# A SIMULATION OF EARTHQUAKE RESPONSE OF REINFORCED CONCRETE BUILDINGS

by

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## SYNOPSIS

Nonlinear earthquake response of reinforced concrete one story building frames to a recorded ground motion was simulated by the computer-actuator on-line system and the results were compared with the computer simulation using the hysteretic loop developed by the authors; OS-Model, which considered the nonlinear stress-strain relationships of concrete and steel. Four frames of column yielding type having different natural periods were tested by the on-line system and one by cyclic loading test. The earthquake response obtained by the on-line test showed fairly good agreement with that by the computer analysis using the proposed analytical model.

## INTRODUCTION

In order to simulate the earthquake response of structures, the system for the dynamic testing; the computer-actuator on-line system, has been developed at the Institute of Industrial Science, University of Tokyo (1). This paper is concerned with the simulation of nonlinear earthquake response of reinforced concrete building frames by the on-line system and the computer simulation based on the analytical model, called OS-Model, for the restoring force characteristics derived from the assumed nonlinear stress-strain relationships of concrete and reinforceing steel (2).

## SIMULATION BY THE COMPUTER-ACTUATOR ON-LINE SYSTEM

Principle: A principle of the simulation by the on-line system is to solve a nonlinear differential equation for earthquake response by a digital computer taking into account the real restoring force characteristics obtained by the pseudo-dynamic loading test of the structural element or frame executed in parallel with the computation.

$$M \ddot{X}^i + F^i = -M \ddot{X}_o^i \qquad \cdots\cdots(1)$$

where, $M$ : Mass of the system
$\ddot{X}^i$: Relative acceleration of the system at i-th step
$F^i$: Restoring force at i-th step
$\ddot{X}_o^i$: Ground acceleration at i-th step

Frames and Test Specimens: Four frames of column yielding type; with strong and stiff beam, having different initial natural periods were analyzed (Table 1 and Fig.1). The mass of each frame was estimated using the natural period and the initial stiffness of the frame obtained by the cyclic loading test performed previous to the on-line test. Test specimens having the shear span of a half of the column height of the frame were used assuming the inflection point of the column was located at the mid-height. The detail of the specimen is shown in Fig.2 They were designed according to the AIJ Building Code (3) so that the shear failure did not occur prior to the

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flexural yielding. The reinforcing steels were welded to the end plates.

Loading System: Test setup is shown in Fig.3. Axial stress of 7.2 % of the concrete compressive strength was applied by an actuator beginning the test and kept constant during the test. Lateral force was applied by another actuator driven by the command from the computer. The test specimen could rotate freely at an end and rotate in sliding at another end.

Flow Diagram of On-line System: The flow diagram of the on-line system is shown in Fig.4. The computer system-I(Main) and the on-line system were used for the on-line simulation. A response displacement of the frame to the ground motion at a certain step was calculated and transformed to that of the specimen in the main system. The displacement was applied to the specimen through the D-A convertor and the restoring force was measured in the loading system. The measured force was returned through the A-D convertor to the main system and transformed to the restoring force of the frame. This procedure was repeated until the record of the ground motion was terminated.

Numerical Analysis: For numerical integration, the central difference method (Lumped-impulse method (4)) was used. However, since the method was not self-starting, the linear acceleration method was used until the response displacement reached at a certain limited value within linear range. The acceleration record of the Hachinohe 1968 (NS) was used for the ground motion. The duration time was 12 seconds with zero data at the last 2 seconds. The amplitude of the acceleration was modified so that the ratio of the lateral strength of the frame in terms of the base shear coefficient to the peak ground acceleration normalized by the acceleration of the gravity became constant (≒1.13) for all frames considering the results of the cyclic loading test (Table 1). The time interval for numerical integration was 0.01 second, however, the real time to execute a step of the on-line simulation was expanded to about 8 seconds to make the observation of the behavior of the specimen easy. A viscous damping was not considered.

