Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.V)

7-3-10

ULTIMATE EARTHQUAKE RESPONSE AND DAMAGE ANALYSIS OF STRUCTURES BY PULSE AND FINITE RESONANCE METHOD — FOR THE GENERALIZATION OF EARTHQUAKE RESPONSE AND DAMAGE ANALYSIS

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SUMMARY

A method is proposed in this paper for evaluating earthquake responses and damages of structures by means of the "Ultimate Response Analysis (U.R.A.)", for the generalization of earthquake response and damage analysis. In the case of a single degree of freedom system (Fig.1) with bi-linear restoring force characteristics of positive, zero, and negative plastic stiffness (Fig.2), a procedure is presented to estimate the maximum response displacement and damage factor by means of U.R.A..

INTRODUCTION

In order to clarify the ultimate earthquake response characteristics, the authors have proposed the "Ultimate Response Analysis (U.R.A.)", which can evaluate not only earthquake responses but also damages of structures. U.R.A. consists of the "Pulse Response Analysis (P.R.A.)" (Refs.1,2) and the "Finite Resonance Response Analysis (F.R.R.A.)" (Refs.3-5). In U.R.A., the response behaviours of structures are divided into two limit response states, i.e., the maximum monotonic response (Fig.3) and cyclic resonance response (Fig.4). The ground motion is given as a trapezoidal spectrum in four-way-log plane such as shown in Fig.5 (Ref.6), where $\mathbf{T}_G$ and $\mathbf{T}_C$ are considered as predominant period of building site and of epicenter respectively. The object of this paper is to estimate the maximum response displacement and damage factor by means of U.R.A.. The results of U.R.A. are compared with those of the usual dynamic time-history earthquake response analysis (E.R.A.), and the usefulness of U.R.A. is discussed.

ULTIMATE RESPONSE ANALYSIS

Pulse Response Analysis (P.R.A.) When a single degree of freedom system is given shocks by the maximum ground motion, the system will collapse with a very large monotonic deformation. Such a type of response as shown in Fig.3 (Refs.1,2) is analyzed by P.R.A.. In this paper, the followings are assumed (Ref.2); (1) input pulse amplitudes $\mathbf{v}_p$(rectangular)=$\mathbf{v}_p$(sinusoidal), $(\pi/2)\alpha_p$ (rectangular)= α_p(sinusoidal), (2) $\mathbf{T}=4\mathbf{t}_p$, (3) initial velocity $\mathbf{V}_o$. In P.R.A., the response displacement by input velocity pulse (V-P.R.A.) and by input acceleration pulse (A-P.R.A.) are calculated respectively. When the system is shifted to the point P($\mathbf{x}=\mathbf{x}_p$) by rectangular input pulse(Fig.3), velocity pulse response spectrum ($\mathbf{v}_p$-$4\mathbf{t}_p$ relation) and acceleration pulse response spectrum ($(\pi/2)\alpha_p$-$4\mathbf{t}_p$ relation) are calculated and plotted in the same figure with the

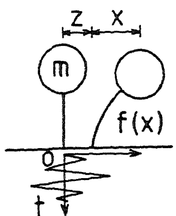
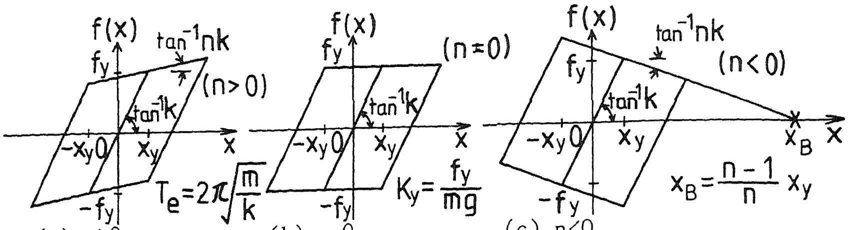


