REGIONAL EVALUATION OF SEISMIC DAMAGES OF REINFORCED CONCRETE BUILDINGS
- Case Study : Standard R/C School Building in Hyogo Prefecture, Japan -

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SUMMARY

A systematic procedure is proposed with a case study to evaluate the ultimate aseismic capacity of a standard type R/C high school building in Hyogo prefecture, Japan. The ultimate aseismic capacity is finally quantified in terms of "Damage Factor" which represents the grade of damages until fracture. Regional distributions of damage factors make clear the effects of earthquake types (intra- and inter-plate), earthquake magnitudes, epicentral distances and predominant periods of ground not only on the grade of damages but also on the response types and fracture modes of the standard type R/C school building.

INTRODUCTION

Ultimate aseismic capacity of structures should be evaluated in consideration of the relations among earthquake mechanisms, earthquake ground motions, structural responses and fracture criteria of structures. The Authors have already proposed a primitive method for the evaluation of the ultimate aseismic safety against fracture of R/C structures (Ref.1). In this paper, such an evaluation procedure is improved and refined to be a systematic flow chart, and applied to the regional evaluation of structural damages of a real type R/C building subjected to expected destructive earthquake excitations.

FLOW DIAGRAM FOR SEISMIC DAMAGE EVALUATION

The outline of the procedure for the evaluation of the ultimate aseismic capacity of R/C dtructures is shown as a flow diagram in Fig.1 (Ref.2). In comparison with Ref.1, the factors of earthquake types (intra- and inter-plate), ground motions in source region (Ref.3) and maximum monotonic deformations by pulse response analysis are taken into account, and "Damage Factor" is adopted as a common index representing the grade of damages of structures (Ref. 2).

R/C BUILDING AND LOCATIONS

In this paper, a standard type of R/C high school building employed in Hyogo prefecture, Japan, is examined. The plot plan of the school is shown

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in Fig.2 and damage factors are calculated only in regard to C block in it. The more detailed plan, column and shear wall sections on the ground floor and frameworks in ridge and span directions of C block are shown in Fig.3. R/C school buildings with such a standard type are located at the following cities and towns in Hyogo prefecture: Kobe, Himeji, Chigusa, Sasayama, Toyooka, Kasumi and Mihara, which are shown in Fig.4. The predominant periods of all their sites are supposed to be 0.1 sec. and 0.8 sec., which correspond to harder and softer grounds, respectively.

EARTHQUAKES AND EPICENTERS

As expected maximum earthquake which will attack Hyogo prefecture in future the following two types of earthquake are selected: intra- and interplate earthquakes I,II. Earthquake I corresponds to the former one which is expected to be caused by Yamazaki Fault with the maximum length, 80 km. The earthquake magnitude M=7.4 is given by Otsuka's equation of the maximum fault length-magnitude relation (Ref.4). Earthquake II is the same one as Nankai-do earthquake (M=8.1) 21 Dec. 1946, the epicenter of which is located on Nankai trough. The locations of them are shown in Fig.4, where the epicentral distances (Δ km) of the cities and towns concerned at Earthquakes I,II are presented.

EARTHQUAKE GROUND MOTIONS

The outline of the propagation path of earthquake waves from earthquake origin to site ground is shown in Fig.5, based on which earthquake ground motions are presented by a trapezoid maximum amplitude spectrum in the tripartite logarithmic plane such as shown in Fig.6 and expressed by Figs.1-6, i.e., functions of earthquake magnitude M, epicentral distance Δ(km) and predominant period of ground T_G (sec) (Ref.3).

$\Delta \leqq \Delta_B$ (within source region): $\Delta \geqq \Delta_B$ (out of source region):

$$T \geqq T_c : |z| = Z_m = (1/4)(T_G/0.15)10^{0.5M-1.30}, \quad -(1) \qquad |z| = Z_m(\Delta_B/\Delta)^2, -(4)$$

$$T_G \leqq T \leqq T_c : |\dot{z}| = V_m = (\pi/2)(T_G/0.15)\bar{\dot{d}}, \quad -(2) \qquad |\dot{z}| = V_m(\Delta_B/\Delta)^2, -(5)$$