SIMULATION BY THE OS-MODEL

Principle: A computer simulation using the analytical model for the restoring force characteristics was also done. The method consists of the computer system-I and the computer system-II of the flow diagram shown in Fig.4. The response displacement was transformed to the curvature at the critical section of the specimen; the face of the stub, and the bending moment was calculated based on the nolinear stress-strain relationships of concrete and reinforcing steel. The calculated bending moment was transformed into the restoring force of the frame and returned to the main system. The distribution of the curvature along the column length was assumed to be proportional to that of the bending moment except in the stub. The numerical analysis and the parameters in the main system were same as those for the on-line simulation.

Moment-Curvature Relationship: The critical section was divided into 15 concrete elements and 3 steel elements as illustrated schematically in Fig.5. The bending moment corresponding to the given curvature was calculated by the iteration method so that the strain compatibility of the elements and the equilibrium condition of the axial force were satisfied (2,5, 6). The error at each step in solving the equilibrium equation was less than 0.005 % of the applied constant axial load. The Ramberg-Osgood function (7) having $\alpha$ of 0.5 and $\gamma$ of 11 was used for the stress-strain relationship of the reinforcing steel (Fig.6). The assumed stress-strain relationship of concrete is shown in Fig.7. The envelop curve for the compressive stress was assumed to be the e-function (8) with a slight modification, where the relation was linear within a certain limit in the elastic range. The unloading rule was assumed to be linear. The stiffness degradation proportional to the stress degradation was considered beyond the maximum strength. The tensile strength was not considered in any range of the strain. The reloading rule was assumed to follow the unloading rule.

## RESULTS OF SIMULATIONS

Cyclic Loading Test: Lateral force vs. displacement relationships of the cyclic loading test (FD-6) are shown in Fig.8(a). The lateral force and displacement are transformed to the shear force of the column and the displacement of the frame, respectively. The skeleton curve could be modeled by a tetra-linear with three breaking points as shown in Fig.10. Three breaking points occurred at flexural cracking stage, yielding stage of the tensile reinforcements (first yielding) and yielding stage of the middle reinforcements (second yielding). Extension of flexural-shear crack was observed around the first yield point and the crush of concrete in compressive zone after the second yield point. Strength deterioration occurred during several cycles of the cyclic loading with the amplitude of twice of the second yield displacement ($\mu \fallingdotseq 2$) and then the hysteretic loop became almost stable. After the 51-st cycle, the displacement was increased to four times of the second yield displacement ($\mu \fallingdotseq 4$) and the cyclic load was applied . Concrete outside the core spalled, the compressive reinforcements took buckling and the column collapsed completely at the 54-th cycle. Thus, the displacement capacity of the column was evaluated between twice and four times of the second yield displacement.

The calculated response by the OS-model is shown in Fig.8(b). As recognized by the figures, the calculation predicted well the stiffness degradation due to cyclic loading and the good agreement between the test result and the calculated one was obtained in the first and second cycles, while further revision of the analysis would be needed to explain the strength deterioration at the peaks.

On-line Test: The hysteretic loops by the on-line test are shown in Fig.9. Their shapes are similar to that by the cyclic loading test. The maximum response displacements are shown in Table 2 and Fig.11. As expected, the maximum response in terms of the ductility ratio increased according to the decrease of the initial natural period. The maximum response ductility ratio was 2.32 which almost corresponded to the conservatively estimated deformation capacity by the cyclic loading test. Similar but less damage was observed by the on-line test than by the cyclic loading test.

