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SEISMIC DESIGN PROCEDURE OF CONCRETE BUILDING STRUCTURES BY SUBSTITUTE DAMPING

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ABSTRACT

A hysteresis model of concrete members was proposed based on the idealization proposed by Thompson and Park (1980), and experimental results of prestressed concrete beam-column joint subassemblies carried out by the authors. The model covers conventionally reinforced concrete, partially prestressed concrete and prestressed concrete. Dynamic response analyses of SDOF systems and multi-story building structures were conducted using the proposed model.

Based on the dynamic response analyses, substitute dampings for conventionally reinforced, partially prestressed and prestressed concrete systems were calculated. They were used to introduce a procedure for predicting dynamic response of concrete building structures using the similar concept as Gulkan and Sozen (1974) proposed. The substitute damping was proved to give a good approximation of responses of those systems.

KEYWORDS

Seismic design; prestressed concrete; substitute damping; reinforced concrete; seismic response

INTRODUCTION

Past research on prestressed concrete have shown larger response of prestressed concrete building structures than reinforced concrete. This is because the hysteresis loops of prestressed concrete members have less energy dissipation than those of reinforced concrete members. Some researchers have conducted dynamic response analyses on prestressed and reinforced concrete systems and compared their responses. The first dynamic analyses on prestressed concrete systems were reported by Thompson and Park (1980). They idealized moment-curvature hysteresis loops of prestressed concrete sections on the basis of the experimental results of prestressed, partially prestressed and reinforced concrete beam-column joint assemblies and the analytical work. The idealized hysteresis loops were involved in the dynamic response analysis program as a load-displacement relationship of a single-degree-of-freedom system. The conclusion they obtained from the analysis was 30% in average larger response of the prestressed concrete systems than that of the reinforced concrete systems with the same initial period of vibration. However, the calculated results varied widely.

In this paper, a hysteresis model of concrete members is proposed based on experimental results of prestressed concrete beam-column joint subassemblies carried out by the authors. The model covers conventionally reinforced concrete, partially prestressed concrete and prestressed concrete. Based on the dynamic response analyses, substitute dampings for conventionally reinforced, partially prestressed and prestressed concrete systems are calculated. They are used to introduce a procedure for predicting dynamic response of concrete building structures using the similar concept as Gulkan and Sozen (1974) proposed.

MOMENT - CURVATURE IDEALIZATION OF PRESTRESSED, PARTIALLY PRESTRESSED AND REINFORCED CONCRETE SECTIONS

In this section, a new idealization of prestressed, partially prestressed and reinforced concrete members is proposed. This is based on the idealization proposed by Thompson and Park (1980) and the experimental results reported by Nishiyama et al (1991).

Thompson and Park developed an idealization, illustrated in Fig. 1, for the moment - curvature characteristics of partially prestressed concrete members (ranging between fully prestressed and reinforced concrete members) under reversed cyclic loading by combining the response of the prestressed concrete idealization presented by Blakeley with some modifications and the Ramberg-Osgood idealization. Their idealization is quite useful because it can cover the whole range of concrete members from fully prestressed members to conventionally reinforced concrete members depending on the contribution of prestressing steel to the ultimate moment capacity of the member section. However, it has two main defects;

1) In the large ductility range their prestressed concrete model indicates a somewhat pinched hysteresis, which is quite different from typical hysteresis loops for prestressed concrete sections.

2) Flexural cracking cannot be explicitly defined in their reinforced concrete model because it is described by a Ramberg-Osgood function.