$$T \leqq T_G : |\ddot{z}| = A_m = (\pi^2/0.15)\bar{\dot{d}}, \quad -(3) \qquad |\ddot{z}| = A_m(\Delta_B/\Delta)^2, -(6)$$

where predominant period of earthquake T_c (sec), radius of source region Δ_B (km) and average slip velocity of fault $\bar{\dot{d}}$ (kine) are given by

$$\log T_c = 0.5M - 1.30 - \log \bar{\dot{d}}, \quad -(7) \qquad \log \Delta_B = 0.5M - 2.1, \quad -(8)$$

$$\left.\begin{aligned} \bar{\dot{d}} &= 15 \text{ kine (for interplate earthquake)}, \\ &= 50 \text{ kine (for intraplate earthquake)}. \end{aligned}\right\} \quad -(9)$$

EARTHQUAKE LIMIT RESPONSE ANALYSIS

Finite Resonance Response Analysis

When a one degree of freedom system shown in Fig.7 is subjected to random waves, it tends to select the waves with the same period as its own and to reach the resonant state (Ref.5). Based on this tendency, the Authors proposed the "Finite Resonance Response Analysis" method (Ref.6). Regardind a hysteretic system with a possible hysteretic loop such as shown in Fig.8, its displacement amplitude x_a is able to be given by the intersecting point of the earthquake ground motion spectrum (Fig.6) and a finite resonance spectrum as

shown in Fig.9 (Ref.2). As for the former spectrum the velocity amplitude $|\dot{z}|$ in Fig.6 is to be replaced by v_o, $v_o = |\dot{z}|/\beta_{0.2}$, -(10)
where $\beta_{0.2}$ is the approximate amplification factor $\beta = 0.6/(\pi h + 0.4)$ (Refs. 2, 6) with damping ratio h = 0.2. The latter spectrum is given by the finite resonance response equation (Ref.1), i.e.,

$$\sqrt{m}v_o = (1/1.2\pi)(A/\sqrt{Q_a x_a}) + 0.212\sqrt{Q_a x_a}, \quad -(11)$$

Due to pseudo-resonance period T is nearly equal to equivalent natural period T_e given by

$$T_e = 2\pi\sqrt{m x_a/Q_a}. \quad -(12)$$

If x_a is constant during responses, the total number of response cycles n_o is estimated by

$$n_o = t_o/T_e, \quad -(13)$$

where t_o is duration time of predominant ground motions and given by (Refs.1, 2)

$$\log t_o = 0.5M - 2.28. \quad -(14)$$

Pulse Response Analysis

When ground excitations are extremely large, the system will collapse with a very large monotonic deformation. The Authors have already proposed the "Pulse Response Analysis" for such a type of response (Ref.2). By means of this analysis method, corresponding to the maximum monotonic deformation x_{max} shown in Fig.10, acceleration pulse response spectrum (α_p-$2t_p$ relation) and velocity pulse response spectrum (v_p-$2t_p$ relation) are calculated. If input impulse is rectangular, the former and the latter relations are reduced to

$$2\int_0^{x_p} dx/\{(2/m)(m\alpha_p x - A(x))\}^{1/2} = 2t_p, \quad -(15)$$

where

$$x_p = A(x_{max})/(m\alpha_p), \qquad A(x) = \int_0^x f(x)dx, \quad -(16)$$

and

$$2\int_0^{x_{max}} dx/\{v_p{}^2 - (2/m)A(x)\}^{1/2} = 2t_p, \quad -(17)$$

respectively. When they are tangent to the earthquake motion spectrum as shown in Fig.11, there are two corresponding x_{max} values, the maximum of which is considered to be the possible maximum monotonic response deformation.

RESTORING FORCE CHARACTERISTICS OF R/C STRUCTURES

The C block of the R/C building shown in Fig.3 consists of columns with flexural yielding type (Fig.12) and shear walls with shear fracture type (Fig. 13). Shear force Q - lateral displacement x relations of them are idealized as shown in Fig.14 and 15, where the values of the critical points, Q_y, Q_s, x_y, Q_B, x_B^W are calculated by the equations presented in Ref.1.

