EARTHQUAKE RESPONSE ANALYSIS OF STEEL STRUCTURES BY RAPID COMPUTER-ACTUATOR ON-LINE SYSTEM

(1) A Progress Report

Trial System and Dynamic Response of Steel Beams

by

Koichi TAKANASHI I), Kenichi OHI II)

1. INTRODUCTION

The technique of non-linear response analysis by a computer-actuator on-line system, which was developed by the researchers of the Institute of Industrial Science, University of Tokyo[1][2], has been widely accepted as a significant means to simulate earthquake responses on the basis of the real behaviours of the structures and structural members.

The response speed simulated by the above system, however, has remained in quasi-static range in comparison with the actual response speed. For example, an equation of motion for a structure of single degree of freedom is expressed as follows:

$$M\ddot{x} + F(x, \dot{x}) = -M\ddot{x}_0 \tag{1}$$

where M: the mass of the structure
x: the response displacement
$\dot{}$: time derivative
$\ddot{x}_0$: ground acceleration

In general the restoring force F depends on the history of both the response displacement and velocity in the wide sense. In the preceding computer-actuator on-line system, a quasi-static loading test is carried out to measure the restoring force F, and eq.(1) is replaced by the following equation:

$$M\ddot{x} + F(x, \dot{x} \simeq 0) = -M\ddot{x}_0 \tag{2}$$

It is very important to verify the validity of the above analysis based on the quasi-static test procedure by making comparison with the dynamic test results. On this purpose the authors have intended to improve the above system, so that structural responses can be simulated as near as possible in the actual response speed. This paper describes an outline of the first trial system, namely the *rapid* computer-actuator on-line system, and also demonstrates the dynamic responses of inelastic steel beams simulated by the system.

I) Professor, II) Research Associate of Institute of Industrial Science University of Tokyo

2. DESCRIPTION OF THE SYSTEM

2.1 NUMERICAL INTEGRATION

In the computer-actuator on-line system the equation of motion is numerically integrated in step-by-step manner using the restoring force measured in a loading test, which is carried out in parallel with the computation:

$$M \ddot{x}_i + F_i = - M \ddot{x}_{0i} \tag{3}$$

where subscript i: the step number of numerical integration

Newmark β method is expressed by the following two relations:

$$\dot{x}_{i+1} = \dot{x}_i + 0.5 \ddot{x}_i \Delta t + 0.5 \ddot{x}_{i+1} \Delta t \tag{4}$$

$$x_{i+1} = x_i + \dot{x}_i \Delta t + (0.5 - \beta) \ddot{x}_i (\Delta t)^2 + \beta \ddot{x}_{i+1} (\Delta t)^2 \tag{5}$$

where Δt : the time increment of each step
β : the parameter introduced by N.M.Newmark[3]

Considering that eq.(3) is satisfied at each step, eqs. (4) and (5) are modified into the following recurrence formula:

$$\begin{aligned} x_{i+1} &= 2 x_i - x_{i-1} \\ &- (\Delta t)^2 \Big[\beta \Big(\ddot{x}_{0i-1} + \frac{F_{i-1}}{M} \Big) \\ &+ (1 - 2 \beta) \Big(\ddot{x}_{0i} + \frac{F_i}{M} \Big) + \beta \Big(\ddot{x}_{0i+1} + \frac{F_{i+1}}{M} \Big) \Big] \end{aligned} \tag{6}$$

When the test procedure is completed to the i-th step, only the term F_{i+1} is unknown yet in the right side of eq.(6). If no attempt is made to extrapolate F_{i+1}, the value of β should be set to zero; the next displacement x_{i+1} can be calculated by:

$$x_{i+1} = 2 x_i - x_{i-1} - (\Delta t)^2 \Big(\ddot{x}_{0i} + \frac{F_i}{M} \Big) \tag{7}$$

Eq.(7) is also obtained by substituting the central difference approximation for $\ddot{x}_i$ in eq.(3). This method of integration, Newmark β method with zero β, is adopted both in the quasi-static system and also the *rapid* system reported herein.

2.2 CONTROLLING OF STRUCTURAL DISPLACEMENT

The principal difference between the *rapid* and the preceding system is the condition to complete the controlling of the structural displacement in each step. As for the preceding system, the following condition is adopted to complete the (i+1)-th step controlling:

$$\left| x_{ci+1} - x_m \right| \leqq e \tag{8}$$

where x_{ci+1} : the (i+1)-th step displacement calculated from eq.(7).

x_m : the structural displacement measured consecutively.
e : the upper limit of admissible errors

In the *rapid* system, the following condition is adopted:

$$(x_{ci+1} - x_{ci}) (x_m - x_{ci+1}) \geqq 0 \tag{9}$$

In other words, the overshooting of structural displacement is permitted in the *rapid* system.

