PSEUDO-DYNAMIC TESTS ON A 2-STORY STEEL FRAME
BY COMPUTER-LOAD TEST APPARATUS HYBRID SYSTEM

by

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SUMMARY

Several examples of the non-linear earthquake response analyses have been reported in the previous papers(2,3), since the basic idea and the procedure on these analyses by the computer-load test apparatus hybrid system, so-called "on-line system", were described in the first paper(1). Here, some improvements in the system and the non-linear response analysis of a 2-story steel frame as a further example are demonstrated. This is the first application of the hybrid system to two degrees of freedom system structures.

INTRODUCTION

Non-linear restoring force characteristics such as bi-linear, tri-linear, Ramberg-Osgood type function etc. have been widely adopted as analytical models for the earthquake response analysis of structures, while the necessity to adopt more-realistic analytical models which can represent the stiffness and strength deterioration of structures during earthquake has been strongly recognized. However, it has been also recognized that even a complicated analytical model can hardly represent the real non-linearity of the structures which depends much upon a lot of uncertain factors such as non-linearity of materials, local failure, loss of stability, etc.

The authors have developed a non-linear earthquake response analysis method by the computer-load test apparatus hybrid system, so-called "on-line system", where the response calculations are carried out on the basis of real restoring force characteristics. The basic idea of the hybrid system is shown in Fig.1, comparing with the "pure" computer analysis based on assumed restoring force characteristics models. In the figure, the block diagram surrounded by the left dashed-line box shows the "pure" computer analysis widely used. On the otherhand, the fundamental flow of the procedure in the hybrid system (on-line system) can be expressed by the right dashed-line boxed diagram. There, the integration of the equation of motion is carried out by the computer also, but the restoring forces for the calculation are provided by the load test on the frame specimen identical to the frame analysed. The restoring forces are sensed during the test, controlling the test apparatus to impose the exactly same response displacements to the frame specimen as the calculating values. Therefore, it might be said that the assumption of restoring force characteristics is replaced by the load test in the hybrid system procedure.

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PROCEDURE OF THE HYBRID SYSTEM

Integration of Equation of Motion

To solve the equation of motion numerically, the open-type finite difference method is used. It is adequate to the hybrid system(on-line system), because this method does not require the stiffnesses of a frame, but the values of restoring forces directly. The accuracy in measurement of the restoring forces makes less effect on the accuracy of the solution than that of stiffness. Moreover, much advantage is recognized in the analysis of multi-story frames. The integration of each equation of motion of floors can be carried out independently by use of the finite difference method, otherwise these equations must be solved simultaneously.

The response values of the k-th floor in a multi-story frame can be obtained by integrating the equation of motion;

$$M_k\ddot{X}_k + F_k = -M_k\ddot{X}_o \tag{1}$$

in the computer for the given acceleration of a ground motion $\ddot{X}_o$, where M_k, X_k and F_k are the mass, the displacement at the floor level and the restoring force of the k-th floor, respectively. In general, the restoring force is a non-linear function of the displacement X_k and time t. Then the direct use of the restoring forces measured at the simultaneously running test can provide the real response of non-linear structures.

An incremental calculation for integration of Eq.1 is adopted. The simplest central difference method gives the following expression for the acceleration of the k-th floor, $\ddot{X}_k$:

$$\ddot{X}_k = (X_k^{i+1} - 2X_k^{i} + X_k^{i-1}) \ / \ (\Delta t)^2 \tag{2}$$

where Δt denotes the time increment and the superscript i denotes the variables at the time, $t=i\Delta t$. As an example, to solve Eq.(1) at the time, $t=i\Delta t$, is now considered. Eq.(1) can be solved and X_k^{i+1} can be calculated by use of Eq.(2) approximately, since F_k^i , X_k^i and X_k^{i-1} are already known. The response value at $t=(i+1)\Delta t$, X_k^{i+1} , is the input to the controller of the load test apparatus. The frame specimen is forced to change its deflection mode by this response displacement X_k^{i+1} at the k-th floor level. The reaction forces for these displacements are sensed by the load cells and converted into the restoring force F_k^{i+1} . Then, all jobs at $t=i\Delta t$ are completed. This procedure is continued successively.

