RESONANCE - FATIGUE - CHARACTERISTICS
FOR EVALUATION OF THE ULTIMATE ASEISMIC CAPACITY OF STRUCTURES

by

M. Yamada[I] and H. Kawamura[II]

SYNOPSIS

RESONANCE-FATIGUE-CHARACTERISTIC of structures is proposed for evaluation of the ultimate aseismic capacity of structures based upon FRACTURE. Comparing it with earthquake-wave cahracteristics, deterministic and probabilistic evaluation methods are shown. Steady-state resonance and steady forced vibration are employed as fundamental medium phenomena which make possible the direct comparison among them and produce a new conception [1] RESONANCE-CAPACITY (or RESONANCE COEFFICIENT) which shows energy absorption capability of structures. Finally, experimental RESONANCE-FATIGUE-CHARACTERISTICS of reinforced concrete rigid frames and shear walls are shown, and an ultimate aseismic design philosophy on reinforced concrete structures is discussed on.

1. INTRODUCTION

Many modern buildings have been broken down by destructive earthquakes. However, many theoretical and experimental researches on aseismic design are intended to make clear only vibrational and cyclic phenomena of buildings and members, but not the very phenomena of FRACTURE. The purpose of this paper is to propose a fundamental idea on ultimate aseismic design based upon FRACTURE. As the first step, an adequate fracture condition of structures subjected to cyclic loading must be described. In this paper, a new conception, RESONANCE-FATIGUE-CHARACTERISTICS of structures is introduced, which is composed of energy absorption capacity and fatigue characteristics based upon steady-state response or steady forced vibration. Comparing it with earthquake-wave characteristics described in a space with the same physical meaning, the ultimate aseismic capacity of structures is able to be given quantitatively. Finally, some experimental RESONANCE-FATIGUE-CHARACTERISTICS of reinforced concrete structural elements are shown and their ultimate aseismic characteristics are discussed on.

2. ASEISMIC FACTORS

When a structure is subjected to cyclic horizontal sway with an amplitude of $\pm X_a$ under a constant vertical load N such as shown in Fig. 1, a horizontal load F - displacement x hysteresis loop with a displacement amplitude of X_a and a loading amplitude of F_a will be able to be drawn such as shown in Fig. 2. This hysteresis loop has an area A, and F_a, X_a and A are of course given by a function of the number of cycles N_c.

Suppose that the structure in Fig. 1 is able to be idealized as an equivalent one-mass oscillator subjected to sinusoidal ground acceleration waves with an amplitude of α_0 such as shown in Fig. 3 and that the oscillator is in steady-state forced vibration with the same F - X hysteresis loop such as shown in fig. 2. Integrating the differential equation

I Professor of Structural Engineering, Faculty of Engrg., Kobe University.
II Research Assistant, Faculty of Engrg., Kobe University, Kobe, Japan.

of motion and neglecting the effect of viscous damping, the following energy equilibrium equation is finally derived;

$$A = m\ \alpha_0\ \pi\ X_a\ |\sin\phi| \qquad (1),$$

where ϕ is the phase difference between input acceleration and response displacement.

Assuming steady-state resonance as an ultimate vibration phenomenon, Eq.(1) is reduced to

$$\frac{1}{\pi}\frac{A}{X_a} = m\ \alpha_0 \qquad (2),$$

and the left hand side of Eq.(2) is in this paper defined as RESONANCE-CAPACITY C_R, then

$$C_R = \frac{1}{\pi}\frac{A}{X_a} \qquad (3).$$

From the point of view of equivalent linear vibration, furthermore, an equivalent linear natural period T_{se} of the structure in Fig. 1 or the one-mass oscillator in Fig. 3 may be given by

$$T_{se} = 2\pi\sqrt{\frac{W}{g}\frac{X_a}{F_a}} \qquad (4).$$

The RESONANCE-FATIGUE-CHARACTERISTICS, which is introduced in this paper for evaluation of the ultimate aseismic capacity of structures, consists of these aseismic factors C_R, X_a, T_{se} and N_c, defined above as the measures of energy capacity, displacement capacity, period property and fatigue characteristics, respectively.