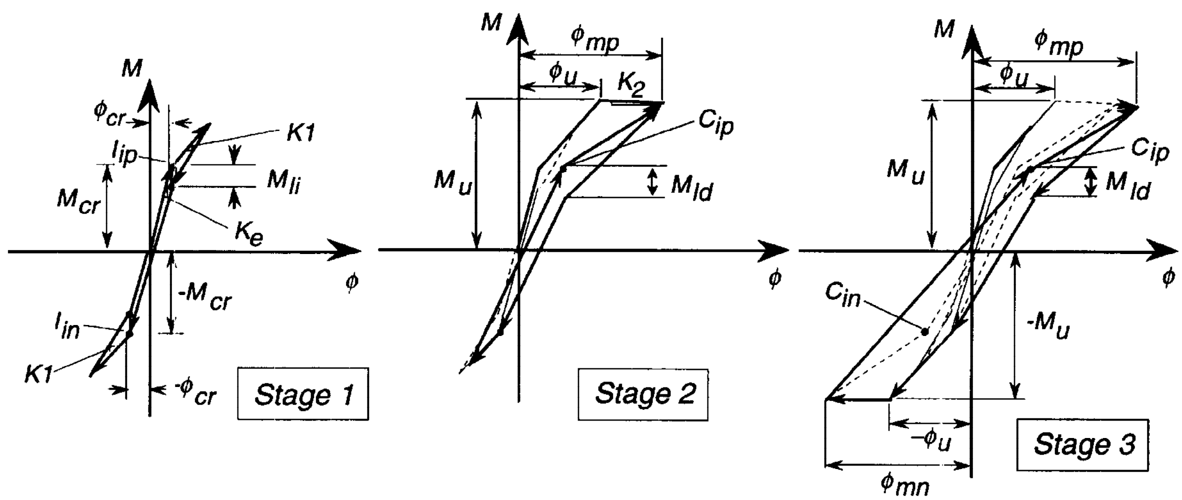

Fig.1 Prestressed concrete idealization by Thompson and Park (1980)

Modifications with the prestressed concrete idealization

Some modifications to the prestressed concrete idealization proposed by Thompson and Park were made. In their idealization a negative stiffness for the envelope curve was assumed after curvatures greater than ϕ_u have been sustained in either direction. The negative slope was resulted from the capacity reduction due to crushing and spalling of the unconfined cover concrete. However, it depends on the intensity of prestressing force introduced into the member, the cover thickness, the amount of transverse reinforcement and so on. A larger amount of prestressing force usually causes a larger reduction in moment capacity in the earlier stage of loading. The stiffness k_2 for the envelope curve beyond the crushing curvature ϕ_u was assumed to be a linear function of the prestress level η on the basis of the comparison with the experimental results.

$$k_2 = (-0.04\eta + 0.004)k_e \qquad (1)$$

where, $\eta = P_e/(f_c' \cdot A_g)$, P_e = effective prestressing force, f_c' = compressive strength of concrete and A_g = gross sectional area of the member.

The idealization for a prestressed concrete section made by Thompson and Park was found to indicate pinched hysteresis loops, which are typical for reinforced concrete members controlled by bond deterioration in the large deformation region. This contradicts the test results obtained in the past research on prestressed concrete members. This is because the moment of the point C_{ip} which was given in the original model is considered too small when large curvatures are imposed on the section. Therefore, the coordinates of $C_{ip}(\phi, M)$ were determined as follows,

$$M = 0.8M_u \tag{2}$$

for $\phi_u < \phi_{mp} < 10\phi_u$
$$\phi = \phi_{mp}\left(0.3 + 0.05\frac{\phi_{mp}}{\phi_u}\right) \tag{3}$$

for $\phi_{mp} > 10\phi_u$
$$\phi = 0.8\phi_{mp} \tag{4}$$

The loop width described by $M_{ld} / M_u = 0.4\phi_r / \phi_m$ was found so large for prestressed concrete members that the expression was modified to $M_{ld} / M_u = 0.3\phi_r / \phi_m$.

Partially prestressed and reinforced concrete idealization

The prestressed, partially prestressed and reinforced concrete idealizations are expressed by the same functions, in which the loop widths at the coordinate of I_{ip}, I_{in}, C_{ip} and C_{in} vary depending on the parameter α.

$$M_{li} / M_{cr} = \left(0.2 + 0.8\sqrt{\alpha}\right)\phi_r / \phi_m \tag{5}$$

$$M_{li} / M_{cr} = \left(0.3 + 0.6\sqrt{\alpha}\right)\phi_r / \phi_m \tag{6}$$

α is the ratio of contribution of non-prestressed ordinary reinforcement to the total flexural strength of the section.