The response obtained from the computer simulation by the OS-model are shown in Table 2 and Fig.11. The cpu time in executing the calculation of each frame by the FACOM 230-55 computer was about 20 minutes. The deviation between the test results and the analytical results was at most 3 % for FD-7 (0.6 sec.) and FD-10 (0.15 sec.) and around 20 % for FD-8 (0.4 sec.) and FD-9 (0.2 sec.). For the comparison, the examples of the calculations using more simple analytical models; Degrading Tri-linear model and Origin-Oriented model (9), are also shown in Table 2 and Fig.11. In determining the tri-linear curve, the equivalent tri-linear curve shown in Fig.10 by a broken line was adopted to simplify the tetra-linear skeleton curve. The tri-linear curve was determined so that the complementary energy at the second yield point became equal to that of the tetra-linear curve. Examples of the time history of the response shear force and the displacement (FD-9) are shown in Fig.12. It should be noted that the discrepancy between the test results and the calculated results is small, while the example has the worst correspondence of the maximum response displacements as shown in Table 2 and Fig.11.

## CONCLUDING REMARKS

Concluding remarks derived from the computer-actuator on-line simulation of the earthquake response and the computer simulation by the proposed OS-model are:

1) The developed on-line system appears to be useful for the nonlinear earthquake response analysis of the structures having complicated restoring force characteristics such as reinforced concrete buildings, and

2) The proposed analytical model;OS-model, is quite acceptable for the earthquake response analysis of reinforced concrete building frames, while the revision of the computer program is necessary to save computer time.

## ACKNOWLEGMENTS

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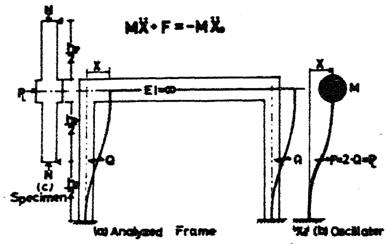