3. RESONANCE-FATIGUE-CHARACTERISTICS

Suppose a space with the Cartesian coordinate axises, C_R, X_a and N_c, the ultimate fracture condition of structures subjected to cyclic loading is able to be defined clearly and visibly in this space. Under the RESONANCE-RESPONSE-Condition, that

$$C_R = \text{const.} \qquad (5),$$

a RESONANCE-FATIGUE-CHARACTERISTIC-Surface S of a structure may be drawn experimentally such as shown in Fig. 4, and the surface may be bounded by a fracture line B on which X_a increases infinitely. This characteristic is named here RESONANCE-FATIGUE-CHARACTERISTIC -CXN. In this characteristic space, energy absorption, fatigue and deformation capacities are involved for the ultimate aseismic state of structures.

In order to evaluate the ultimate aseismic capacity of structures in comparison with earthquake waves, it is convenient to compose RESONANCE-FATIGUE-CHARACTERISTIC -KTN, such as shown in Fig. 5 instead of RESONANCE-FATIGUE-CHARACTERISTIC -CXN. In the RESONANCE-FATIGUE-CHARACTERISTIC -KTN K_R and T_{se} are employed as z and x axises instead of C_R and X_a, where K_R is given by

$$K_R = \frac{C_R}{W} = \frac{C_R}{mg} \qquad (6),$$

and named here RESONANCE-COEFFICIENT, which is shown to be a physical quantity equivalent to α_0/g by Eqs.(2) and (3). Consequently the axises K_R, T_{se} and N_c correspond to acceleration amplitudes, periods and numbers of earthquake waves, and the direct comparison between RESONANCE-FATIGUE-CHARACTERISTIC -KTN of structures and earthquake-wave-characteristic makes it possible to evaluate the ultimate aseismic capacity of structures. A characteristic surface $\bar{S}$ and fracture line $\bar{B}$ must be analogous to those of RESONANCE-FATIGUE-CHARACTERISTIC -CXN, S, B, because there is no essential change in the transformation of axises. As an example, this is illustrated in Fig. 5.

EARTHQUAKE-WAVE-CHARACTERISTICS

Corresponding to RESONANCE-FATIGUE-CHARACTERISTIC -KTN space, earthquake-wave-characteristics are able to be described in a space with coordinate axises of acceleration amplitude α_0, period T_E, and the number of waves N_E such as shown in Figs. 6 and 7. As examples, earthquake-wave-characteristics are illustrated in Fig. 6(a),(b) by means of deterministic and probabilistic descriptions, respectively. In Fig. 6(a), a structure is considered to undergo in its life earthquake waves with α_{0i}, N_{Ei} and $T_E \leqq T_{Ei}$, regulated to resonate it, where α_{0i}, T_{Ei} and N_{Ei} are the coordinates of a point P_i, which exists on all the deterministically given surface D under equal probability. Fig. 6(b) shows a probabilistic description of earthquake-wave-characteristics and the probability of the existence of P_i in a region $\alpha_0 \pm \frac{1}{2}\Delta\alpha_0$, $T_E \pm \frac{1}{2}\Delta T_E$, $N_E \pm \frac{1}{2}\Delta N_E$ is given by $f_E(\alpha_0,T_E,N_E)\ \Delta\alpha_0\Delta T_E\Delta N_E$, where $f_E(\alpha_0,T_E,N_E)$ is a probabilistic density function. In reality, it may be a difficult problem to determine the surface D or $f_E(\alpha_0,T_E,N_E)$, but it is not impossible to determine the expected characteristics of future earthquake waves by the progress of science.

5. EVALUATION OF ULTIMATE ASEISMIC CAPACITY

The ultimate aseismic capacity of structures is able to be estimated by the direct comparison between RESONANCE-FATIGUE-CHARACTERISTIC -KTN in Fig. 5 and earthquake-wave-characteristics in Fig. 6. If all the curved surface D in Fig. 6(a) is covered with the curved surface C, defined by a set of straight lines, which pass the line $\overline{B}$ and is parallel to the T_{se} axis in Fig. 5, considering only steady-state resonance, a deterministic ultimate aseismic safety is considered to be enough.