In the ridge direction consisting only of columns, the monotonic and envelope Q-x relation is given in Fig.16, where x_y is supposed to be twice lager than x_y of columns due to pseudo-elastic beam deformations. In the span direction consisting of columns and shear walls, Q-x relation is given in Fig.17, where x_y of columns is assumed to be equal to x_B^W of shear walls which is nearly equal to $2x_y$. The calculation conditions are as follows: strength of concrete F_c = 210 kg/cm^2, yield strength of steel ${}_s\sigma_y$ = 3,500 kg/cm^2 and yield strain of steel ${}_s\varepsilon_y = 1.75\times10^{-3}$. Axial load N of each column is computed by proportional allotment of the total weight 6,043 tons on the higher floors than the ground one according to its bearing area in plan.

FRACTURE CRITERIA OF R/C COLUMNS AND SHEAR WALLS

The outlies of fracture criteria of R/C columns with flexual yielding type and shear walls with shear fracture type are shown in Fig.18. As for columns, two conditions should be taken into consideration, i.e., the one due to compressive concrete fracture and the other due to tensile reinforcement fracture. The former is given in Ref.1, and the latter is introduced on the basis of the following fatigue fracture criterion of reinforcing bars such as shown in Fig.19 (Ref.7): $(\varepsilon_a - {}_s\varepsilon_y)N_B{}^{3/4} = 150_s\varepsilon_y \times 0.5^{3/4}$, -(18)
where ε_a is strain amplitude and N_B is number of cycles until fracture. ε_a is given by:

in monotonic case ($N_B = 0.5$), $\varepsilon_a = \varepsilon_B = D\Phi_B(1 - d_1 - x_{n1})$, -(19)

in cyclic case, $\varepsilon_a = D\Phi_a(1 - 2d_1)$, -(20)

where the meanings of $D\Phi$, d_1, x_{n1} and the translation method from the curvature $D\Phi$ to lateral displacement x are the same as in Ref.1. In monotonic case, x_B^c and x_B^s become the ultimate displacements of columns by concrete and reinforcing bar, respectively. As for shear walls, x_B^W is the ultimate deformation both in monotonic and cyclic cases.

RESPONSE DISPLACEMENTS

Response Analysis is carried out on the assumption of one degree of freedom system. The maximum response displacements x_{max} (cm) by velocity and acceleration pulse responses and displacement amplitude x_a (cm) by finite resonance response of the R/C school building subjected to the excitations of Earthquakes I and II are shown in Fig.20(a)-(d).

DAMAGE FACTORS AND DISTRIBUTIONS

The index "Damage Factor (D.F.)" is introduced to quantify the grade of R/C building damages calculated in various response and fracture cases. D.F. is determined as follows:

In the monotonic response, $D.F. = x_{max}/x_B$, -(21)

and only for columns, if $x_{max} \leq x_y$, $D.F. = 0$, -(22)

In the cyclic response, for shear walls, $D.F. = x_a/x_B^W$, -(23)

and for columns, $D.F. = n_o/N_B$. -(24)

In this paper D.F. is calculated regarding the main shear walls (W_1) and columns (C_2). x_{max} and x_a of columns are of course the values reduced by the beam deformations. D.F. is plotted in Figs.21(a)-(d), the parameters of which are the same as in Fig.20(a)-(d). D.F. larger than the unity means fracture, but it is calculated and shown for reference. D.F. has the following nine types: (velocity pulse, acceleration one, Finite Resonance) × (Shear walls, reinforcing bar and concrete of columns).

The distributions of the maximum D.F. regarding each direction and location of the R/C standard type school building in Hyogo prefecture are shown in Figs.22(a)-(d). As for span direction, D.F. of shear walls is plotted, because shear walls are predominant aseismic structural elements in that direction.

CONCLUDING REMARKS

Judging from Figs.22(a)-(d), the following things are concluded:

(1) The effects of predominant periods of ground and epicentral distances upon the damages of R/C standard type school building are reasonable.

(2) If predominant periods of ground round the source region are short, the damages in the span direction with predominant shear wall type are larger than

in the ridge direction consisting only of columns (see Fig.22(a)).
(3) In case of Earthquake II, i.e., interplate earthquake, and long predominant period of ground, columns have the possibility of fatigue collapse in the ridge direction (see Fig.22(d)).

The regional informations obtained in this case study are very useful for disaster prevention and for future planning of R/C school building.