Fig.1 Frame & Specimen

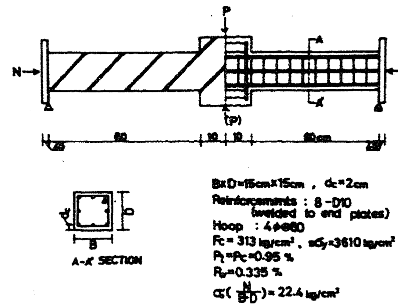



Fig.2 Detail of Specimen

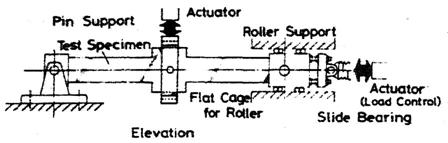



Fig.3 Test Setup

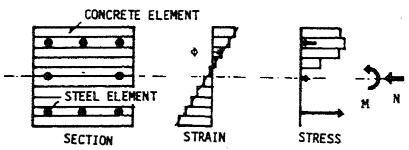



Fig.5 Stress & Strain of Section

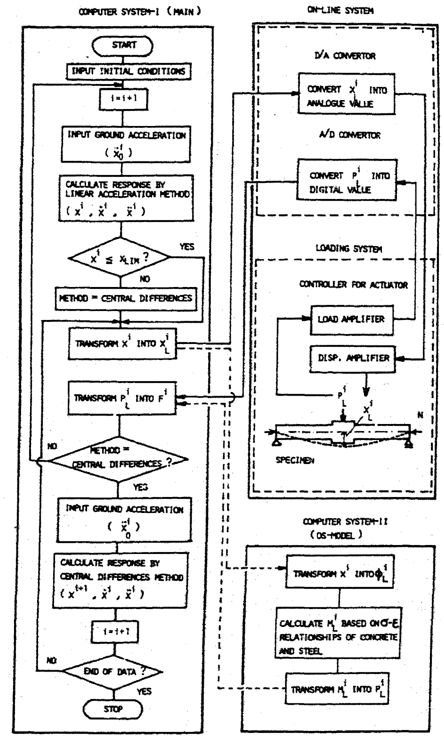



Fig.4 Flow Diagram of On-line System & Calculation by OS-Model

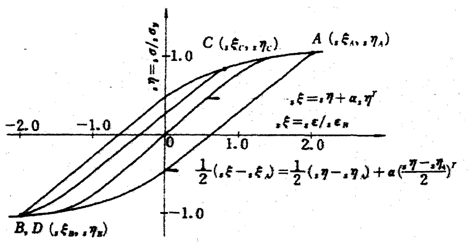


Fig.6 Stress-Strain Relationship of Reinforcing Steel

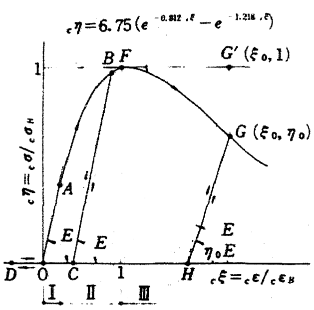
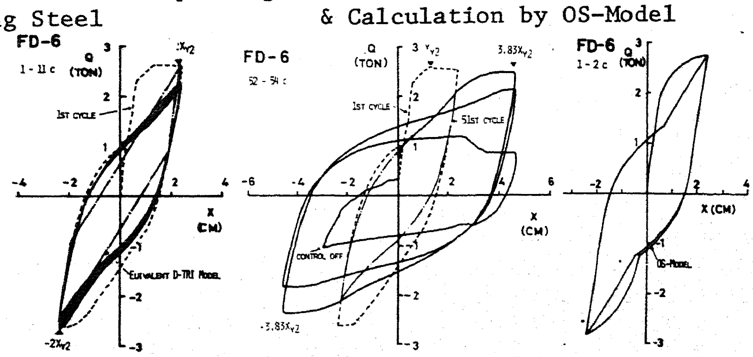