PREDICTION OF DISPLACEMENT RESPONSE BY SUBSTITUTE DAMPING

Past research has been trying to represent a non-linear hysteresis loop by a vibrating linear system. Jacobsen suggested in his paper that a particular hysteresis loop may be approximately interpreted by a vibrating linear system with equivalent viscous damping.

Gulkan and Sozen (1974) calculated an average value of the substitute damping ratio, β_s on the basis of the test results on one-story one-bay frames. β_s was obtained using the following equation.

$$\beta_s\left[2m\omega_0\int_0^T \dot{x}^2 dt\right] = -m\int_0^T \ddot{y}\dot{x}dt \tag{7}$$

where, m = mass, $\ddot{y}$ = base acceleration, $\dot{x}$ = mass relative velocity and $2m\omega_0$ = critical damping coefficient for a single-degree-of-freedom oscillator.

The equation implies that energy input from horizontal uniaxial base motion which is represented by the right-hand term is entirely dissipated by an imaginary viscous damper associated with horizontal velocity of mass carried by the frame. The critical damping coefficient for a single-degree-of-freedom oscillator, $2m\omega_0$, was introduced to express the substitute damping coefficient as a ratio of the critical damping.

Substitute damping

The substitute damping was calculated using the base acceleration, mass relative velocity time history response and Eq. 7. Fig. 2 indicates the calculated substitute damping plotted against ductility ratio, *m*, which is defined as a ratio of maximum absolute displacement to yield displacement. The substitute damping was obtained from the calculation results of the single-degree-of-freedom system. The dynamic response analyses of SDOF systems are reported in the reference (Nishiyama, 1993a). Those of multi-story buildings are included in the paper (Nishiyama, 1993b). The two earthquake wave records were used: El Centro 1940 NS component and the earthquake motion recorded at the first floor of the building at Tohoku University during the Miyagiken-oki earthquake in 1974. The natural period of vibration investigated ranged between 0.1 and 3.0 seconds. The coefficient of viscous damping was assumed to be 0.05. The parameters investigated are β_{cr} = 1.0, 2.0 and 3.0, T_e / T_y = 1.0, 2.0 and 4.0. β_{cr} is a ratio of yield capacity to cracking capacity. T_y is a natural period of vibration based on the secant stiffness at yield displacement. T_e = a natural period of vibration based on the elastic stiffness. The ratio of yield capacity to the weight of a structure, which is denoted as β_u ranged 0.2 to 1.4. The plotted data in Fig. 2 are from the results in which the maximum absolute displacement exceeded the yield displacement.

Gulkan and Sozen (1974) suggested the substitute damping ratio, β_s, would vary with attained ductility, μ, as ratio of area *EBC* to area *ABF* indicated in Fig. 3. Therefore, the following relationship can be obtained.