Fig.1, A Single Degree of Freedom System



(a) n>0 (b) n=0 (c) n<0

Fig.2, Bi-linear Restoring Force Characteristics with plastic stiffness nk

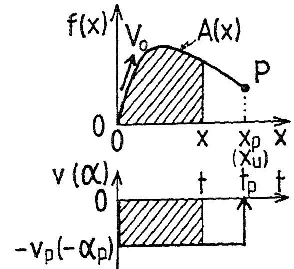


Fig.3, Monotonic Response and Input Pulse

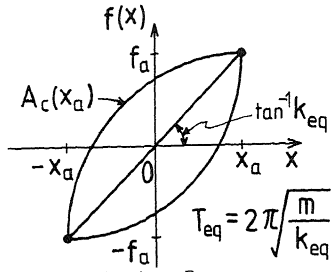


Fig.4, Cyclic Resonance Response

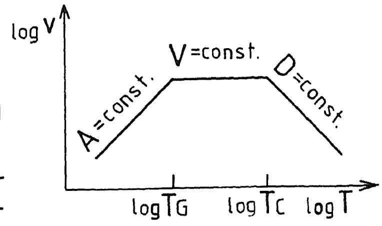


Fig.5, Earthquake Ground Motion Spectrum

earthquake ground motion spectrum (Fig.6). The ($\mathbf{v}_p$-4$\mathbf{t}_p$)relation and ((π/2)α_p-4$\mathbf{t}_p$)relation are reduced to

$$4\int_0^{x_p} dx/\sqrt{(V_0+v_p)^2-(2/m)A(x)}=4t_p \qquad -(1)$$

$$4\int_0^{x_p} dx/\sqrt{2\alpha_p x-(2/m)A(x)+V_0^2}=4t_p \qquad -(2)$$

$$\cdot x_p=(A(x_u)-(m/2)V_0^2)/(m\alpha_p) \qquad -(3)$$

$$A(x)=\int_0^x f(x)dx \qquad -(4)$$

When these spectra are tangential to the earthquake ground motion spectrum as shown in Fig.6, there are $\mathbf{x}_p$ by V-P.R.A. and $\mathbf{x}_u$ by A-P.R.A.. The $\mathbf{x}_p$, $\mathbf{x}_u$ are considered to be the possible maximum monotonic response displacements. The earthquake ground motion spectrum is a trapezoidal spectrum approximated from the pseudo-velocity response spectrum with a damping ratio **h**=0.2, when $\mathbf{A}_{max}$, $\mathbf{V}_{max}$, $\mathbf{D}_{max}$ in Fig.6 are considered to be nearly equal to the maximum acceleration, velocity, displacement amplitudes of the earthquake ground motion respectively (Ref.7).

Finite Resonance Response Analysis (F.R.R.A.) When a single degree of freedom system is subjected to random waves, it tends to select from the input waves with the same period as its own and to reach the resonant state as shown in Fig.4, and such a type of response is analyzed by F.R.R.A.. By regarding inelastic hysteresis response as an equivalent elastic response (Fig.4), its displacement amplitude $\mathbf{x}_a$ is calculated. In Refs.4,5, the finite resonance velocity capacity is reduced to

$$v_0=(5/6\pi)A_c(x_a)/\sqrt{mx_a f_a}+(2/3)\sqrt{x_a f_a/m}=C'_{RV} \qquad -(5)$$

When a displacement amplitude $\mathbf{x}_a$ is assumed, the velocity value $\mathbf{v}_o$ is calculated by Eq.(5) and the equivalent elastic period $\mathbf{T}_{eq}$ is calculated by the equation.

$$T_{eq}=2\pi\sqrt{mx_a/f_a} \qquad -(6)$$

In Eqs.(5)(6), $\mathbf{f}_a$ is a force amplitude corresponding to $\mathbf{x}_a$ (Fig.4). For various $\mathbf{x}_a$, the ($\mathbf{v}_o$-$\mathbf{T}_{eq}$) relation is calculated and plotted as a spectrum in the same figure with the earthquake ground motion spectrum, and the possible displacement amplitude $\mathbf{x}_a$ is given by their intersecting point (Fig.7). The earthquake ground motion spectrum is a trapezoidal spectrum approximated from the pseudo-velocity response spectrum with a damping ratio **h**=0.473, when the approximate amplification ratio $\beta=3\pi/(5\pi h+2)$ (Refs.4,5) is equal to unity.

