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Pulse response analysis of asymmetric structures

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ABSTRACT: Base on PULSE RESPONSE ANALYSIS method, a procedure to estimate seismic responses of asymmetric structures is presented. By applying the procedure to an idealized monosymmetric system subjected to a unidirectional earthquake excitation, it is concluded that, 1) this method provides a reasonable estimate for the maximum responses of asymmetric structures by comparing with those by time-history analysis, and 2) unfavorable influences of eccentricity greatly cause unequal distribution of deformation energy to resisting elements, so that effect of eccentricity on responses in noneccentric direction should be also considered in aseismic design.

1 INTRODUCTION

Time-history analysis methods have been used to determine overall elastic or inelastic response behaviors of structures under earthquake excitation. However, in most cases of the aseismic design of buildings many approximate and appropriate methods are more practical and convenient for estimating such scales as the maximum displacement and energy absorption. The PULSE RESPONSE ANALYSIS for ULTIMATE ASEISMIC DESIGN (UAD) proposed by Yamada, Kawamura (1976, 1980) is just one to practically use to the response analysis. In the UAD, it is considered that structural failure of buildings subjected to dynamic loading may be generally classified to two modes, one is due to accumulated damages from cyclic responses and the another is due to excessive one-side deformation of a structure or its member. Therefore, this means there are two types of ULTIMATE ASEIMIC CAPACITIES corresponding to the both critical behaviors above for the UAD. To evaluate these ULTIMATE SEISMIC CAPACITIES, FINITE RESONANCE RESPONSE ANALYSIS (FRRA) for the former and PULSE RESPONSE ANALYSIS (in its application, represented as VELOCITY PULSE RESPONSE ANALYSIS: VPRA and ACCELERATION PULSE RESPONSE ANALYSIS: APRA) for the latter have been Proposed by Yamada and Kawamura, and successfully applied to estimate the maximum responses of SFD system.

On the other hand, almost all the buildings are eccentric in stiffness or strength, and respond in coupled lateral-torsional behaviors to the earthquake motion, even when there is no rotational component. It is necessary for response analysis of asymmetric structures to consider the torsional degree of freedom in addition to the translational those usually considered in the SFD system. Based on the UAD, FRRA of the asymmetric structures has been developed by authors (1988). The purpose of this study is to expand VPRA/APRA to a torsionally coupled system with nonlinear resisting elements, and to demonstrate its application by applying the procedure to a parametric problem and discussion on the results.

2 IDEALIZED SYSTEM AND EQUATIONS OF MOTION

To investigate the inelastic behaviors of the eccentric buildings, a one-mass single-story model shown in Fig. 1 is adopted. The system consists of a rigid deck supported by idealized planar resisting elements X1, X2 and Y1, Y2 situated at its periphery. And to simplify the problem, it is assumed that the system is eccentric for horizontal excitation in the x-direction only, and its eccentricity is a result of unbalanced stiffnesses of the elements X1 and X2. In this way, the system has two coupled degrees of freedom, namely lateral displacement Xc of the mass center (CM) relative to the ground motion and rotation θc about the vertical axis.

Let lxi, lyi represent the distances from CM, fxi, fyi represent the lateral restoring forces, and δxi, δyi represent the lateral displacements of i-th element along the principal axes, respectively. Then δxi, δyi and fxi, fyi can be expressed as

$$\delta_{xi} = X_c - l_{yi}\cdot\theta_c ;\ \delta_{yi} = l_{xi}\cdot\theta_c \qquad (1)$$

$$f_{xi} = f(\delta_{xi});\qquad f_{yi} = f(\delta_{yi}) \qquad (2)$$

where f=a general function for the geometric description of the skeleton curve shown in

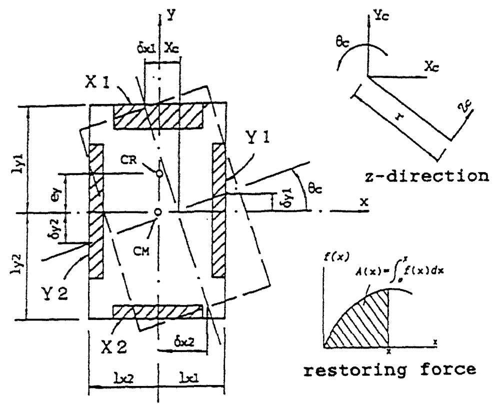
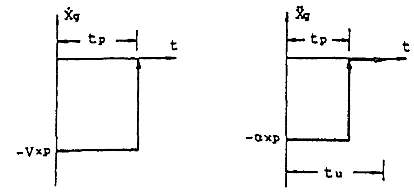