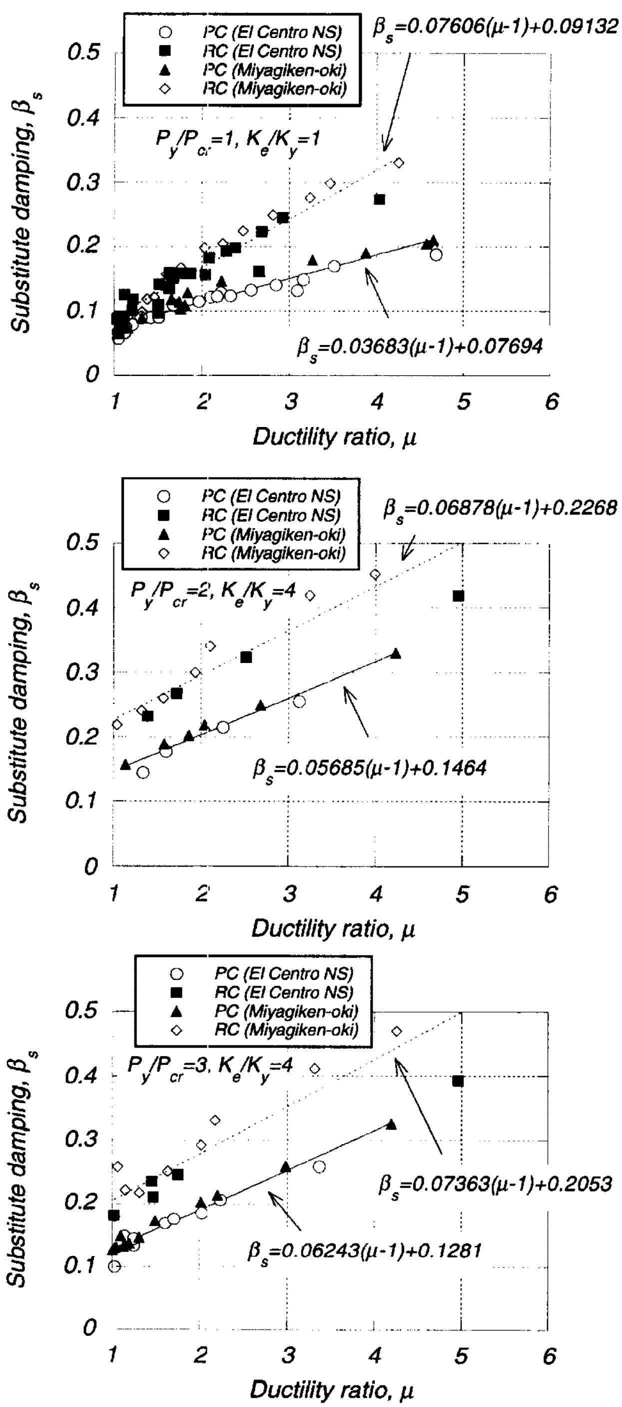

Fig. 2 Substitute damping ratio

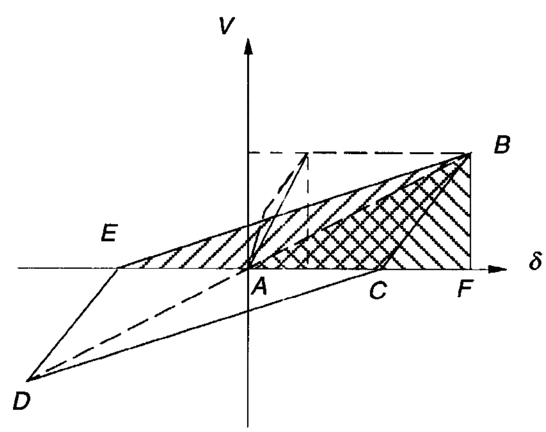

Fig. 3 Substitute damping ratio by Gulkan and Sozen (1974)

$$\beta_s \propto \left(1 - 1/\sqrt{\mu}\right) \tag{8}$$

They also suggested that if β_s is assumed to have a threshold value of 0.02 at $\mu = 1.0$, Eq. 8 is expressed as,

$$\beta_s = \left\{1 + 10\left(1 - 1/\sqrt{\mu}\right)\right\}/50 \tag{9}$$

In this study, however, the best-fit linear equations in the range of μ = 1~5 for the plotted data are included in Fig. 2 by a solid line for prestressed concrete systems and by a dotted line for reinforced concrete systems. Iwan (1980) proposed the following empirical relationship between an effective period shift T_{eq}/T_e and a ductility ratio μ on the basis of the calculation results of single-degree-of-freedom systems with hysteretic restoring force characteristics associated with linear, simple hysteretic and degrading hysteretic behavior.

$$T_{eq}/T_e = 1 + 0.121(\mu - 1)^n \quad : n = 0.939 \tag{10}$$

To streamline the discussion, n is assumed to be unity. Within the range of μ = 1~5, the difference between $n = 0.939$ and $n = 1.0$ is as much as 3%.