Fig.7 Stress-Strain of Concrete




(a) On-line Test (b) OS-Model

Fig.8 Shear Force vs. Disp. Relationship by Cyclic Loading

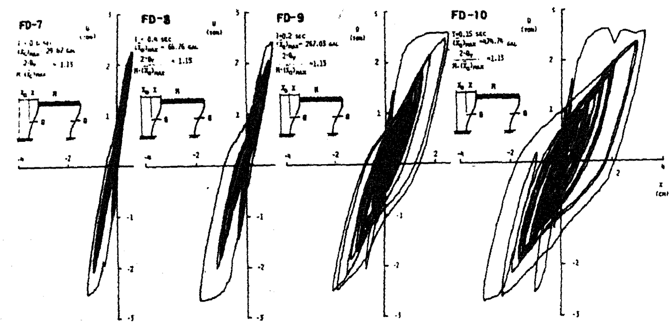



Fig.9 Response Shear Force vs. Displacement Relationships by On-line Test

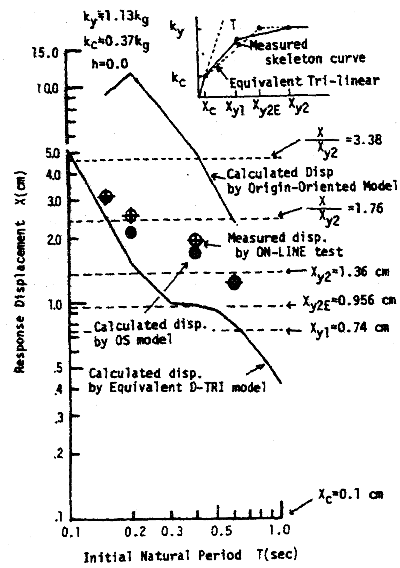



Fig.11 Response Spectrum

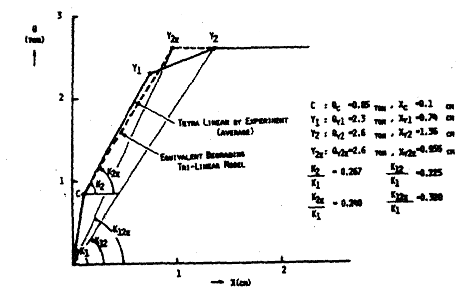
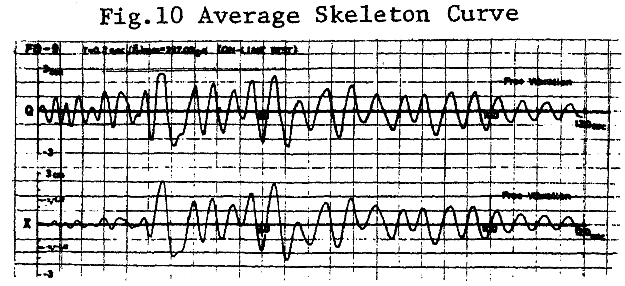
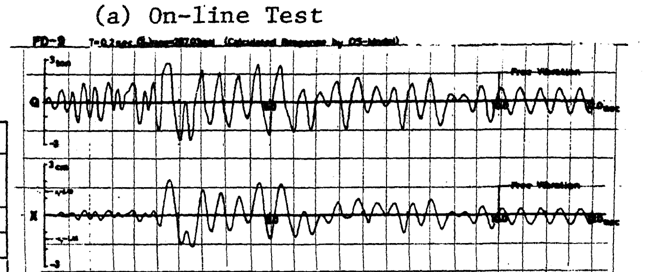


Fig.10 Average Skeleton Curve



(a) On-line Test



(b) Calculation by OS-Model

Fig.12 Response Shear & Displacement

Table 1 Frames & Ground Motion

| FRAME ID | INITIAL PERIOD T (SEC) | MASS M ($KG.CM^{-1}.SEC^2$) | PEAK GROUND ACCELERATION $(\ddot{X}_0)max$ (GAL) | $K_g = \frac{(\ddot{X}_0)max}{980}$ |
|---|---|---|---|---|
| FD- 6 | — | — | — | — |
| FD- 7 | 0.60 | 155.020 | 29.67 | 0.0303 |
| FD- 8 | 0.40 | 68.900 | 66.76 | 0.0681 |
| FD- 9 | 0.20 | 17.224 | 267.03 | 0.2725 |
| FD-10 | 0.15 | 9.688 | 474.74 | 0.4844 |

Table 2 Response Displacements of Frames

| Frame ID | Initial Period $T_1$ (SEC) | Cracking Stage $X_c$ (CM) | Yield Stage $X_{y1}$ (CM) | Yield Stage $X_{y2}$ (CM) | Maximum Response Displacement — On-Line Test: Displacement $X_{OT}$ (CM) | On-Line Test: Rotation Angle $R=X_{OT}/h_0$ | On-Line Test: Ductility Ratio $\mu=X_{OT}/X_{y2}$ | Calculation (CM): OS- Model $X_{OS}(X_{OT}/X_{OS})$ | Calculation (CM): D-Tri Model $X_{DT}(X_{OT}/X_{DT})$ | Calculation (CM): Origin-Oriented Model $X_{OO}(X_{OT}/X_{OO})$ |
|---|---|---|---|---|---|---|---|---|---|---|
| FD- 6 | - | 0.09 | 0.60 | 1.20 | Monotonic Loading | $X=2.4_{CM}$(R=0.020)<br>$X=4.6_{CM}$(R=0.038) | 1-51 cycle<br>52-54 cycle | - | - | - |
| FD- 7 | 0.6 | 0.09 | 0.74 | 1.40 | -1.23 | 0.010 | 0.88 | -1.20 (1.03) | -0.81 (1.52) | 2.30 (0.53) |
| FD- 8 | 0.4 | 0.10 | 0.64 | 1.40 | -1.93 | 0.016 | 1.38 | -1.65 (1.17) | -0.99 (1.95) | 4.87 (0.40) |
| FD- 9 | 0.2 | 0.12 | 0.82 | 1.40 | 2.54 | 0.021 | 1.81 | 2.10 (1.21) | 1.50 (1.69) | 13.14 (0.19) |
| FD-10 | 0.15 | 0.11 | 0.80 | 1.40 | 3.25 | 0.027 | 2.32 | 3.17 (1.03) | -2.58 (1.26) | -9.34 (0.35) |