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

6-1-14

STUDY ON EVALUATION OF CUMULATIVE DAMAGE EARTHQUAKE RESPONSE OF STRUCTURES BASED ON COMPUTER-ACTUATOR ON-LINE TEST

Koji MIZUHATA[1] and Yukinori MAEDA[2]

[1]Department of Architecture, Kobe University,
Nada-ku, Kobe, Japan
[2]Department of Architecture, Kobe University,
Nada-ku, Kobe, Japan

SUMMARY

Since several years ago, the authors have been proposing the method to evaluate dynamic seismic safety of reinforced concrete structures based on the authors' hypothesis of cumulative damage. The objectives of this study are to show the computer-actuator on-line test system utilizing the Digital Dynamic Simulator and to verify this method of evaluation by the on-line test and to compare the authors' hypothesis with Park and Ang's and Chung, Meyer and Shinozuka's.

INTRODUCTION

The authors have been proposing the method to evaluate dynamic seismic safety of reinforced concrete structures based on the hypothesis that the damage factor D_k of the structure subjected to dynamically varying load is the sum of the ratio of the maximum displacement δ_{max} to the collapse displacement δ_F and the cumulative low cycle fatigue damage, $a(n_i/N_{fi})^b$, as Eq.(1).

$$D_k(n)=|\delta_{max}|/\delta_F+a\sum_{i=1}^{k}(n_i/N_{fi})^b(1-\Delta\delta_i/2\delta_F) \tag{1}$$

where N_{fi} = number of cycles (with displacement range $\Delta\delta_i$) to failure; n_i = number of cycles (with displacement range $\Delta\delta_i$) actually loading; a, b = material constants. From results of monotonic loading tests and low-cycle fatigue tests, damage factor $D_k(n)$ of reinforced concrete frame becomes (Ref. 1)

$$D_k(n)=|\delta_{max}|/\delta_F+\left[\begin{array}{ll} 0.609\sum_{i=1}^{k}(n_i/N_{fi})^{0.715}(1-\Delta\delta_i/2\delta_F) & (0.078\geqq n_i/N_{fi}>0) \\ \sum_{i=1}^{k}(n_i/N_{fi})^{0.910}(1-\Delta\delta_i/2\delta_F) & (1\geqq n_i/N_{fi}>0.078) \end{array}\right. \tag{2}$$

In order to determine whether this method of evaluation is good or not, it is necessary to examine reinforced concrete frames subjected to real earthquake motions. For this purpose, the authors developed the computer-actuator on-line test system using the Digital Dynamic Simulator (Ref. 2). In this paper, the on-line test system and on-line test are briefly described, results of on-line test are discussed and the damage factor $D_k(n)$ is compared with others.

ON-LINE TEST SYSTEM

A brief block diagram of the on-line test system is shown in Fig. 1. This system is able to be divided into two parts, control system and loading system.

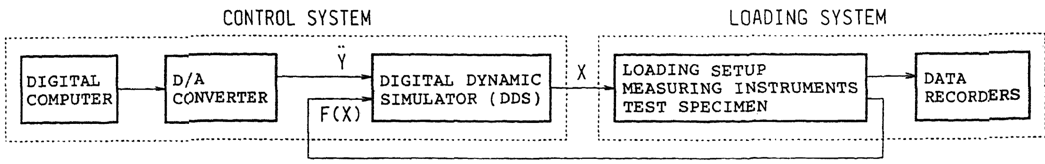

Fig. 1 Block Diagram of the Computer-Actuator On-Line Test System

The control system consists of a digital computer to store earthquake ground motions, the Digital Dynamic Simulator to solve differential equation and A/D and D/A converters.

This on-line test system has the following features;
(1) Logic of the Digital Dynamic Simulator is the same as that of an analog computer. Therefore, the numerical integration method, such as the linear acceleration method or the central difference method, needs not be used to solve the non-linear equation of motion, and the programing and input/output control are easy.
(2) As calculations are excuted in digtal manner in this Digital Dynamic Simulator, there is no drift and higher precision is obtained.