When the period characteristics of input waves and the fracture condition of structures are intended to be taken into account, the following equation must be applied to,

$$K_R = \frac{\alpha_0}{g}|\sin\phi| \qquad (7),$$

which is derived from Eqs.(1),(3) and (6), and based upon steady forced vibration. $|\sin\phi|$ is given by the phase function such as shown in Fig. 8,

$$|\sin\phi| = S(T_{seu}/T_E,\ h_{eu}) \qquad (8),$$

in which T_{seu} and h_{eu} are the equivalent natural period and the equivalent viscous damping factor of structures in ultimate state. Replacing α_0-axis by $\frac{\alpha_0}{g}|\sin\phi|$-axis, where $|\sin\phi|$ is estimated by using T_{seu}, h_{eu} on the fracture line $\overline{B}$ in Fig. 5, the curved surface D in Fig. 6(a) is transformed into a new one $\overline{D}$ such as shown in Fig. 9. Let $\overline{B}'$ and $\overline{D}'$ be the projections of $\overline{B}$ and the edge line of $\overline{D}$ to the K_R-N_c-plane such as shown in Fig. 9, a deterministic ultimate aseismic capacity of structures d_s is given by

$$d_s = \lim_{N_c\to\infty} \frac{1}{N_c}\int_1^{N_c} L(N_c)\ dN_c \qquad (9),$$

where $L(N_c)$ is the difference length between $\overline{B}'$ and $\overline{D}'$ at N_c.
A probabilistic ultimate aseismic capacity, i.e. probability of survival of structures, p_s is able to be given by

$$p_s = \int_\Omega f_E(\frac{\alpha_0}{g}|\sin\phi|,T_E,N_E)\ dK_R dT_{se} dN_c \qquad (10),$$

where $f_E(\frac{\alpha_0}{g}|\sin\phi|,T_E,N_E)$ is a probability density function, to which $f_E(\alpha_0,T_E,N_E)$ is reduced by transforming α_0-axis into $\frac{\alpha_0}{g}|\sin\phi|$-axis, and Ω is the region under the curved surface C in Fig. 5. Considering only steady-state resonance, that transformation is not necessary. In the both deterministic and probabilistic cases, steady-state resonance gives the first order upper bound of the ultimate aseismic capacity of structures, and steady forced vibration the second order upper bound with the more reality than the first.

6. EXPERIMENTAL RESONANCE-FATIGUE-CHARACTERISTICS

Two kinds of test specimens, i.e. reinforced concrete rigid frames and reinforced concrete shear walls are employed such as shown in Fig.10 [2][3]. Cyclic tests are carried out under the condition of constant displacement amplitudes instead of RESONANCE-RESPONSE-Condition because of technical conveniences. The ultimate fracture mode of RC-rigid frame specimen is beam-yielding flexural type and that of RC-shear wall is diagonal compression brittle failure of concrete panel and beam-yielding flexural type. RESONANCE-FATIGUE-CHARACTERISTICS -KTN of the both specimens are shown by thick solid and broken lines in Fig. 11(a),(b).

Although the number of data may be few and the testing condition is not exactly RESONANCE-RESPONSE-Condition, the tendency of RESONANCE-FATIGUE CHARACTERISTIC surfaces and fracture lines is however easily expected and their expected outlines are illustrated by thin curved lines in Fig. 11. Fig. 11 shows the existence of the remarkable differences between the aseismic characteristics of RC rigid frames and those of RC-shear walls. Judging from Fig. 11, an ultimate aseismic design philosophy of reinforced concrete structures is able to be summerized as follows ; RC-structures with flexural and ductile yielding type have a great aseismic capacity against earthquake-waves with the shorter periods and the larger number of cycles, on the other hand, RC-structures with shear and brittle fracture type against earthquake-waves with the longer periods and the smaller number of cycles.

7. CONCLUSIONS

Compareing RESONANCE-RESPONSE-CHARACTERISTICS of structures in the K_R-T_{se}-N_C-space (Fig. 5) with earthquake-wave characteristics in the α_0-T_E-N_E-space (Fig. 6), the ultimate aseismic capacity of structures is able to be given quantitatively by d_s (Eq.9), and p_s (Eq.10), by means of deterministic and probabilistic treatments, respectively. Finally, based upon the experimental RESONANCE-FATIGUE-CHARACTERISTICS, the aseismic capacity of reinforced concrete structures is made clear.

8. BIBLIOGRAPHY

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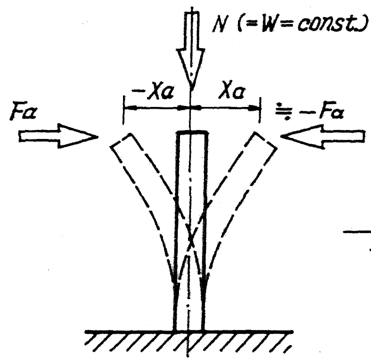