In the case that the term of viscous damping must be included in Eq.1, the finite difference expression of velocity

$$\dot{X}_k^i = (X_k^i - X_k^{i-1}) \ /\Delta t + \ddot{X}_k^i \ \Delta t \tag{3}$$

is used. The velocity at time $t=i\Delta t$, $\dot{X}_k^i$, can be also calculated by the displacements and acceleration which are already known.

Control of Load Test

To apply the calculated response displacements as exactly as possible is the key to the success of this analysis. There is but little experience. Here, only a experience in the 1-bay, 2-story frame analysis can be described. For example, the procedure between $t=i\Delta t$ and $t=(i+1)\Delta t$ is discussed. The lower and upper floor displacements relative to the column base at $t=(i+1)\Delta t$, X_1 and X_2, are calculated by Eqs.1 and 2. Then, the increments of these displacements at this step, ΔX_1^0 and ΔX_2^0, are known, which determine the loading path in X_1 $-X_2$ plane as shown in Fig.2. The displacements imposed to the frame specimen are controlled along the path. If the displacement increment is too large to drive the testing machine smoothly without any shock and disturbance, the increment must be divided into smaller increments, each of which is given to the frame specimen at a moment. In the analysis described later, the small amount of displacement, a(=0.5mm in the following analysis), is defined beforehand as a scale unit, which governs the increment at a moment. The increment of the lower floor at a moment is;

$$\begin{array}{lll} (1)\ a & \text{for} & \Delta X_1^j \geq a \\ (2)\ a/2 & \text{for} & a > \Delta X_1^j \geq a/2 \\ (3)\ \Delta X_1^j & \text{for} & a/2 > \Delta X_1^j \end{array} \qquad (4)$$

where ΔX_1^j is the remaining displacement to be supplied as shown in Fig.2. The increment of the upper floor must be always multiplied by $\beta(=\Delta X_2^0/\Delta X_1^0)$.

The preciseness of control depends mainly on the elements of the system. So, it cannot be discussed in general. It should be only noted here that the following tolerance in the displacements is permitted in the case of the 1-bay, 2-story frame analysis:

$$\begin{array}{lll} |\Delta X_{1,2}^j / X_{1,2}| \leq 1/200 & \text{for} & X_{1,2} \leq 0.4\text{cm} \\ |\Delta X_{1,2}^j| < 0.002\text{cm} & \text{for} & X_{1,2} > 0.4\text{cm} \end{array} \qquad (5)$$

Time Increment

It is well known that an adequate time interval is required in the numerical integration of Eq.1, and it must be determined on the basis of the natural periods of structures analyzed. In the hybrid system (on-line system) the time increment can be determined in the same manner, but an additional limitation must be taken into consideration from the viewpoint of performance of the load test. In the analysis described later, 0.01 sec. is used for the time increment, Δt. This time increment is not sufficiently small for compared with the period for 2nd mode of the frame analysed. However, the error caused by the response of 2nd mode can be negligible for the 1st mode in the elastic response.

LOAD TEST

Frame Specimen and Test Set-up

The load test on a frame specimen is carried out to obtain the restoring force characteristics for use of response analysis. The load test is completely controlled by the computer linking to the response calculation. The frame specimen and the general test set-up are shown in Fig.3. The frame specimen is a set of identical rigid frames of H-shaped columns of H-150X150X7X10 (SM50 steel) and beams of H-200×100×5.5×8 (SM41 steel). A set of the frames separated by a space of 70cm is placed in parallel on the anchor beams, in order to avoid premature out-of-plane buckling failure. The calculated displacements X_1, X_2 at the lower and upper floor levels are imposed by the actuators (fully automatic controlled hydraulic jacks) through the loading beams pinned at the centers of the beams. The restoring forces F_1 ,F_2 at the floor levels are measured by the load cells. The displacements at the floor levels measured by transducers and strain gage type displacement meters.

Initial Stiffness of the Frame Specimen

The initial stiffness of the frame was estimated by the results of static load tests within elastic range, i.e.

$$\begin{Bmatrix} F_1 \\ F_2 \end{Bmatrix} = \begin{bmatrix} 31.37 & -14.76 \\ -14.76 & 10.84 \end{bmatrix} \begin{Bmatrix} X_1 \\ X_2 \end{Bmatrix} \quad \text{(unit: t/cm)} \tag{6}$$

Firstly, the obtained stiffness was used for the elastic response calculation in the beginning of the analysis, since the central difference method adopted in the hybrid system is not a self-starting manipulation. The response values at the first step of time interval must be calculated by an another method, say, the linear acceleration method with the initial stiffness. Practically, this booster calculation was continued until the upper floor level displacement reached 3mm. The second use of the stiffness is to make the modal vectors in conjuction with the masses assumed later. The modal vector will be a tool for data processing.