Detail of the control system of the on-line test developed by the authors is shown in Fig. 2. In this figure, "DYNAMIC LOADING SYSTEM" is used to control the on-line test, and "STATIC LOADING SYSTEM" to install a test specimen on the loading frame and to control monotonic loading test. An electro-hydraulic-servo-mechanism is utilized for the loading system.

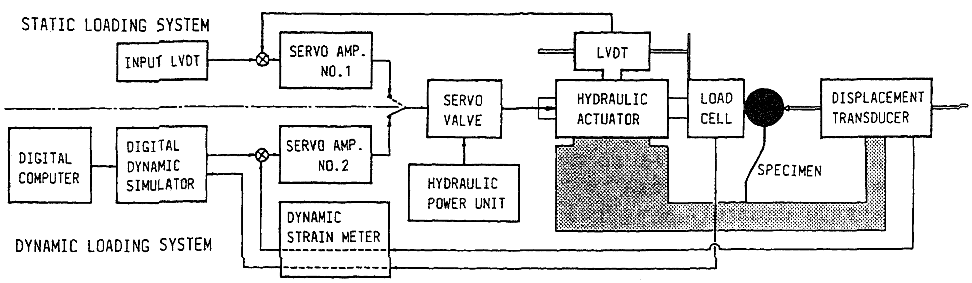

Fig. 2 Control System of the On-Line Test

In the on-line test, the specimen is assumed to be a shear-type single-degree-of-freedom system. Then the non-linear equation of motion is

$$m\frac{d^2x}{dt^2}+f(x)=-m\frac{d^2y}{dt^2} \tag{3}$$

where m = mass; x = response displacement; f(x) = non-linear restoring force; d^2y/dt^2 = input acceleration. In eq.(3), viscous damping is neglected because hysteretic damping is dominant in inelastic region. In this on-line test, eq.(3) can be solved by a conventional method used to obtain a solution of the differential equation with analog computer. The set-up diagram to solve Eq.(3) is shown in Fig. 3.

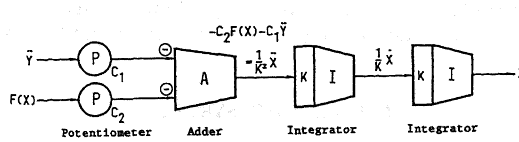

Fig. 3 Set-up Diagram of Analog Computer

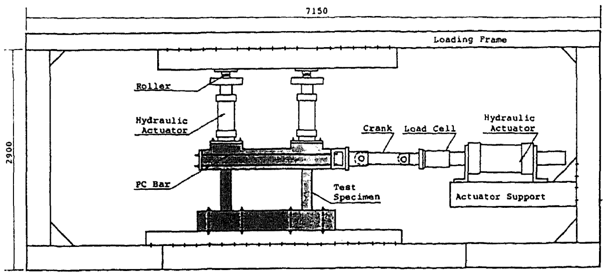

Fig. 4 Loading Setup

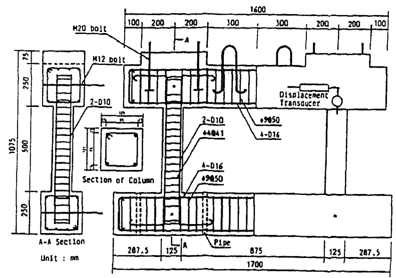

Fig. 5 Test Specimen

ON-LINE TEST

Loading setup is shown in Fig. 4. Using a horizontally load-applying actuator controled by the above-mentioned system, the test specimen receives the same displacement that is calculated with the Digital Dynamic Simulator. Simultaneously, two vertically load-applying actuators, which are set on the test frame, give constant axial loads to two columns. The on-line test is continued until either of the columns becomes unable to support the vertical load.