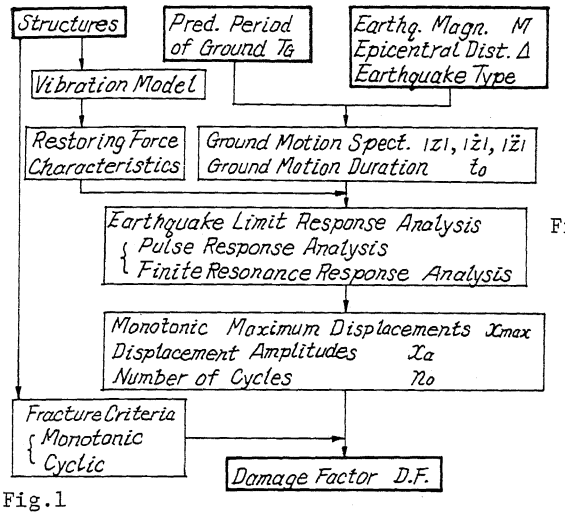


Fig.1
Flow Diagram for Seismic Damage Evalutation

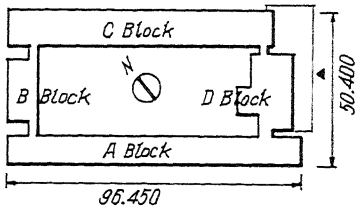
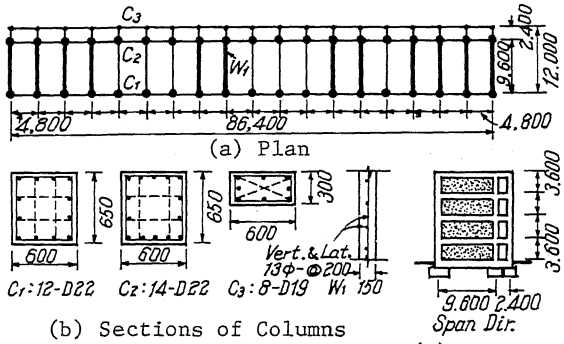