When calculating the substitute damping, $\sqrt{\mu} \cdot T_e$ was used as an equivalent period of vibration. The substitute damping must be modified by the factor given by the following equation based on the effective period shift suggested by Iwan (1980).

$$\gamma = \left[1 + 0.121(\mu - 1)\right]/\sqrt{\mu} \tag{11}$$

The substitute dampings were then modified. For prestressed concrete with $\beta_{cr} = 1.0$ and $T_e/T_y = 1.0$, for example,

$$\beta_s = 0.03683(\mu - 1)\frac{\left[1 + 0.121(\mu - 1)\right]}{\sqrt{\mu}} + 0.07694 \tag{12}$$

Response spectra are usually given in respect to a particular damping ratio. The response spectra for dampings other than this particular damping are assumed to be given using the following equations (Inoue, et al. 1988).

For $h \geq 0.05$

$$\frac{S(h_{eq})}{S(0.05)} = \frac{2.25}{1.75 + 10h_{eq}} \qquad \left(0.1s \leq T_{eq} \leq 2.5s\right) \tag{13}$$

$$\frac{S(h_{eq})}{S(0.05)} = 1 - \left(1 - \frac{2.25}{1.75 + 10h_{eq}}\right)\left(\frac{1 - \log T_{eq}}{0.60}\right) \qquad \left(2.5s \leq T_{eq} \leq 10.0s\right) \tag{14}$$

For $h \leq 0.05$

$$\frac{S(h_{eq})}{S(0.05)} = \frac{1.5}{1 + 10h_{eq}} \qquad \left(0.1s \leq T_{eq}\right) \tag{15}$$

Prediction of displacement response by substitute damping

A procedure based on linear response can be used to predict maximum displacement response and to evaluate design base shear. The procedure involves the following steps.

1. Assume an admissible value of μ.
2. Calculate an effective period T_{eq} by using the assumed value of μ and Eq. 10 (n is assumed to be unity).
3. Calculate β_s corresponding to the assumed value of μ.
4. Obtain maximum displacement by entering spectral response diagram with the effective period of T_{eq} and a damping ratio equal to β_s determined in Step 3. If the spectral response diagram is given in terms of the damping ratio other than β_s, Eqs. 13-15 are used for extrapolation.
5. If the difference between a ductility factor which is obtained from the maximum displacement and the yield displacement, and the assumed value of μ becomes within a tolerable limit, the maximum

displacement and the base shear are considered to give a good approximation. If the error is not in the tolerance, return to Step 1 with a new assumed value of μ.

Example

Consider a single-degree-of-freedom structure with prestressed concrete type hysteresis loops. A period of 1.0 second is assumed on the basis of the secant stiffness at yield displacement. When a mass of the structure M is 1.0 kg, the secant stiffness at yield displacement K_y is 39.478 $\mathrm{kg \cdot cm/s^2/cm}$. If the yield capacity of the structure is assumed to be $Q_y = 0.2M \cdot g$, the yield displacement is given by $Q_y / K_y = 4.965\mathrm{cm}$, where g is acceleration of gravity. The skeleton curve of the system is assumed to be an elasto-perfectly plastic type : $\beta_{cr} = 1.0$ and $T_y / T_e = 1.0$.

If μ is assumed to be 4 the period is modified to 1.363 seconds. Eq. 12 gives a substitute damping ratio of 0.152. For a particular ground motion, a displacement response can be obtained by entering a spectral displacement response, for instance an average response spectra by Umemura summarized in Table 1.

Table 1 Umemura Spectra

T (s)	S_D (cm)	S_V (cm/s)	S_A (cm/s²)
$T \le 0.5$s	$90T^2 k_G$	$566Tk_G$	$3.6 \cdot g \cdot k_G$
$0.5 < T \le 3$	$45Tk_G$	$283k_G$	$1.8 \cdot g \cdot k_G / T$
$3 < T$	$135k_G$	$849k_G / T$	$5.4 \cdot g \cdot k_G / T^2$

where, $g = 980$ cm/s² and k_G = ratio of maximum ground acceleration to acceleration of gravity. Assuming the maximum ground acceleration of 319 cm/s², which is the maximum acceleration record of El Centro 1940 NS Component, the displacement response of 19.97 cm is obtained. Since Umemura spectra is considered to be given for an oscillator with a damping ratio of 0.05, the response should be transferred to a displacement response with the substitute damping of 0.152 by using Eq. 13. This results in the displacement response of 13.73 cm, which corresponds to the ductility factor of 2.765. The difference between the assumed value and the result is significant. Then, return to Step 1 with a new assumption of $\mu = 2.765$.