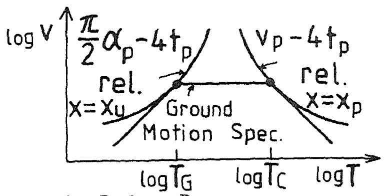


Fig.6, Pulse Response Analysis

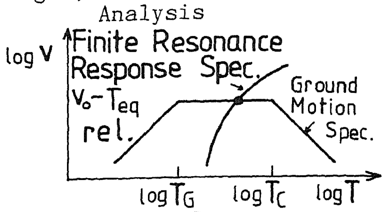


Fig.7, Finite Resonance Response Analysis

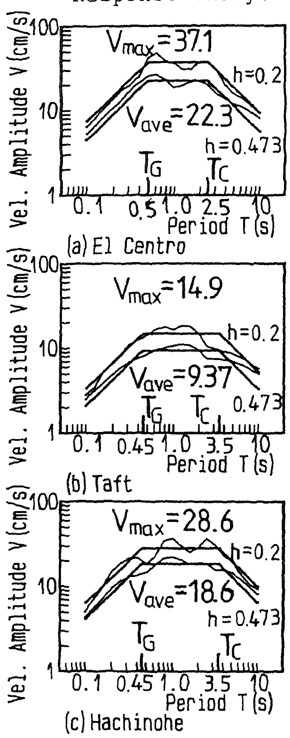


Fig.8, Earthquake Ground Motion Spectra

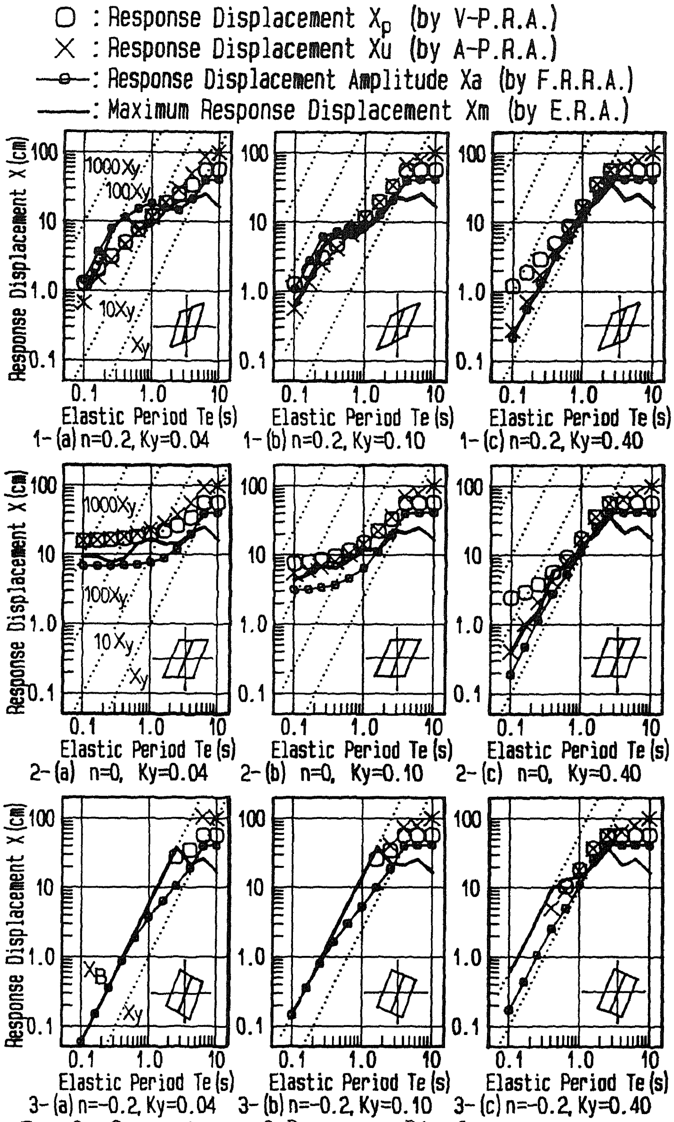


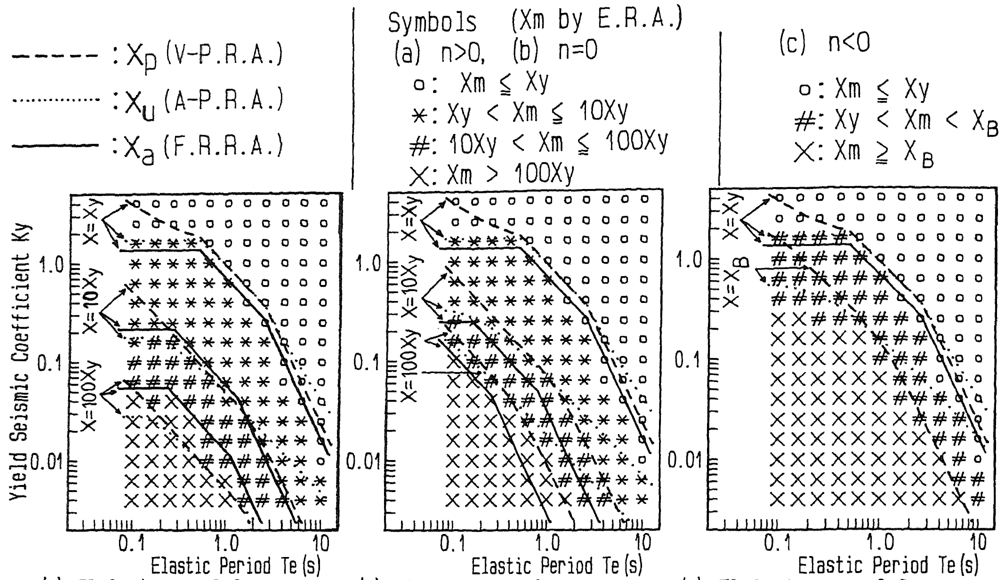
Fig.9, Comparison of Response Displacements by V-P.R.A., A-P.R.A., E.R.A. (El Centro)

RESPONSE EVALUATION

The following three earthquake ground motion accelerograms are used.

1) El Centro 1940 NS, α_{max}=342 (cm/s^2), t_a=15.00 (s) (Ref.8)
2) Taft 1952 NS, α_{max}=153 (cm/s^2), t_a=15.00 (s) (Ref.8)
3) Hachinohe 1968 NS, α_{max}=248 (cm/s^2), t_a=40.00 (s) (Ref.9)

α_{max} is the the maximum ground acceleration amplitude, and t_a is duration time. The earthquake ground motion spectra for U.R.A. are shown in Fig.8. Some examples of response displacement for the earthquake of El Centro are plotted in Fig.9. With positive plastic stiffness (n=0.2), as shown in Fig.9.1-(a)-(c), x_m by E.R.A. is nearly equal to x_a by F.R.R.A.. With zero plastic stiffness (n=0),



(a) El Centro, n=0.2 (b) El Centro, n=0 (c) El Centro, n=-0.2

Fig.10, Parametric Zoning of Response Displacements by V-P.R.A., A-P.R.A., F.R.R.A. (El Centro)