Fig.2 Plot Plan of R/C High School



(b) Sections of Columns and Shear Walls

(c) Frameworks

Fig.3 Structural Outlines of C Block

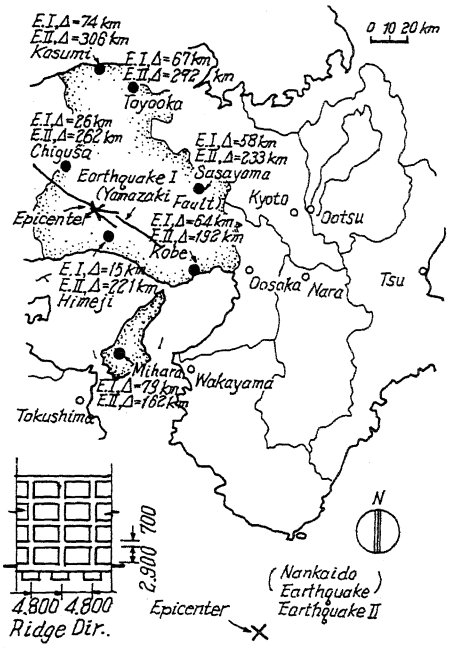


Fig.4 Locations of R/C School Buildings and Epicenters, Hyogo Prefecture, Japan

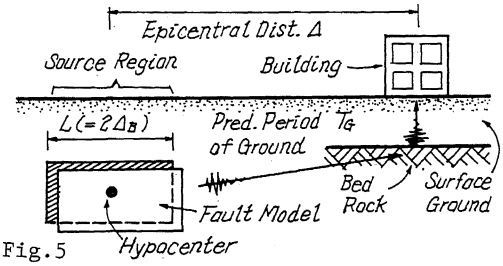


Fig.5
Propagation Path of Earthquake Waves

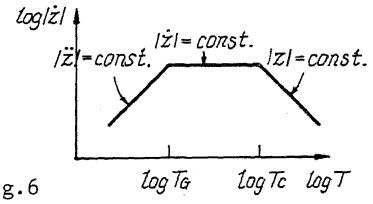


Fig.6
Earthquake Ground Motion Spectrum

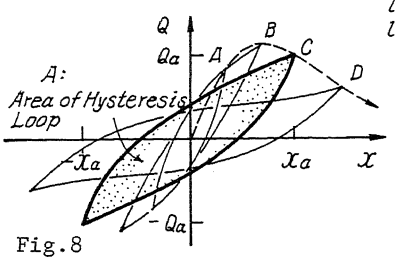


Fig.8
Hysteresis Loops in Finite Resonant Responses

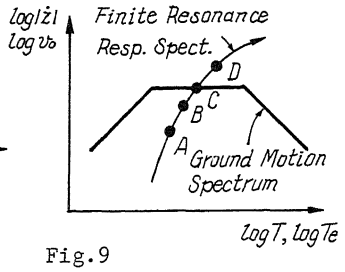


Fig.9
Finite Resonance Response Analysis by Spectra