$\mu = 2.765$ results in the effective period of 1.214 seconds and the substitute damping of 0.124. The displacement response obtained is 13.36 cm corresponding to the ductility ratio of 2.69. The difference is still large. Return to Step 1 with a new assumption of $\mu = 2.69$. This results in the effective period of 1.20 seconds, the substitute damping of 0.123 and the displacement response of 13.34 cm corresponding to the ductility ratio of 2.69.

The result of the time-history analysis for El Centro 1940 NS Component whose spectra are similar to Umemura spectra gives the maximum displacement of 10.43 cm. The rather favorable comparison between the "exact" and approximate value of the maximum displacement suggests that the substitute damping method may be used successfully in the region covered by the exact analyses.

COMPARISON OF DYNAMIC RESPONSE BETWEEN PRESTRESSED CONCRETE AND REINFORCED CONCRETE SYSTEMS

When comparing dynamic response of prestressed concrete systems with that of reinforced concrete system, a clear conclusion cannot be derived because of considerable scatter in the calculation results. Use of substitute damping gives a structural designer a good indication of how large displacement can be reached in a prestressed concrete system during an earthquake motion.

In the case of designing a prestressed concrete building frame it is of great importance to know how large the maximum displacement is reached during an earthquake comparing with a reinforced concrete building frame. There are two cases concerned : (1) the same yield capacities are given to both prestressed and reinforced concrete systems or (2) the same maximum displacement is predicted to be reached in both systems.

The same yield capacity

The procedure described in the preceding example is followed to obtain the maximum displacement response of a reinforced concrete structure with the same yield capacity and secant stiffness at yielding as that of a prestressed concrete structure.

For instance, Fig. 4 shows the ductility ratio response of prestressed and reinforced concrete systems to Umemura spectra of $k_G = 0.3255$. Their period at yielding is 1.0 second. Smaller yield capacity results in a larger ductility ratio as past research has pointed out. The difference between the responses of the prestressed and reinforced concrete systems becomes larger as their yield capacities decrease.

However, the situation is changed when their responses are expressed by the maximum displacements. Fig. 5 illustrates the maximum displacement response of these systems by a solid line for the prestressed concrete system and by a dotted line for the reinforced concrete system. For the prestressed concrete system the maximum displacement response slightly decreases as the yield capacity increases. For the reinforced concrete system, however, the maximum displacement response rather increases as the yield capacity increases. These curves show that even if the yield capacity of the prestressed concrete system increases to some degree in order to reduce the maximum displacement response, it never reduces to as much a displacement response as the reinforced concrete system unless they respond in an elastic manner.

NZS 4203 (Standard Association of New Zealand, 1984) specifies 25% larger seismic design load for a prestressed concrete ductile frame than an equivalent reinforced concrete. However, the fact described above reveals that additional yield capacity alone cannot lead to a reduced displacement response as much as the equivalent reinforced concrete structure. It is not so useful to increase yield capacity in order to reduce the maximum displacement response.