Using the above-mentioned on-line test system, the authors examined the earthquake responses of 17 one-bay, one-storied reinforced concrete frames with very stiff beams, as shown in Fig. 5, subjected to 5 real earthquake motions. Properties of reinforcing bars and concretes used for the test specimens are listed in Tables 1 and 2, respectively. One sixth of the axial load capacity, that is calculated from results of material tests, is adopted as the axial load of the column. The input earthquake motions are Taft 1952 NS, Sendai TH030 1978 NS, El Centro 1940 NS, SCT1850919BL(Mexico earthquake,1985) and Hachinohe 1968 NS. Each accerelogram is condensed to one half of the period of duration, taking the dimension of the test specimen into consideration, and its magnitude is decided by following equation:

$$|d^2y/dt^2|_{max} = \beta Q_y/m \qquad (4)$$

where β = input ratio; Q_y = yield strength. Considering a dominant period of each input earthquake motion, three or four natural periods are decided as that of the analizing model. The values of these parameters are tabulated in Table 3.

EXPERIMENTAL RESULTS

As an example of the experimental results, time history of displacement and hysteresis loop of RC-ON-12 are shown in Figs. 6 and 7, comparing with two kinds

Table 1 Properties of Reinforcing Bars

	Yield Strength $_s\sigma_y$ (t/cm^2)	Tensile Strength $_s\sigma_t$ (t/cm^2)
D10	3.78	5.65
ϕ 4	5.02	5.90

	Young's Modulus E_s (t/cm^2)	Elongation (%)
D10	2130	18.8
ϕ 4	2120	3.85

Tabel 2 Properties of Concrete

Specimen	F_c (kg/cm^2)	$N=\frac{1}{6}N_0$(t)	Qy(t)
RC-ON-1	463.0	13.6	9.7
RC-ON-2	368.0	11.0	8.7
RC-ON-3	270.2	8.7	7.6
RC-ON-4	578.1	16.6	10.9
RC-ON-5	248.5	8.1	7.5
RC-ON-6	170.8	6.2	6.7
RC-ON-7	295.7	9.4	8.1
RC-ON-8	293.6	9.3	8.0
RC-ON-9	257.2	8.4	7.4
RC-ON-10	313.6	9.8	8.0
RC-ON-11	347.0	10.7	8.4
RC-ON-12	285.3	9.1	7.7
RC-ON-13	333.8	10.3	8.3
RC-ON-14	217.7	7.3	6.9
RC-ON-15	280.4	9.0	7.7
RC-ON-16	280.7	9.0	7.7
RC-ON-17	215.1	7.3	7.0

F_c: Compressive Strength of Concrete
N_0: Axial Load Capacity N: Axial Load
$Q_y=4M_y/h=4/h\cdot\{g_1\cdot q+0.5\eta_0(1-\eta_0)\}F_c bD^2$

Table 3 Values of the Parameters of Analyzing Model & Earthquake Motion

Specimen	Natural Freq. T(sec)	Mass m ($\frac{kg\cdot sec^2}{cm}$)	Input Ratio β ($=\frac{m\ddot{z}_{max}}{Qy}$)	Analysis Max. Acc. $\ddot{z}_{max}$(gal)	Analysis Damage Factor	Experiment Max. Acc. $\ddot{z}_{max}$(gal)	Input Earthquake Motion
RC-ON-1	0.05	4.9	1.03	1364	0.63	2060	Taft 1952 NS
RC-ON-2	0.1	19.7	2.00	660	0.58	890	
RC-ON-3	0.3	177.3	6.18	226	0.60	270	
RC-ON-4	0.2	78.8	4.23	348	0.71	590	
RC-ON-5	0.05	4.9	1.05	1383	0.54	1569	Sendai TH030 1978 NS
RC-ON-6	0.1	19.7	0.95	313	0.60	312	
RC-ON-7	0.3	177.3	4.71	173	0.71	208	
RC-ON-8	0.2	78.8	2.25	185	0.80	223	
RC-ON-9	0.1	19.7	1.62	534	0.80	610	El Centro 1940 NS
RC-ON-10	0.2	78.8	3.61	298	0.85	366	
RC-ON-11	0.3	177.3	5.63	207	0.80	267	
RC-ON-12	1.0	1970.2	15.97	53	0.80	63	SCT1850919BL
RC-ON-13	0.5	492.5	2.47	33	0.80	41	
RC-ON-14	1.5	4432.9	31.92	47	0.80	50	
RC-ON-15	0.3	177.3	4.47	164	0.80	192	Hachinohe 1968 NS
RC-ON-16	0.5	492.6	10.67	141	0.80	166	
RC-ON-17	0.7	965.4	14.51	98	0.80	105	