as shown in Fig.9.2-(a)-(c), x_m by E.R.A. is nearly equal to or somewhat smaller than x_p by V-P.R.A.. In the case of (c), when T_e (s) is relatively short, x_m by E.R.A. is nearly equal to x_u by A-P.R.A.. With negative plastic stiffness (n=-0.2), as shown in Fig.9.3-(a)-(c), x_m by E.R.A. is nearly equal to x_p by E.R.A.. In the case of earthquake of Taft and Hachinohe, the similar results are obtained. The relations, like a contour line, of elastic period T_e (s) and yield seismic coefficient K_y, are shown in Fig.10 for the earthquake of El Centro, that the response displacement x_a, x_p, x_u are constant respectively. In Fig.10(a)(b), upper lines mean that x_a, x_p, $x_u=x_y$, middle lines mean that x_a, x_p, $x_u=10x_y$, and lower lines mean that x_a, x_p, $x_u=100x_y$. In Fig.10(c), upper lines mean that x_a, x_p, $x_u=x_y$, and lower lines mean x_p, $x_u=x_B$ which is collapse displacement. With positive plastic stiffness (n=0.2), as shown in Fig.10(a), the range of value x_m by E.R.A. is likely to that of x_a by F.R.R.A.. With zero plastic stiffness (n=0), as shown in Fig.10(b), the range of value x_p by V-P.R.A. shifts to the safe side range of x_m by E.R.A.. With negative plastic stiffness (n=-0.2), as shown in Fig.10(c), the range of x_m by E.R.A. is likely to that of x_p by V-P.R.A..

