro 1940 NS (El Centro NS) and two artificial waves. The JMMA record and one of the artificial waves (New2) are considered to be near-fault 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 (1994), which is assumed to follow normal distribution, was used. The standard deviation assigned for the New2 and New4 artificial earthquakes were 0.06 and 0.20, respectively. Two maximum wave velocity levels were assumed: 50 cm/s and 75 cm/s. The generated artificial waves are shown in Fig. 4.

2.3 Energy time history

An equation for energy from \( t = 0 \) to \( t = t_0 \) was derived by integration of the motion equation, as follows,

\[
\int_0^{t_0} m \dddot{x} dt + c \int_0^{t_0} \dddot{x}^2 dt + \int_0^{t_0} Q(x) \dot{x} dt = -\int_0^{t_0} m y_0 \dot{x} dt
\]

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

\[
E_k + E_d + E_h = E_g
\]

where \( E_k \) = kinematic energy, \( E_d \) = damping energy, \( E_h \) = hysteretic energy, and \( E_g \) = energy of ground motion. Figure 5 shows the energy time history for artificial near-fault earthquake New2 with a maximum velocity of 75 cm/s. The total amount of energy from the ground motion in both cases is almost the same. Figure 6 shows enlarged images of part of Fig.5 (from 8 to 11 seconds). Figures 5 and 6 reveal that the damping energy \( E_d \) is
slightly larger in the prestressed concrete than in the reinforced concrete, and the fluctuation in $E_h$ of the prestressed concrete system is much larger than that of the reinforced concrete system. Kinematic energy $E_k$, which is derived as a difference between $E_g$ and $E_d+E_h$ in Fig. 6, is larger in the prestressed concrete than in the reinforced concrete. This indicates that in the prestressed concrete, the input earthquake energy was dissipated mainly kinematically.

Ductility design, which is implemented in modern seismic design codes worldwide, relies on energy dissipation by members’ plastic deformation, that is, damage to the members. As shown in this paper, prestressed concrete systems dissipate less hysteretic energy than conventional reinforced concrete systems. This means that such systems suffer less damage and less residual deformation. Energy that should be absorbed during earthquakes is dissipated kinematically and by viscous damping due to higher acceleration and velocity. This may be another way of resisting earthquakes, leaving buildings undamaged after earthquakes. However, higher acceleration and velocity may be harmful to the contents of the structures and some sort of damping device may be attached.

Uang and Bertero (1990) pointed out in their paper that the absolute energy equation is physically more meaningful than the relative energy equation. They also pointed out that the relative energy formulation is suitable for short period structures. In this paper, the relative energy equation was used and the systems considered had relatively short periods.

### 2.4 Required capacity spectra

Figure 7 shows the required capacity spectra, in which the period is based on the elastic stiffness of the systems. The target ductility values are 2 and 4. The load capacity of the system was adjusted until the target ductility values were obtained. Required capacity for prestressed concrete systems is larger than that for reinforced concrete systems in all four earthquake waves. This fact indicates that larger seismic design load should be assigned to prestressed concrete systems if almost the same amount of displacement response as conventional reinforced concrete systems is required. However, there are some cases where prestressed concrete systems showed smaller responses than reinforced concrete systems. This fact was also shown by dynamic analyses on structural frames presented by Nishiyama (1993).
2.5 Damping factors

In Fig. 8, substitute damping $h_s$ calculated using Eq. 6 from the analytical results is plotted against ductility factor $\mu$ using white circles (New2), white squares (New4), black circles (JMMA) and black squares (El Centro NS).

$$h_s = \frac{\int \ddot{y}_v^2 dt}{2 \alpha \int \ddot{x}_v^2 dt}$$  \hspace{1cm} (6)

Also shown in this figure are the following equations.

$$h_s = \alpha \left( 1 - \frac{1}{\sqrt{\mu}} \right) + 0.05 \text{ for Takeda model} \hspace{1cm} (7)$$

$$h_s = \alpha \left( 1 - \frac{1}{\sqrt{\mu}} \right) + 0.02 \hspace{1cm} \text{for modified Thompson and Park model} \hspace{1cm} (8)$$

For Takeda model, $\alpha$ ranges 1/5, 1/4 and 1/\pi for the Takeda model, and 1/15 and 1/10 for the modified Thompson and Park model. Equivalent viscous damping $h_{eq}$ obtained from a stationary load-displacement curve of the model is also plotted by thick dashed lines. 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 dampings because it is obtained from a stationary response and may result in overestimating hysteretic energy dissipation. However, due to the following reasons, there are some cases in which substitute damping is larger than equivalent viscous damping:

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

As far as the analyses in this paper are concerned, suitable values for $\alpha$ are 0.2 for the Takeda model and 0.06 for the modified Thompson and Park model. It should be noted that the equations are lower bounds and response prediction using them would overestimate a real
response.

The author carried out dynamic response analyses using the ratio of non-prestressed mild-steel contribution in the member section to the total moment capacity as a parameter. Based on the analytical results and the square root of \( \eta \) dominating the hysteresis energy absorption in the idealization, the following equation is a proposal for equivalent structural damping for concrete structures covering load-displacement hysteresis curves from ordinary reinforced concrete members to prestressed concrete members depending on the contribution of non-prestressed mild-steel reinforcement to the total moment capacity:

\[
h^{\text{eq}}(\mu, \eta) = (0.06 + 0.14\sqrt{\eta})(1 - 1/\sqrt{\mu}) + (0.02 + 0.03\sqrt{\eta})
\]

(9)

where \( \eta \) = the ratio of non-prestressed mild-strength reinforcement contribution to the total moment capacity of the member section, \( \eta = M_{r} / M_{u} \), \( M_{r} \) = moment capacity by non-prestressed mild-steel reinforcement, and \( M_{u} \) = total moment capacity. \( \eta = 0 \) stands for fully prestressed sections that contain prestressing steel only, and \( \eta = 1 \) for ordinary reinforced concrete sections that contain non-prestressed mild steel only.

Kato et al. (2000) carried out pseudo-dynamic testing on a three-story two-bay precast prestressed concrete frame. All the members were assembled by post-tensioning and were considered to have \( \eta \) of 0. The test results show that the equivalent viscous damping obtained from the story shear force-interstory drift was approximately 6% at the interstory drift of 1/50, which almost coincided with the damping factors obtained from the modified Thompson and Park model in Fig. 8.

Prestressed concrete building structures usually consist of reinforced, partially prestressed and prestressed concrete structural members. The substitute structure method proposed by Shibata and Sozen (1976) may be used to obtain an equivalent damping for a structure.

Fig. 8 Damping factors.
3. Conclusions

1. An equivalent structural damping that can be used for response prediction using the capacity spectrum method was proposed for concrete buildings ranging from conventional reinforced concrete to prestressed concrete. The parameter is the ratio of ordinary mild-steel reinforcement contribution to the total moment capacity of the structural member section.

2. The energy response of prestressed concrete systems was investigated and compared with that of conventional reinforced concrete systems. The results revealed that damping energy $E_d$ is slightly larger in prestressed concrete than in reinforced concrete, and the fluctuation in $E_d$ of the prestressed concrete system is much larger than that of the reinforced concrete system. In the prestressed concrete, the input earthquake energy was dissipated mainly kinematically.

3. Prestressed concrete building structures usually consist of reinforced, partially prestressed and prestressed concrete structural members. A building may have several kinds of structural members that have different equivalent dampings. A method such as the substitute structure method proposed by Shibata and Sozen should be developed to obtain the equivalent structural damping for the building.

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References