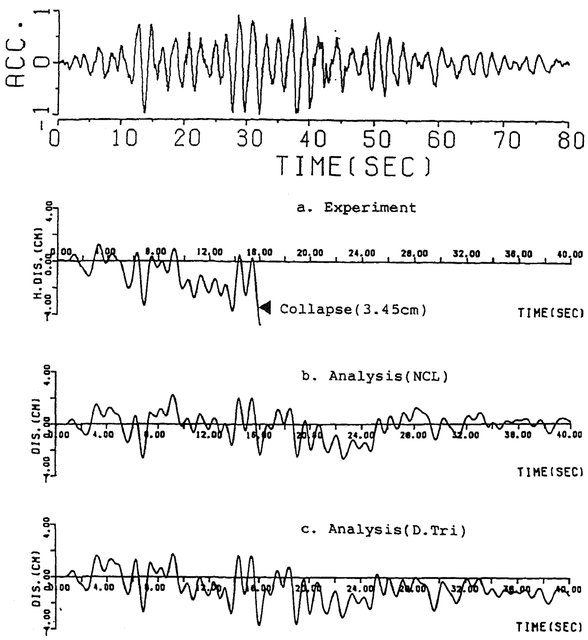

Fig. 6 Input Acceleration and Time History of Response (RC-ON-12, T=1.0sec)

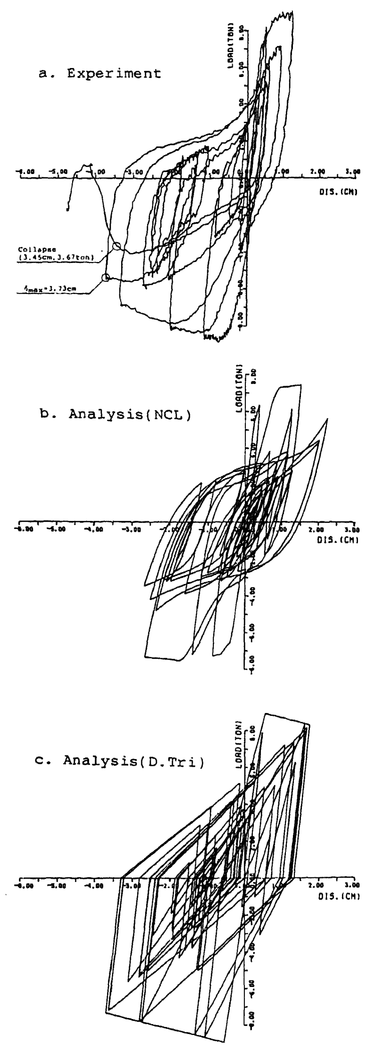

Fig. 7 Hysteresis Loops (RC-ON-12, T=1.0sec)