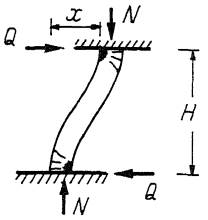


Fig.12
R/C Column

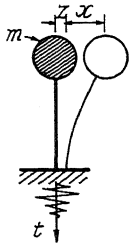


Fig.7
One Mass Oscillator

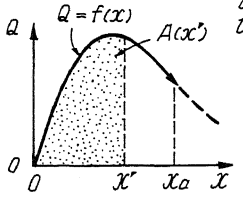


Fig.10
Monotonic Shear Force-Displacement Relation in Pulse Response

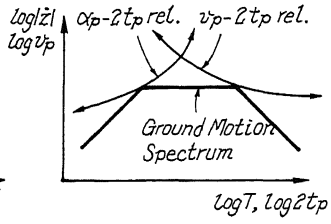


Fig.11
Pulse Response Analysis by Spectra

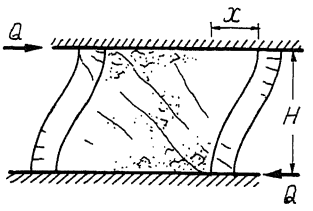


Fig.13
R/C Shear Wall

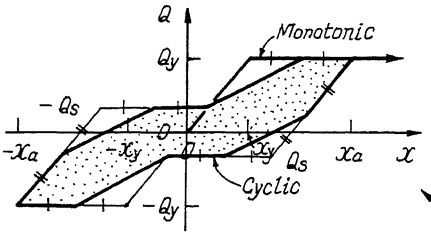


Fig.14
Hysteresis Loop of R/C Columns

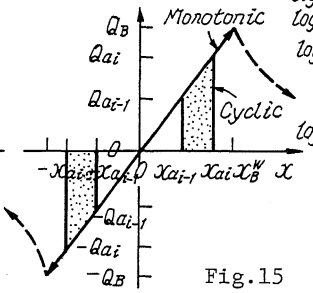


Fig.15
Hysteresis Loop of R/C Shear Walls

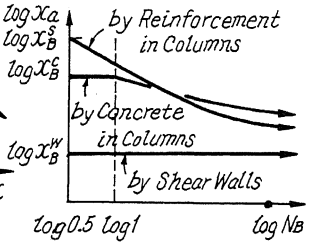


Fig.18
Fatigue Criteria of R/C Columns and Shear Walls