INPUT DATA FOR ANALYSIS

Assumed Mass

The mass of the frame can be assumed arbitrarily. In fact, there is no weight on the frame specimen. In this example, the equal amount of masses at the two floor levels is assumed from the weights which would exist on the floors if the members were designed in accordance with a traditional allowable stress design method. Then,

$$[M] = \begin{bmatrix} 0.01453 & 0 \\ 0 & 0.01453 \end{bmatrix} \quad \text{(unit: t sec}^2\text{/cm)} \tag{7}$$

Natural Periods and Modal Vectors

The natural periods and the corresponding modal vectors can be calculated from Eqs.6 and 7.

Natural periods

$$T_1 = 0.4283 \text{ sec}, \qquad T_2 = 0.1211 \text{ sec} \tag{8}$$

Modal vectors

$$\{\phi_1\} = \begin{Bmatrix} 0.5226 \\ 1.0 \end{Bmatrix} \qquad \{\phi_2\} = \begin{Bmatrix} -1.914 \\ 1.0 \end{Bmatrix} \tag{9}$$

where the subscripts, 1,2 denote the 1st and the 2nd mode, respectively.

Ground Motion

The ground motion used in the analysis is a part of the acceleration record at Hachinohe in the 1968 Tokachi-oki earthquake, which includes the maximum value of acceleration, $\ddot{X}_0max$=248.33gal as shown in Fig.4. Its duration time is 8 sec. The analysis comprises three cessions: Run A-1, Run A-2 and Run A-3. The maximum accelerations in the cessions are listed below:

$$\begin{array}{ll} \text{Run A-1} & A1 = 0.25\ddot{X}_0max = 0.177\ \alpha_Y \\ \text{Run A-2} & A2 = 1.0\ddot{X}_0max = 0.706\ \alpha_Y \\ \text{Run A-3} & A3 = 1.5\ddot{X}_0max = 1.06\ \alpha_Y \end{array} \tag{10}$$

where α_Y denotes the yield acceleration which is defined as (base shear/ total mass) of the statically deformed frame in the same mode as the 1st mode of vibration. The free vibration during 1 sec. follows after the ground motion.

RESULTS OF ANALYSES

Results of Elastic Response Analysis

The 1st mode response displacement is presumed dominant from the Fourier spectrum of response displacement, A-1, in Fig.5. Therefore, the results of the elastic response analysis are transformed to the normal-coordinate generalized amplitude, q_1, and the normal-coordinate generalized restoring force, R_1, by the following equations:

$$q_1 = \frac{\{\Phi_1\}^T[M]\{X\}}{\{\Phi_1\}^T[M]\{\Phi_1\}} \tag{11}$$

$$R_1 = \{\Phi_1\}^T\{F\} \tag{12}$$

where $\{X\} = \{X_1, X_2\}^T$ and $\{F\} = \{F_1, F_2\}^T$, which are obtained by the hybrid (on-line) analysis.

The time history of q_1 and the R_1 - q_1 relation are shown in Figs.6 and 7. The R_1 - q_1 relation is almost expressed as a straight line, but very narrow hysteresis loops are observed. The reason why the hysteresis loops exist is supposed local tiny yielding in some places. The narrow hysteresis loops cause a small damping which reduces the response displacement in the free vibration after 8 sec. as recognized in Fig.6.

Comparison with the results of "pure" computer analysis

In order to examine the reliability of the hybrid (on-line) system, the above mentioned results by the system must be compared with the results of the "pure" computer analysis for the same frame, where the initial stiffness, Eq.6, the masses, Eq.7, and the same recorded ground acceleration in Fig.4 with the maximum acceleration value, A1, in Eq.(10) were used. Moreover, the small damping observed in the result of the hybrid analysis was also considered. The time history of q_1 by the "pure" computer analysis is shown in Fig.8. The coincidence in the results by those two analyses is considered pretty good.