Table 4 Summary of Experimental Results

Specimen	Natural Freq. T(sec)	β $(=\frac{m\ddot{z}_{max}}{Q_y})$	Q_{max} (t)	δ_{max} (cm)	μ $(=\frac{\delta_{max}}{\delta_y})$	Damage Factor D.F	Damage Factor D.F'	E_t (t·cm)	Collapse Mode
RC-ON-1	0.05	1.03	10.9	3.68	9.2	1.114	←	258.4	S, F→B→SC→Bu
RC-ON-2	0.1	2.00	10.2	4.23	10.6	1.342	←	217.3	S, F→SC→Bu
RC-ON-3	0.3	6.18	8.7	2.41	6.0	1.580	0.569	74.5	S, F→SC→Bu
RC-ON-4	0.2	4.23	12.8	4.22	10.6	1.277	←	162.5	S, F→SC→Bu
RC-ON-5	0.05	1.05	9.3	4.96	12.4	1.468	←	230.0	S, F→B→SC→(Bu)
RC-ON-6	0.1	0.95	7.7	3.84	9.6	1.629	1.153	161.5	S, F→B→SC→LBu
RC-ON-7	0.3	4.71	10.0	3.38	8.4	0.994	←	115.7	S, F→SC→Bu
RC-ON-8	0.2	2.25	9.8	4.17	10.4	1.182	1.166	203.8	S, F→SC→Bu
RC-ON-9	0.1	1.62	6.6	4.19	10.5	1.881	1.190	104.1	S, F→(B)→SC→Bu
RC-ON-10	0.2	3.61	9.6	3.80	9.5	1.229	0.957	103.6	S, F→SC→Bu
RC-ON-11	0.3	5.63	10.7	4.89	12.2	1.196	1.137	98.9	S, F→(B)→SC→Bu
RC-ON-12	1.0	15.97	9.0	3.73	9.3	1.033	←	127.2	S, F→(B)→SC→Bu
RC-ON-13	0.5	2.47	9.2	3.35	8.4	1.326	0.980	225.0	S, F→B→SC→Bu
RC-ON-14	1.5	31.92	7.2	4.86	12.2	2.017	1.128	62.0	S, F→SC→Bu
RC-ON-15	0.3	4.47	9.6	5.00	12.5	2.234	1.416	139.7	S, F→B→SC→Bu
RC-ON-16	0.5	10.67	8.5	4.90	12.2	1.539	1.360	111.1	S, F→(B)→SC→Bu
RC-ON-17	0.7	14.51	7.9	5.11	12.8	1.250	←	69.5	S, F→B→SC→Bu

Et : Cumulative Hysteretic Energy

S : shear crack B : bond splitting failure
F : yield of longitudinal reinforcing bars
SC : shear compression failure
Bu : buckling of longitudinal reinforcing bars
LBu : lateral buckling

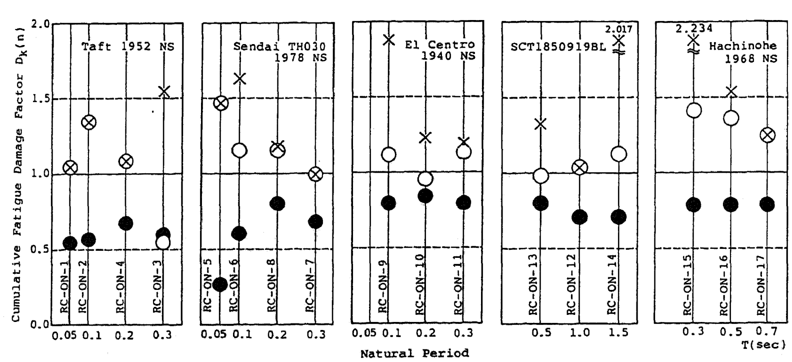

Fig.8 Distribution of Cumulative Fatigue Damage Factor $D_k(n)$

of analytical result. The natural period of this analizing model is 1.0 sec. and the input accelerogram is SCT1850919BL. In the on-line test, the maximum displacement, δ_{max}, was 3.73 cm and the collapse of the column was caused by the displacement of 3.45 cm at about 16 sec., as shown in Figs. 6a and 7a. Before the on-line tests, numerical earthquake response analyses of the structures with NCL type restoring force characteristics, which was assumed from results of the low-cycle fatigue tests of the same specimens (Ref. 3), were carried out in order to estimate the input ratio β. Additional numerical analyses using the degrading trilinear type restoring force characteristics, which is obtained from both the low-cycle fatigue tests and the on-line tests (Ref. 4), were performed after the on-line tests. From these figures, it is pointed out that: (1) Failure of reinforced concrete structure is not always due to first excursion. (2) The peak-occuring times in the time history of response displacement and the shape of the hysteresis loop of both analytical results are similar to the experimental results. (3) The latter analytical result can express the negative plastic flow which occured in the on-line test, but the former cannot.