Fig. 1 Idealized system

initial and final conditions:

time	vlocity impulse	acceleration impulse
t=0	$X_c=0$, $\dot{X}_c=v_{xp}+V_{ox}$ $Z_c=0$, $\dot{Z}_c=V_{oz}$	$X_c=0$, $\dot{X}_c=v_{xp}+V_{ox}$ $Z_c=0$, $\dot{Z}_c=V_{oz}$
$t=t_p$	$X_c=X_{cp}$, $\dot{X}_c=0$ $Z_c=Z_{cp}$, $\dot{Z}_c=0$	$X_c=X_{cp}$ $Z_c=Z_{cp}$
$t=t_u$		$X_c=X_{cu}$, $\dot{X}_c=0$ $Z_c=Z_{cu}$, $\dot{Z}_c=0$



a) velocity impulse b) acceleration impulse

Fig. 2 Rectangular impulses

Fig. 1.

The equations of motion for the system only under translational component Xg of ground motion in the x-direction can be written as

$$\left.\begin{aligned} m\cdot\ddot{X}_c + \Sigma f_{xi} &= m\cdot\ddot{X}_g \\ I\cdot\ddot{\theta}_c - \Sigma f_{xi}\cdot l_{yi} + \Sigma f_{yi}\cdot l_{xi} &= 0 \end{aligned}\right\} \quad (3)$$

where m=the mass of the deck; I=the mass moment of inertia of the deck about the vertical axis through CM; Xg=the acceleration of the ground motion.

To represent Eq. (3) in the same dimension, let's define the z-direction shown in Fig. 1 to represent the rotation, and let

$$Z_c = \theta c\cdot r \quad (r = \sqrt{I/m}) \quad (4)$$

$$\left.\begin{aligned} F_x &= \Sigma f_{xi} \\ F_z &= \Sigma f_{yi}\cdot l_{xi}' = \Sigma f_{xi}\cdot l_{yi}' \end{aligned}\right\} \quad (5)$$

where Zc=the torsional displacement of the deck in the z-direction shown in Fig. 1; Fx, Fz =the total forces of the resisting elements along the x- and z-directions; r=the mass radius of gyration of the deck about the vertical axis through CM; lxi', lyi'=lxi/r, lyi/r. Then, Eq. (3) can be simply written as

$$\left.\begin{aligned} m\cdot\ddot{X}_c + F_x &= m\cdot\ddot{X}_g \\ m\cdot\ddot{Z}_c + F_z &= 0 \end{aligned}\right\} \quad (6)$$

3 PULSE RESPONSE ANALYSIS

For developing the VPRA/APRA procedure, the following assumptions are important.

1) Response of system can be represented as a monotonic behavior shown in Fig. 1. It is a pulse having the maximum amplitude (called as PULSE RESPONSE) picked out from time-history random responses. Effect of its viscoelastic damping can be ignored.

2) Input component for excitation can be represented as rectangular velocity or acceleration impulse shown in Fig. 2, and its amplitude can be given from a normalized caharacteristic spectrum (velocity or acceleration) of earthquake motion shown in Fig. 3 according to its duration tp=1/2Tp.

Now, let's take an indeterminable integral of both sides of Eq. (6) with respect to Xc and Zc, respectively, the following equations can be obtained.

$$\left.\begin{aligned} \int_0^{X_c} m\cdot\ddot{X}_c dX_c + \int_0^{X_c} F_x dX_c &= \int_0^{X_c} m\cdot\ddot{X}_g dX_c \\ \int_0^{Z_c} m\cdot\ddot{Z}_c dZ_c + \int_0^{Z_c} F_x dZ_c &= 0 \end{aligned}\right\} \quad (7)$$

It is clear that Eq. (7) represents the energy equillibium in the x- and z-directions, respectively. Here, let's introduce two variables about energy to implify Eq. (7). Let Axp, Azp denote the integral of the second terms of left sides in Eq. (7) meaning the deformation energy input to the system in the x- and z-directions. Then Eq. (7) can be expressed as

$$\left.\begin{aligned} 1/2\cdot m\cdot\dot{X}_c^2 + A_{xp} &= E_{xp} \\ 1/2\cdot m\cdot\dot{Z}_c^2 + A_{zp} &= E_{zp} \end{aligned}\right\} \quad (8)$$

And according to the both forms of the impulses shown in Fig. 2, the resulting expressions of Exp, Ezp can be also written in the two corresponding forms by completing the integral of Eq. (7) with the initial and final conditions of the impulses noted in Fig. 2.