Results of Inelastic Analysis

As an example of inelastic analyses by the hybrid system, the results of Run A-3 in Eq.10 are shown in Figs.9 to 12. The yielding due to response is not so large as recognized that the ductility ratios $\Theta max/\Theta_p$ is around 2.5 after the M/M_p-Θ/Θ_p loops at the lower beam end in Fig.12, where M_p is the full plastic moment of the beam and Θ_p is the end rotation angle corresponding to M_p .

CONCLUSIONS

The conclusions of this investigation can be summarized as follows:

1. The response analysis of 2-story frames (two degrees of freedom) can be carried out by the computer-load test apparatus hybrid (on-line) system. The elastic response analysis described in this paper shows enough

reliability. The results by the hybrid system shows pretty good coincidence with the results by "pure" computer analysis for the same frame.

2. The application of the hybrid (on-line) system is realized to be extended to more than 2 degrees of freedom system in principle. Further examinations are, however, required on preciseness in controlling the load test and accuracy of measurement of loads and displacements, and on the loading path in the multi-dimensional displacement vector space.

3. The finite difference method used in the analysis is appropriate to the hybrid (on-line) system. There, the restoring forces can be directly used in numerical integration of the equation of motion, Eq.1. This manipulation is to a great advantage for accuracy of analysis.

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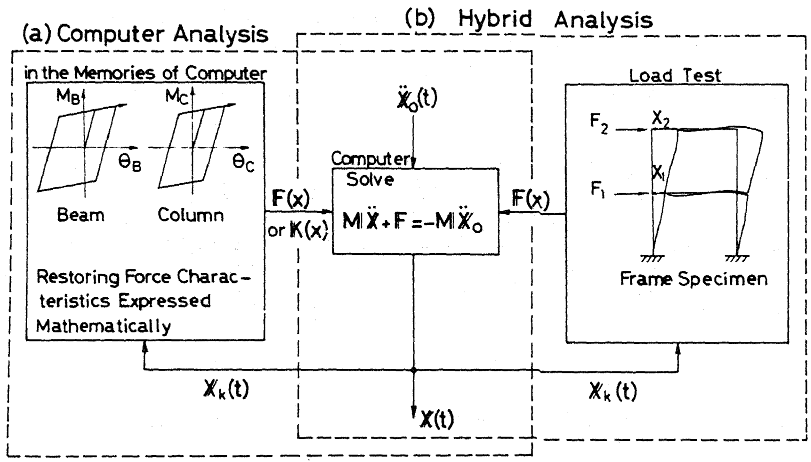