Results of the on-line tests are tabulated in Table 4, and the distribution of the cumulative fatigue damage factor $D_k(n)$ is shown in Fig. 8. If the specimen don't collapse by the end of the input earthquake motion, the monotonic loading test is carried out to cause a collapse. In Fig. 8, ○ and × (or D.F.' and D.F. in Table 4) denote the experimental values of $D_k(n)$ at the end of the on-line test and at the moment of collapse, respectively, and ● means the analytical values of $D_k(n)$ at the end of the on-line test. From this figure, it is noted that : (1) The experimental values of $D_k(n)$ at the moment of collapse are distributed from 1.0 to 2.0 expect for two cases. (2) The analytical values of $D_k(n)$ are pretty smaller than the experimental ones. It means that the NCL type restoring force characteristics is not proper.

COMPARISON WITH OTHER DAMAGE FACTORS

Assuming that seismic structural damage is expressed as a linear combination of the damage caused by excessive deformation and that contributed by repeated cyclic loading effect, Park and Ang proposed the following damage factor D and D':

$$D=\frac{|\delta_{max}|}{\delta_F}+\frac{\alpha}{Q_y\cdot\delta_F}\int dE \qquad (5) \qquad \text{and} \qquad D'=\frac{|\delta_{max}|}{\delta_F}+\alpha\int\left(\frac{\delta}{\delta_F}\right)^{\beta}\cdot\frac{dE}{E_c(\delta)} \qquad (6)$$

in which Q_y = yield strength; $E_c(\delta)$ = hysteretic energy per loading cycle at deformation δ; α, β = non-negative parameters (Ref. 5).

Chung, Meyer and Shinozuka modified Miner's hypothesis with damage acceleration facter α_{ij} and proposed the following damage factor D_e (Ref. 6):

$$D_e=\sum_i\sum_j\left(\alpha_{ij}^{+}\cdot\frac{n_{ij}^{+}}{N_{fi}^{+}}+\alpha_{ij}^{-}\cdot\frac{n_{ij}^{-}}{N_{fi}^{-}}\right) \qquad (7)$$

In order to compare with the damage factor $D_k(n)$, the values of D, D' and D_e were calculated by using the results of the on-line tests. In this discussion, the authors deal with the results of the on-line test in which the specimen collapsed within the duration of the input earthquake motion. In Fig. 9a, the ultimate displacement δ_F is 4.56 cm, which was gained from monotonic loading tests, and,in Fig. 9b, δ_F is calculated by Park and Ang's formulation. In these figures, the calculated values of $D_k(n)$, D, D' and D_e are plotted by ○, △, ▲ and □.

In the case where δ_F = 4.56 cm (as shown in Fig. 9a), it is noted that: The values of $D_k(n)$ are distributed from 1.0 to 1.5 and its average value is 1.09. If the discussion is limited to these eight test specimens, $D_k(n)$ is good index to evaluate cumulative fatigue damage of reinforced concrete structure. The average values of D and D' are 2.04 and 1.88, respectively. The average value of D_e is

1.33, but the scattering is larger. If δ_F is calculated from Park and Ang's formulation(as shown in Fig. 9b), the values of D, D' and De become better;i.e.,the average values of D, D' and D_e are 0.87, 1.17 and 0.97,respectively, and the scatterings become smaller. However, the average value and the scattering of $D_k(n)$ don't get smaller.