Fig.1 Structure Subjected to Cyclic Loading

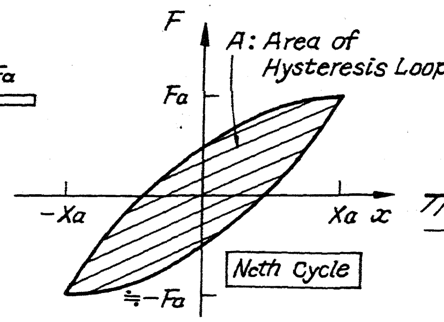


Fig.2 Hysteresis Loop of Restoring Force Function of Structure

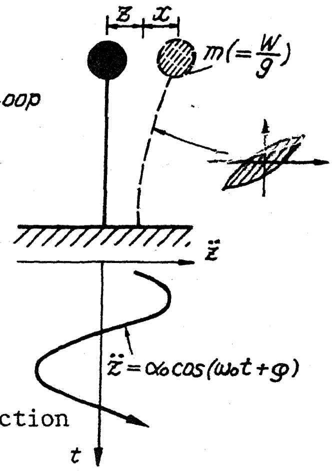


Fig.3 Idealized One-Mass Oscillator

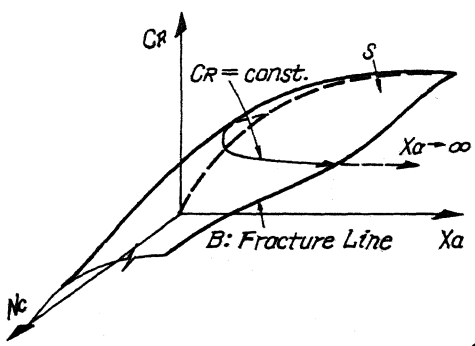


Fig.4 Resonance Fatigue Characteristic-CXN of Structure

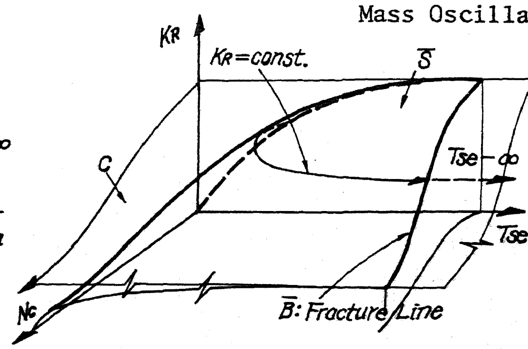
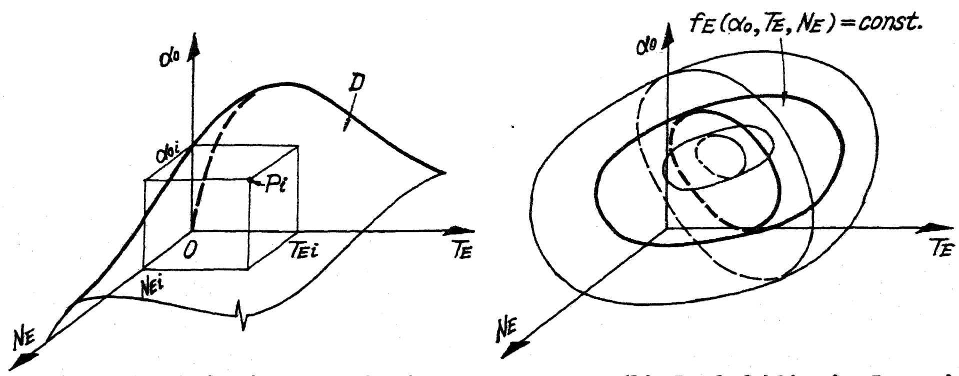