Fig.1 Computer analysis and hybrid analysis

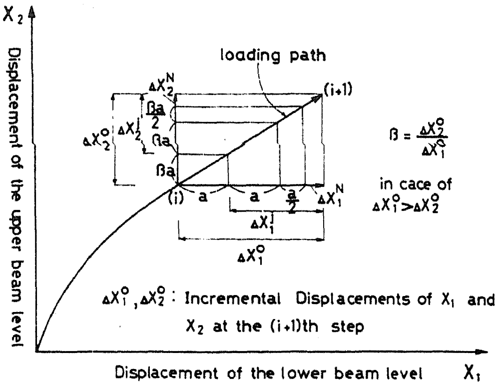

Fig.2 Control procedure of displacement

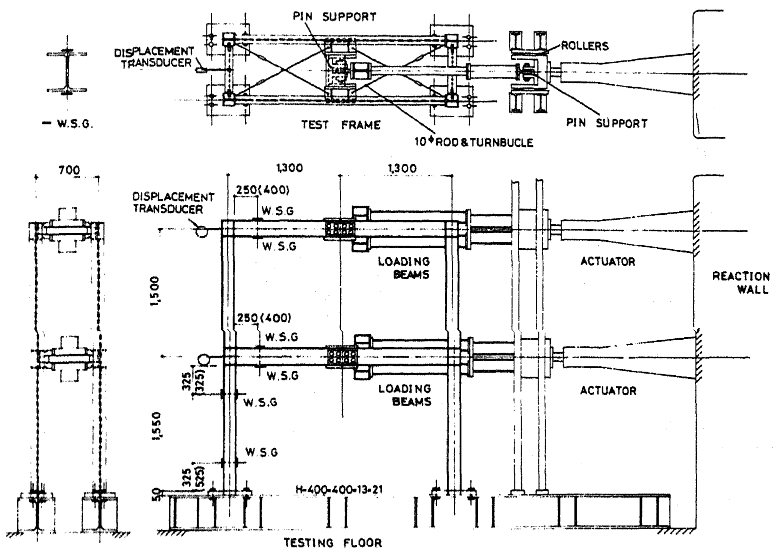

Fig.3 Frame specimen and general test set-up

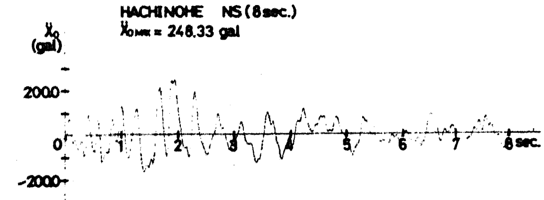

Fig.4 Ground acceleration used in the analysis

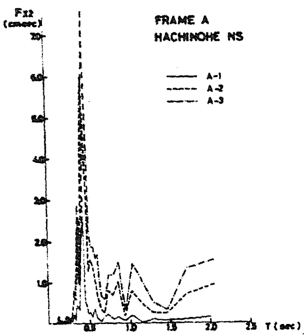

Fig.5 Fourier spectra of X_2

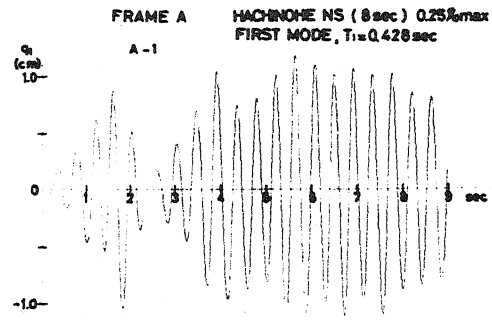

Fig.6 Time history of q_1 by the hybrid system

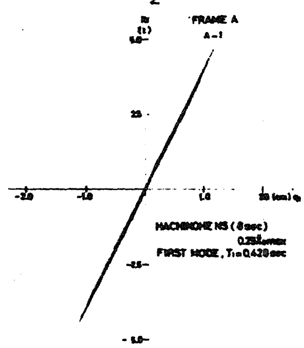

Fig.7 $R_1 - q_1$ relation

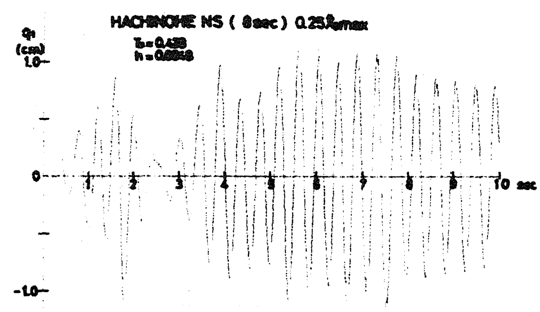

Fig.8 Time history of q_1 by the "pure" computer analysis

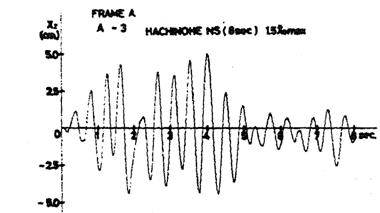

Fig.9 Time history of X_2 in the inelastic response

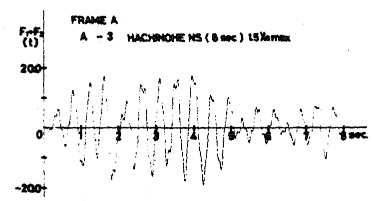

Fig.11 Time history of base shear in the inelastic response

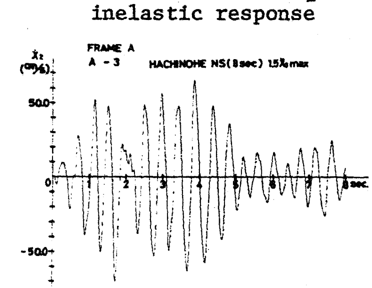

Fig.10 Time history of $\dot{X}_2$ in the inelastic response

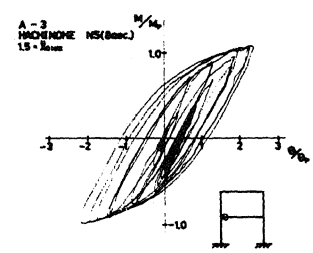

Fig.12 M-Θ relation at the lower floor beam end