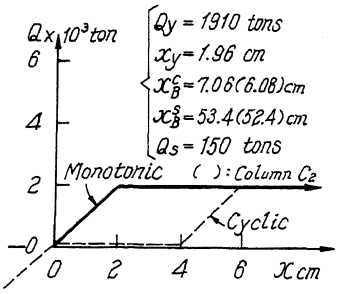


Fig.16
Q-x Relation in Ridge Direction of C Block

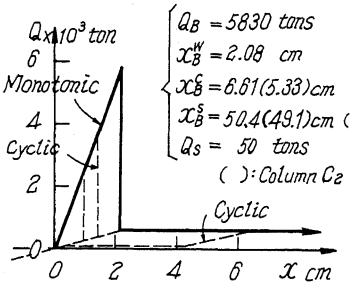


Fig.17
Q-x Relation in Span Direction of C Block

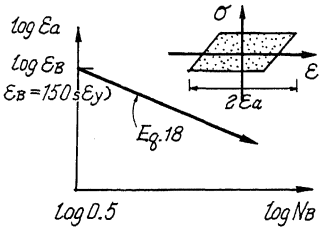


Fig.19
Fatigue Criterion of Reinforcing Bar

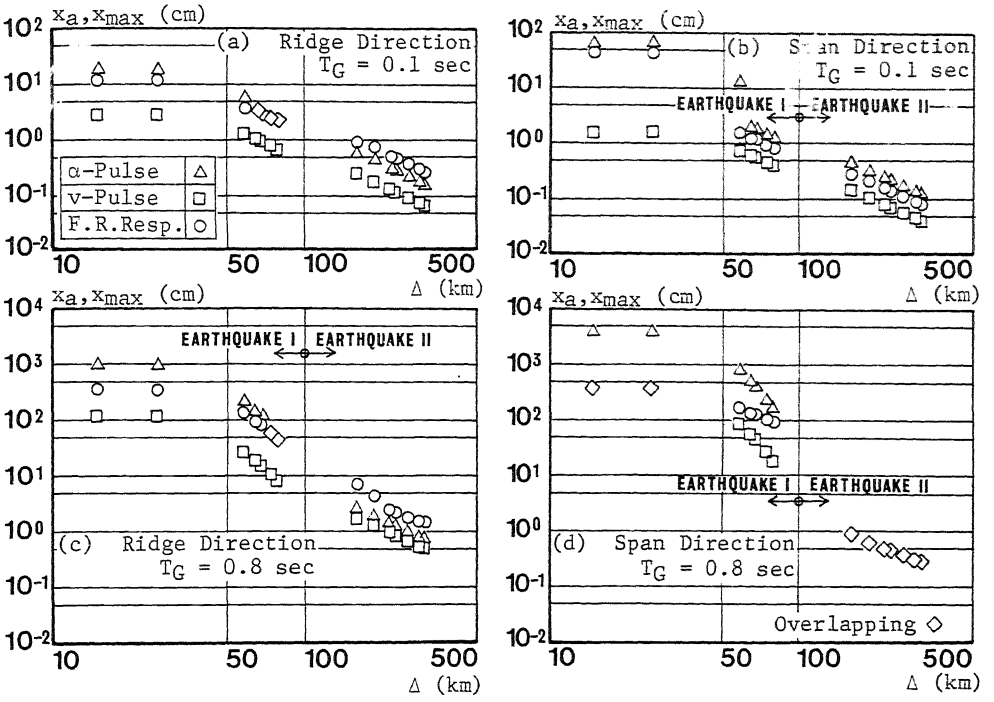


Fig.20 Monotonic and Cyclic Response Deformations

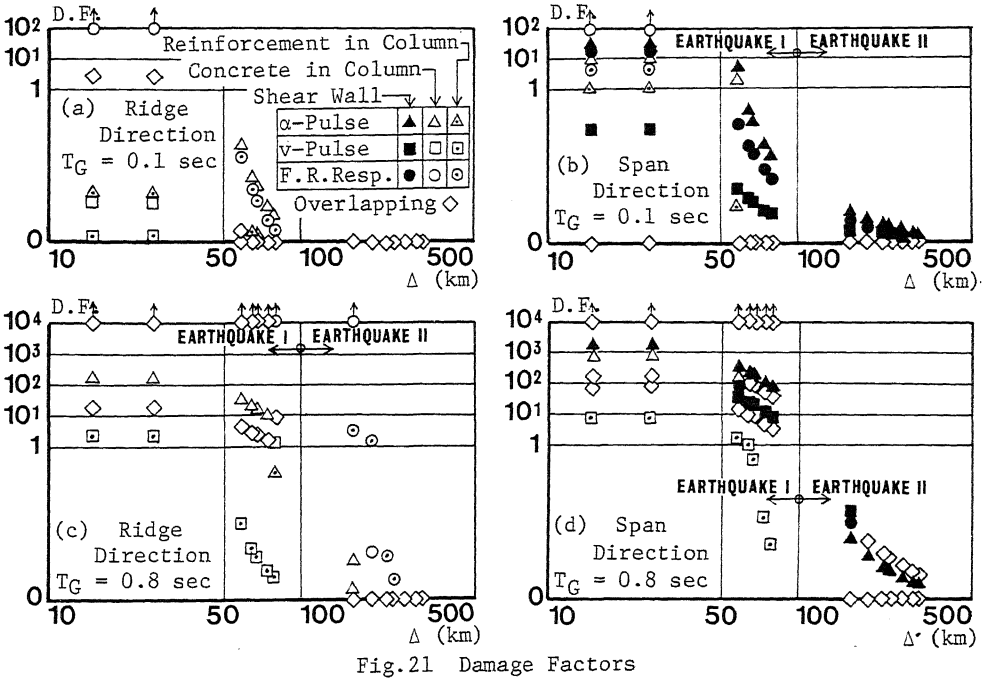


Fig.21 Damage Factors

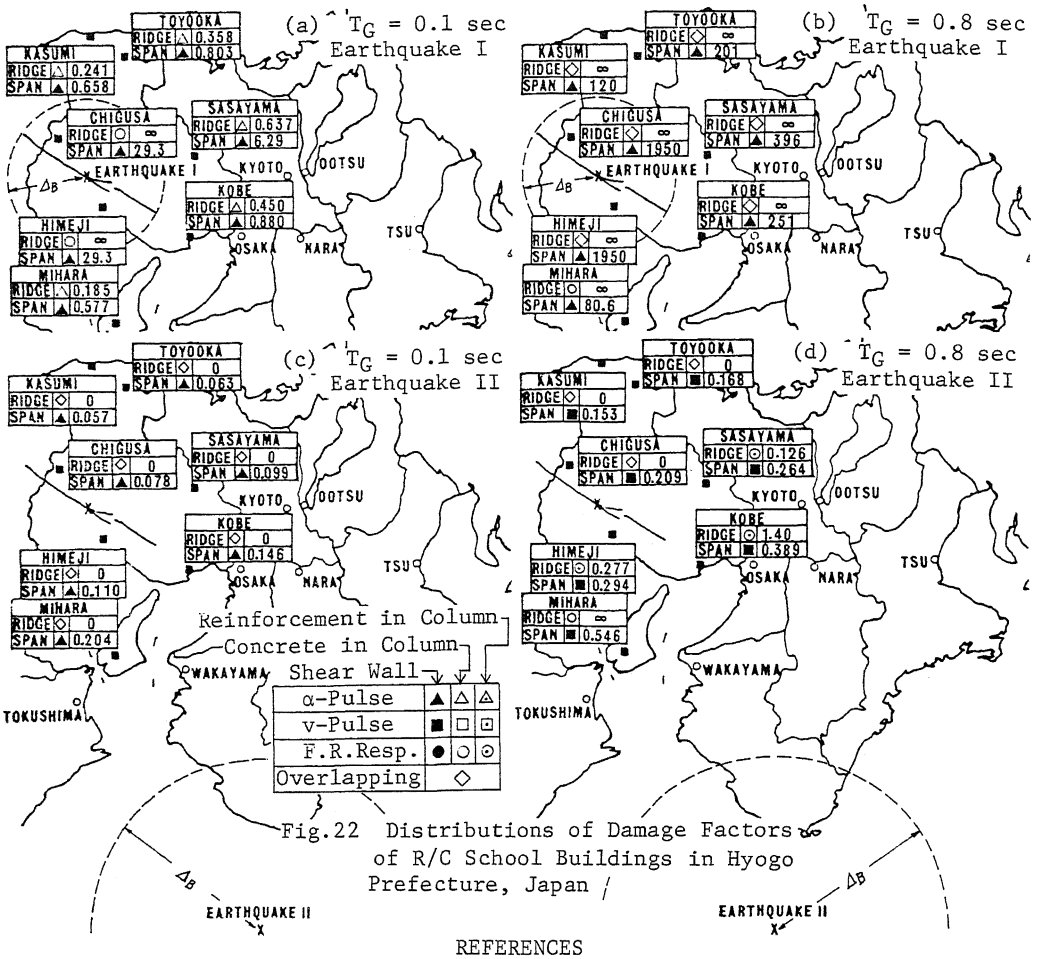


Fig.22 Distributions of Damage Factors of R/C School Buildings in Hyogo Prefecture, Japan

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