DAMAGE EVALUATION

The damage of the system caused by earthquake is considered to be divided into two types. One is monotonic damage by very large monotonic deformation, which falls into so called first passage failure, the other is cumulative damage by cyclic deformation, which falls into so called fatigue failure. The monotonic damage is assumed to be calculated by Eqs.(7)(8).

(by E.R.A.) $D^m_e = ((x_m - x_y)/x_F)^b$ (Fig.11) -(7)

(by P.R.A.) $D^m_p = ((x_p - x_y)/x_F)^b$ (Fig.12) -(8)

D^m_e, D^m_p are damage factors, and x_F is an assumed value of monotonic failure deformation. $x_F=10x_y$ in case of Fig.2-(a)$n>0$,(b)$n=0$, or $x_F=x_B$ in case of Fig.2(c)$n<0$. b is a constant, in this paper $b=1$. The cumulative damage is assumed to be calculated by Eqs.(9),(10).

(by E.R.A.) $D^c_e = (1/2)\Sigma(\Delta x_{pi}/x_F)^a$ (Fig.11) -(9)

(by F.R.R.A.) $D^c_a = n_c(\Delta x_{pa}/x_F)^a$ (Fig.13) -(10)

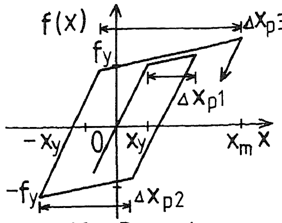


Fig.11, Dynamic Hysteresis Response

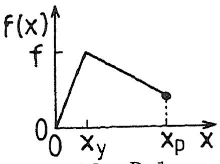


Fig.12, Pulse Response

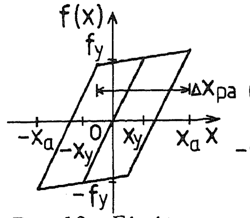


Fig.13, Finite Resonance Response

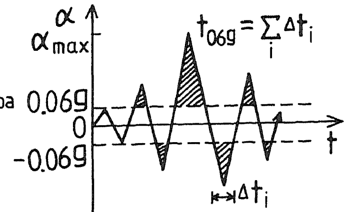


Fig.14, Definition of Earthquake Motion Duration

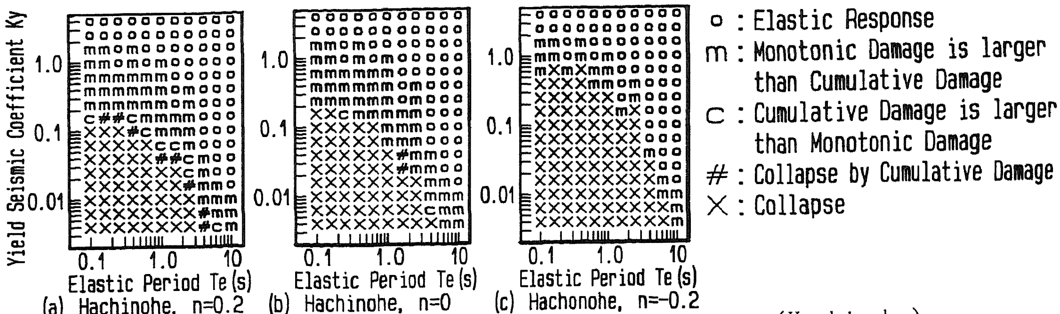


Fig.15, Distributions of Monotonic and Cumulative Damages (Hachinohe)