1) In case of velocity impulse

$$\left.\begin{aligned} E_{xp} &= 1/2\cdot m\cdot(v_{xp} + V_{ox})^2 \\ E_{zp} &= 1/2\cdot m\cdot V_{oz}^2 \end{aligned}\right\} \quad (9)$$

2) In case the acceleration impulse

$$E_{xp} = 1/2 \cdot m \cdot (2X_{cp} \cdot \alpha_{xp} + V_{ox}), \quad E_{zp} = 1/2 \cdot m \cdot V_{oz} \qquad (10)$$

where v_{xp}, α_{xp}=the amplitudes of the velocity and acceleration impulses; V_{ox}, V_{oz}=the initial velocities of the system; X_{cp}, Z_{cp}=the displacements of CM at the time when the impulse duration comes to the end; X_{cu}, Z_{cp}=the displacements of CM at the time when the velocities X_c, Z_c become zero in the x- and z-directions.

Adding the two formulas in Eq. (8) together, it is found that the equation physically interpreting the energy equillibium of the whole system can be obtained. That is

$$1/2 \cdot m(\dot{X}_c^2 + \dot{Z}_c^2) + A_{xp} + A_{zp} = E_{xp} + E_{zp} \qquad (11)$$

$$A_{xp} + A_{zp} = \Sigma A_{xi} + \Sigma A_{yi} \qquad (12)$$

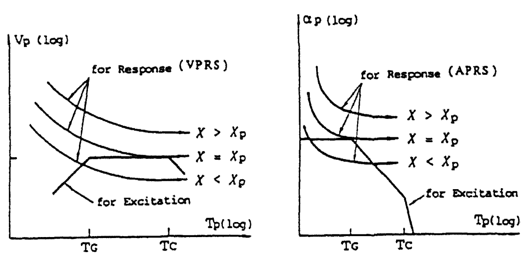
where A_{xi}, A_{yi}=the areas surrounded with f_{xi}-δ_{xi} and f_{yi}-δ_{yi} curves of i-th element.

Now, let's transform Eq. (8) by leaving the terms of kinetic energy $1/2m \cdot X_c^2$, $1/2m \cdot Z_c^2$ in the left sides only, and taking variables-separated integral between [0, tp] for the left, [0, Xcp] and [0, Zcp] for the right sides, respectively, the following expressions can be obtained.

$$t_p = \begin{cases} \int_0^{X_{cp}} dX_c / \sqrt{E_{xp} - A_{xp}} \\ \int_0^{Z_{cp}} dZ_c / \sqrt{E_{zp} - A_{zp}} \end{cases} \qquad (13)$$

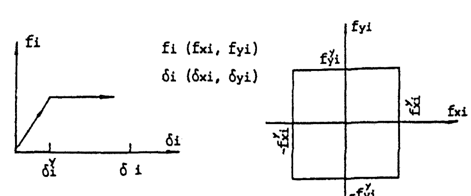
Eq. (13) is a simultaneous equation including four unknown qualities, t_p, X_{cp}, Z_{cp} and v_{xp} or α_{xp}. From the analytical geometry, if one set of (X_{cp}, Z_{cp}) is given to Eq. (13), a corresponding curve can be determined in the T_p-v_{xp} or T_p-α_{xp} coordinates shown in Fig. 3. Here, we define the curve as VELOCITY PULSE RESPONSE SPECTRUM (VPRS) or ACCELERATION PULSE RESPONSE SPECTRUM (APRS) for the excitation of velocity or acceleration impulse, respectively.

The VPRS/APRS give a relationship between the PULSE RESPONSE and the earthquake excitation. So, all of the VPRA/APRA procedures to do is to find the maximum set of (X_{cp}, Z_{cp}) among those which let the VPRS/APRS curves spectrum (velocity or acceleration) of the ground motion excitation.



a) velocity spectra b) acceleration spectra

Fig. 3 Spectra of PULSE RESPONSE and excitation



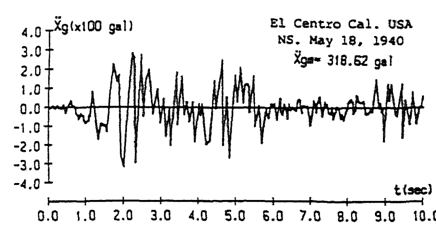
a) force-deformation relationship b) yield function

Fig. 4 Characteristics of restoring force

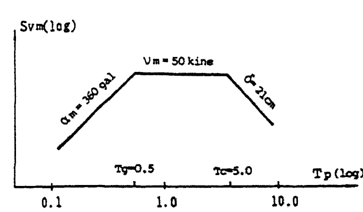
4 EXAMPLE OF ANALYSIS

It is apparent from the equations motion Eq. (3) that the nonlinear response of the monosymmetric system to specified ground earthquake excitation along the x-principal axis of resistance, depend not only on the static eccentricity ey, the plan geometry, but also on the member, location, and strength etc. of the individual resisting element. In order to simplify this problem without losing its essence, the predominant system parameters for the analysis are chosen as follows:

1) ratio of static eccentricity to ly
   $e_y' = e_y/l_y = 0.0 \sim 1.0$
2) uncoupled translational elastic period in the x or y-direction
   $T_{ex} = T_{ey} = 0.1 \sim 10.0$ sec.
3) uncoupled translational yield force coefficient in the x- or y-direction
   $S_x^y = S_y^y = 0.1 \sim 1.0$
4) aspect ratio of the plan shown in Fig. 1



a) acceleration records



b) normalized characteristic velocity spectrum

Fig. 5 Ground motion for analysis

$\lambda ly = ly/lx = 1.0, 5.0$

5) restoring force characteristic of resisting element shown in Fig. 4
   a) force-deformation relationship
   b) yield function
6) ground motion excitation for response analysis shown in Fig. 5
   a) acceleration records : for RUNGE-KUTTA's method (R. K.)
   b) normalized characteristic velocity spectrum : for VPRA and APRA

The analytic results are shown in Figs. 6-8 in which the abscissas denote the parameter ey' or Tex, and the ordinates denote the maximum responses,

- $\delta x1m$: the max. lateral displacement of the element X1 in the x-direction
- Wdsm: the max. deformation energy of the whole system
- Wdxm: the max. deformation energy distributed to elements X1 and X2
- Wdym: the max. deformation energy distributed to elements Y1 and Y2

5 DISCUSSION AND CONCLUSION

$\delta x1m$ is the maximum translational displacement of the elements. The results of $\delta x1m$-Tex based on VPRA/APRA are shown in Fig. 6 by logarithmic coordinates. It is found that the results of VPRA/APRA agree very good with those by R. K. except that there are somewhat overestimates for shorter Tex in VPRA and for longer Tex range in APRA. Therefore, for the application of PULSE RESPONSE ANALYSIS, it is appropriate to use VPRA in $T_{ex} \geq T_{gx}$ and APRA in $T_{ex} \leq T_{gx}$.

Fig. 7 shows the total deformation energy of the system. It is evident that Wdsm appear to be constant in despite of ey changing. Fig. 8, illustrates the distribution of the deformation energy to the elements inthe x- and y-directions. With ey increasing, the distribution to Y1 and Y2 is getting increase while the one to X1 and X2 decrease. It is noted that the eccentricity affects greatly the response of elements not only in the eccentric direction, but also in the noneccentric one.

In summary, a method based on PULSE RESPONSE ANALYSIS is presented to evaluate the maximum responses of asymmetric structures, and applied to an idealized monosymmetric system. Comparison with results by a time-history analysis indicates that the proposed procedure gives reasonable estimates of the responses.

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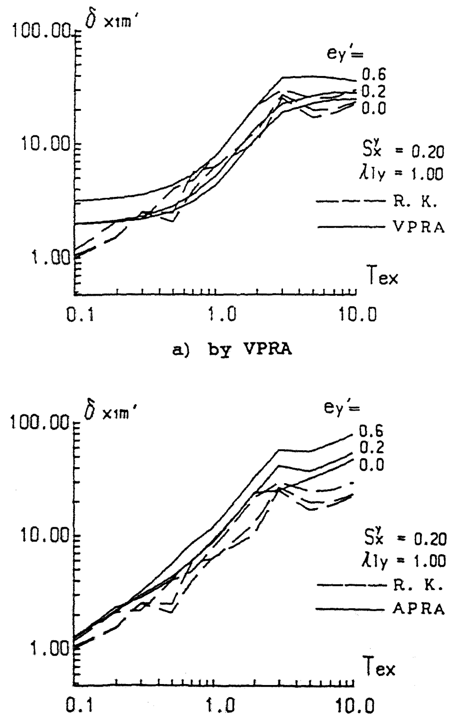
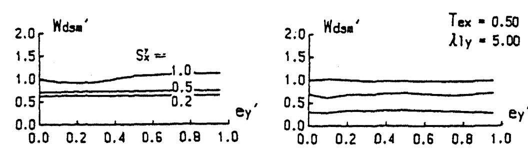


a) by VPRA

b) by APRA

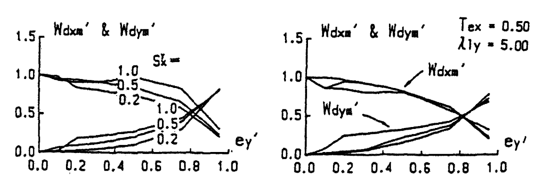
Fig. 6 Comparison of Max. displacement



a) by VPRA

b) by APRA

Fig. 7 Total deformation energy



a) By VPRA

b) by APRA

Fig Distribution of deformation energy