Fig.5 Resonance Fatigue Characteristic-KTN of Structure



(a) Deterministic Description (b) Probabilistic Description

Fig. 6 Earthquake-Wave Characteristics

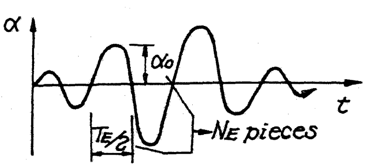


Fig.7 Earthquake Acceleration Waves

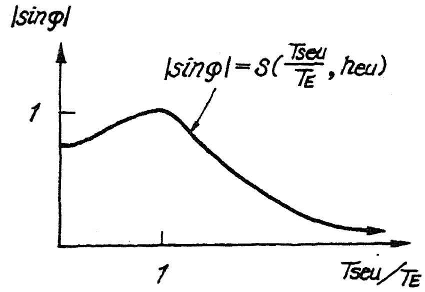


Fig.8 Phase Difference Function

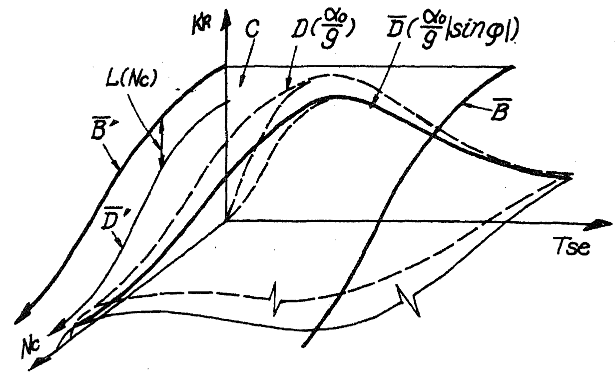
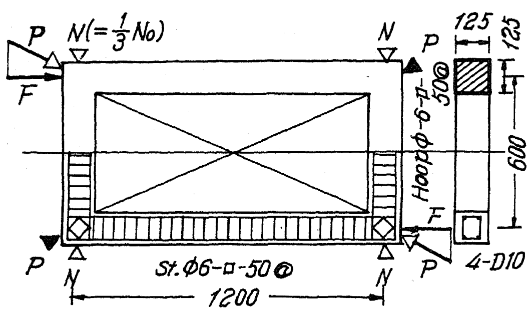
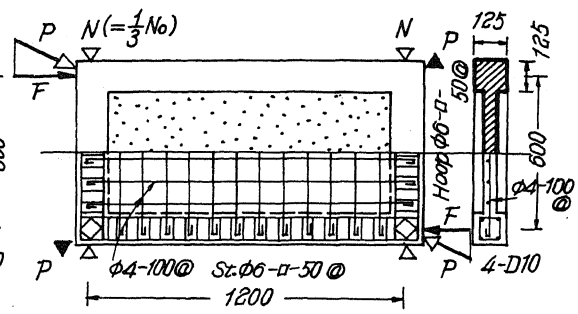


Fig.9 Evaluation Procedure for Ultimate Aseismic Capacity

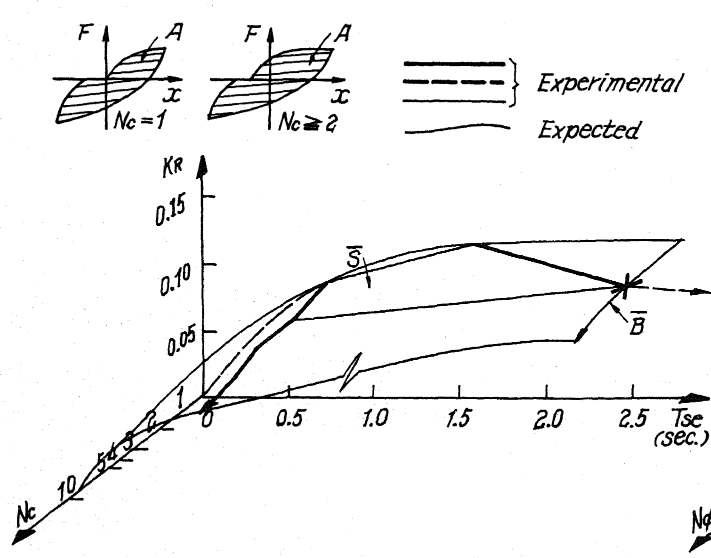


(a) RC Rigid Frame [2]

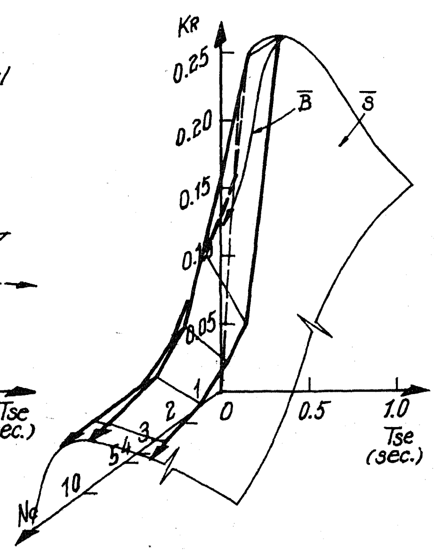


(b) RC Shear Wall [3]

Fig. 10 Test Specimens



(a) RC Rigid Frame



(b) RC Shear Wall

Fig.11 Resonance Fatigue Characteristics-KTN (Test Results)