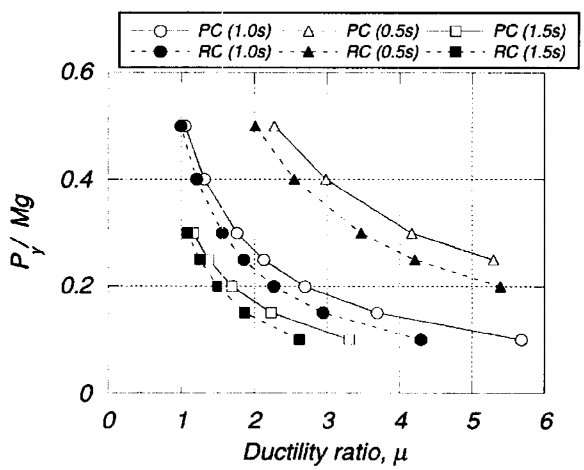

Fig. 4 Yield capacity - ductility ratio response relationships

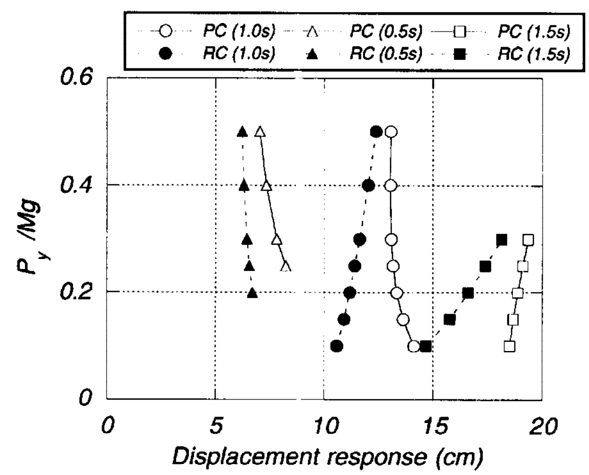

Fig. 5 Yield capacity - displacement response relationships

The same displacement

This case is much more complicated and much more interesting than the former. There are two ways for the two systems to reach the same displacement. One is to boost up the yield capacity of the prestressed concrete system. The maximum displacement of the reinforced concrete system can be obtained by the same procedure described above. If the prestressed concrete system has the same secant stiffness that the reinforced concrete system, an assumed yield capacity gives a yield displacement from which the ductility ratio can be calculated. From this ductility ratio displacement response of prestressed concrete system is obtained. If the displacement response and the above maximum displacement response are the same, the assumed yield capacity is considered to give the same displacement response that the reinforced concrete system. However, as described above, it is difficult to have the same displacements in both systems when the yield capacity alone of the prestressed concrete system increases.

The other is to increase the secant stiffness at yielding of the prestressed concrete system. In this case the yield capacity of the prestressed concrete system is assumed to be equal to that of the reinforced concrete system.

The secant stiffness at yielding of the prestressed concrete system should be increased so that the corresponding yield displacement decreases. From the yield displacement the same procedure in the former case is trailed until as large displacement response as the maximum displacement of the reinforced concrete system is obtained. However, it should be noted that the maximum ductility ratio increases as the secant stiffness decreases.

Example

Consider a single-degree-of-freedom structure with reinforced concrete type hysteresis loops of the same characteristics that the preceding example. If the first trial starts with $\mu = 4$ which modifies the period to 1.363 seconds, a substitute damping ratio of 0.247 is obtained. From Umemura displacement spectra the displacement response can be predicted 10.65 cm. This corresponds to the ductility factor of 2.15.

The second trial : $\mu = 2.15$ and $\beta_s = 0.159$. The predicted response is 11.23 cm, which corresponds to $\mu = 2.26$.
The third trial : $\mu = 2.26$ and $\beta_s = 0.165$. The predicted response is 11.18 cm, which corresponds to $\mu = 2.25$.

The prestressed concrete system with the same yield capacity should have a larger secant stiffness at yielding than the reinforced concrete system. If the period at yielding of the structure is assumed to be $T_y = 0.75$ second, the yield displacement is given by $Q_y / K_y = 2.793\text{cm}$. The maximum displacement obtained is 10.89 cm, which is approximately the same displacement that obtained above in the reinforced concrete system. The ductility ratio attained 3.90, which is 73% larger than that of the reinforced concrete system.

CONCLUSIONS

1. A hysteresis model of concrete members was proposed based on the idealization proposed by Thompson and Park (1980), and the experimental results of prestressed concrete beam-column joint subassemblies. The model covers conventionally reinforced concrete, partially prestressed concrete and prestressed concrete.

2. Substitute damping was introduced and calibrated from the results of the time-history analyses in order to predict dynamic responses of prestressed, partially prestressed and reinforced concrete systems. The substitute damping was proved to give a good approximation of responses of those systems.

3. Some examples using the substitute damping revealed that increasing the strength of some types of structures may increase the maximum displacement.

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