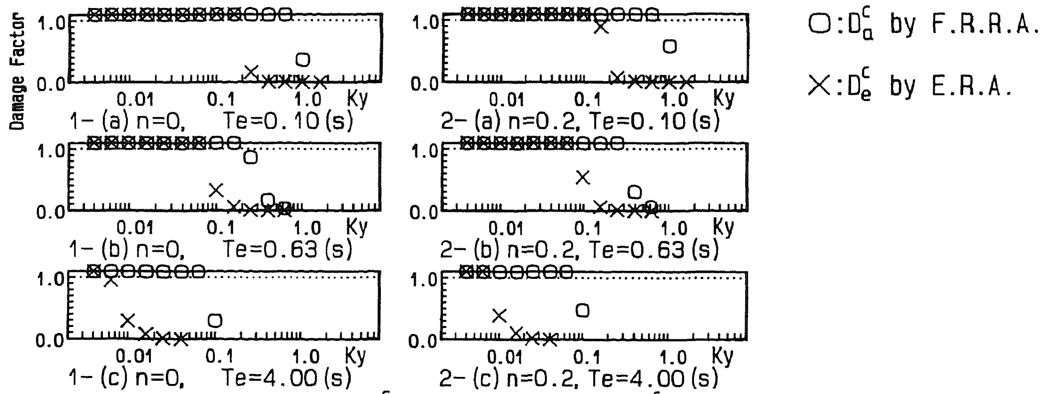


Fig.16, Cumulative Damages D_a^c (by F.R.R.A.) and D_e^c (by E.R.A.)

D_e^c, D_a^c are damage factors, and x_F is the same in case of Eqs.(7)(8). **a** is a constant, in this paper **a**=2. n_c is the number of cyclic responses by F.R.R.A. and is given by the following equations.

$$n_c = t_0/(T_{eq}-T_e) \qquad -(11)$$

$$t_0 = t_{06g}\ t^P \qquad -(12)$$

$$\log(t^P) = -1.56\log(K_y)-1.60 \qquad -(13)$$

t_0 is a duration time of predominant ground motions. t_{06g} is a summed time in which the acceleration $|\alpha|\geq 0.06g$ (g=980 (cm/s^2)) as shown in Fig.14. t^P is a non-dimensional constant given by Eq.(13) which is the same to Eq.(28) in Ref.5. When damage factor is equal to or larger than 1, the system collapses. Monotonic damage factor D_p^m by P.R.A. is considered to be nearly equal or larger than D_e^m by E.R.A., judging from the results of response evaluation. Damage factors D_e^m, D_e^c by E.R.A. for the earthquake of Hachinohe are calculated and the results are shown in Fig.15. When D_e^c is larger than D_e^m, the symbol "c" or "#" are plotted. With negative plastic stiffness (**n**<0), as shown in Fig.15(c), there is not such symbols as "c", "#", so that, in these cases, cumulative damage is not required to be discussed. Then, in the case of **n**>0 (Fig.2(a)) and **n**=0 (Fig.2(b)), cumulative damage factor D_a^c and D_e^c are plotted in Fig.16. D_a^c by F.R.R.A. is larger than D_e^c, so that D_a^c by F.R.R.A. belongs to be in safety side. The reason of the result is that the F.R.R.A. is an analytical method to calculate the possible largest displacement amplitude.

CONCLUDING REMARKS

Judging from Figs.9,10,15,16, the followings are concluded:
(1) When the response displacement amplitude $\mathbf{x}_a$ by F.R.R.A. is smaller than yield deformation $\mathbf{x}_y$, then the maximum response displacement, $\mathbf{x}_a$ by F.R.R.A. (Figs.9,10) is predominant.
(2) When $\mathbf{x}_a$ by F.R.R.A. is larger than $\mathbf{x}_y$, the maximum response displacement is predicted, by $\mathbf{x}_a$ by F.R.R.A. with positive ($\mathbf{n}>0$) plastic stiffness, and $\mathbf{x}_p$ by V-P.R.A. with zero ($\mathbf{n}=0$) and negative ($\mathbf{n}<0$) plastic stiffness (Figs.9,10).
(3) The monotonic damage factor is expected to be predicted by $\mathbf{D}_p^m$ by V-P.R.A..
(4) When the structures have positive ($\mathbf{n}>0$) and zero ($\mathbf{n}=0$) plastic stiffness, the cumulative damage factor is predicted in the safe side by $\mathbf{D}_a^c$ by F.R.R.A. (Fig.16). When the structures have negative ($\mathbf{n}<0$) plastic stiffness, monotonic damage factor is predicted by $\mathbf{D}_p^m$ by P.R.A. (Fig.15(c)).

The maximum response displacement and monotonic or cumulative damage factor are predicted by our proposed U.R.A..

ACKNOWLEDGEMENTS

The authors would like to thank for the encouragement of Shin Okamoto, Director of Research Planning and Information Department, and Tatsuo Murota, Director of Structural Engineering Department, of Building Research Institute, Ministry of Construction. We are pleased to acknowledge the kind collaboration of Miss Toshiko Takayanagi, Secretary, and Kenji Yamamoto, Graduate Student of Kobe University.

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