CONCLUSIONS

From the results of the on-line test and the evaluation and the comparison of the cumulative fatigue damage factors reported in this paper, the following conclusions have been obtained:

1. The non-linear earthquake response of reinforced concrete frames can be analyzed realistically and easily by means of the computer-actuator on-line system utilizing the Digital Dynamic Simulator.
2. The analytical model with degrading tri-linear restoring force characteristics can provide more realistic earthquake response of reinforced concrete frames than that with NCL type restoring force characteristics.
3. The experimental values of $D_k(n)$ of collapse are distributed from 1.0 to 2.0, except for a few cases.
4. If δ_F is 4.56 cm, the damage factor $D_k(n)$ proposed by the authors is better index than others. However, if δ_F is calculated from Park and Ang's formulation, the values of damage factors D, D' and D_e becomes as better as $D_k(n)$.

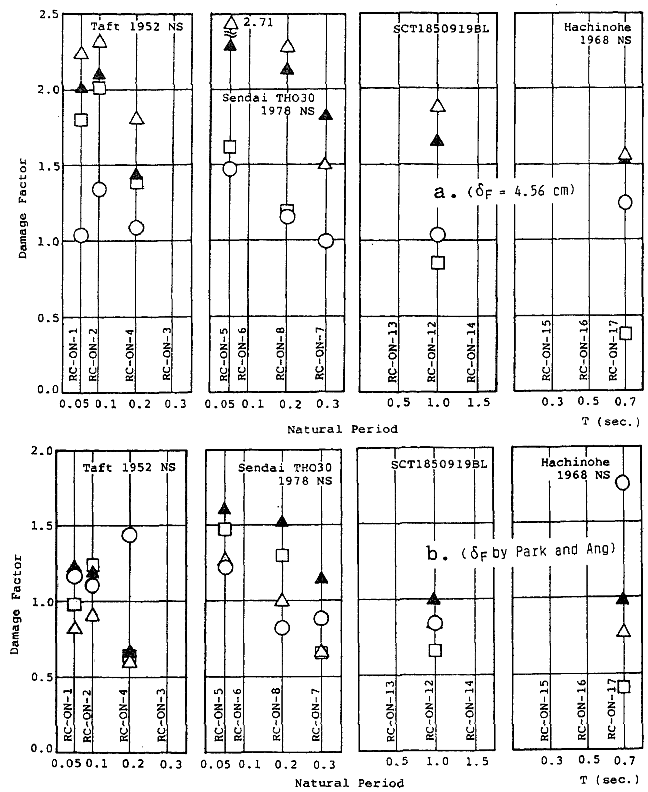

Fig. 9 Comparison of Cumulative Fatigue Damage Factors

REFERENCES

1. Nishigaki,T. and Mizuhata,K., "Experimental Study on Low-Cycle Fatigue of Reinforced Concrete Columns", Trans. of AIJ, No.328, 60-70,(1983),(in Japanese)
2. Mizuhata,K., Kusakabe,K., Maeda,Y., Kimpara,T., Inubushi,A. and Sugiyama,K., "Computer-Actuator On-Line Test of Structures by Digital Dynamic Simulator", Proceeding of the 8th Symposium on the Use of Computers in Building Engineering., 109-114, (1986), (in Japanese)
3. Nishigaki,T. and Mizuhata,K., "Evaluation of Seismic Safety for Reinforced Concrete Structures", Trans. of AIJ, No.332, 19-29, (1983), (in Japanese)
4. Mizuhata,K., Kusakabe,K., Maeda,Y. and Sugiyama,K., "Evaluation of Cumulative Damage Response of Structures by Computer-Actuator On-Line System", Proc.of the 7th Japan Earthquake Engineering Sympo., 1573-1578, (1986), (in Japanese)
5. Park,Y.-J. and Ang,A.H.-S., "Mechanistic Seismic Damage Model for Reinforced Concrete",ASCE, Journal of Structural Engrng., Vol.111, No.4, 722-739, (1985)
6. Chung,Y.S., Meyer,C. and Shinozuka,M., "Seismic Damage Assessment of Reinforced Concrete Members", Technical Report NCEER-87-, 1-82, (1987)