2.3 TEST PROCEDURE

The block diagram of the *rapid* system is shown schematically in Fig.1. The test procedure is carried out in the following way:

(a) At the beginning of the (i+1)-th step controlling, the command signal increment to actuator is set to the value, $\gamma\ (x_{ci+1} - x_{mi})$, where
  γ : a parameter kept constant for a overall test procedure
  x_{ci+1} : the i+1-th step calculation displacement to be attained
  x_{mi} : the structural displacement measured immediately after the completion of the i-th step controlling

(b) The structural displacement x_m is measured consecutively, and at the same time, the above command signal increment is added to the preceding signal every constant time split, until the condition (9) is satisfied.

(c) Immediately after the condition (9) is satisfied, the structural displacement x_{mi+1}, the restoring force F_{i+1}, and other data are obtained. In the strict sense F_{i+1} is not the restoring force corresponding to x_{ci+1}, but it can be regarded as an approximation for the restoring force so long as the overshooting is small.
The (i+2)-th displacement is calculated by:

$$x_{ci+2} = 2\ x_{ci+i} - x_{ci} - (\Delta t)^2 \left(\ddot{x}_{0i+i} + \frac{F_{i+i}}{M} \right) \tag{10}$$

3. DYNAMIC RESPONSE OF FRAMES WITH INELASTIC STEEL BEAMS

3.1 ANALIZED FRAME AND TEST BEAMS

The analized frames are portal frames with pinned feet, shown in Fig.2 (1). The columns are idealized entirely rigid, while the beams behave elastically and also inelastically. In order to evaluate the end moment versus end rotation relationship, the simple beam tests were carried out as shown in Fig.2(2) and Fig.3. The natural period is set to 0.5 sec or 0.3 sec a priori, and the ground motion recorded at El Centro in 1940, the N-S component, was chosen for the input excitation of 8 seconds. In addition the free vibration of 2 seconds after the excitation was simulated in the test procedure.

The time in the computation is denoted by t_c , but the actual time measured in the test procedure is denoted by t_m . It is desirable that the ratio of t_m/t_c approaches to 1.0, but the observed smallest value of t_m/t_c is 4.4 in the tests reported herein, because there are restrictions on the operating speed of the computer and the setting time of the converters.

Three frames, coded as A, B, and C in Table 1, are analyzed and the test beams have the same section of H.200 × 100 × 5.5 × 8. Before the on-line tests, dynamic tension tests and bending tests were carried out with test pieces to investigate mechanical properties of steel material used. The results are summarized in Table 2 and Fig.4. It is observed that the increasing of the strain rate causes the increase of the yield stress[4] [5].

3.2 TEST RESULTS

(a) Elastic Response

The elastic response results of the frame B are shown in Fig.5. The response speed in the test BE2 is 5.5 times greater than that in the test BE1, and correspondingly the peak response in the test BE2 is mitigated in comparison with the test BE1. Besides elastic strain energy steel frames dissipate some of energy due to miscellaneous damping effects, which are often modelled as a viscous damping. These damping effects are underestimated in the slow test BE1.

(b) Inelastic Response

It is reported that most of energy absorption in the inelastic response of steel frames are made by the hysteresis and the viscousity of structural members plays small roles. Two inelastic response results, the *slow* test AP and the *rapid* test BP, are compared in Figs. 6. It is obserbed that the restoring force under the high response speed tends to exceed that of the slow test. This phenomenon can be explained by the property of the yield stress shown in Fig.4. However, there is no significant difference in overall trends of the two response behaviours.

Furthermore, a large inelastic deformation of the frame under earthquakes was simulated in the test CP. The ratio t_m/t_c in the test CP is 5.4. The F_i-x_{mi} relstionship and the F_i-x_{ci}relationship are compared in Fig.7. The F_i- x_{mi} relationship can be regarded as the actual restoring force characteristics of the test frame, while the F_i- x_{ci} relation are used in the computation. It is found that the difference between the two restoring force characteristics, due to the overshooting of displacements, is small enough to be igored in practival use.

4. CONCLUDING REMARKS

A trial *rapid* computer-actuator on-line system has been developed, by which inelastic response analysis can be carried out in parallel with the dynamic loading test on structural models. This system has been proved to provide an effective alternative to investigate the structural responses, which depend on the response speed. As demonstrated in chapter 3, about one-fifth of actual response speed has been successfully reached in the beam tests. This suggests that a computer-actuator on-line system will have a enough potential to simulate structural responses in the actual speed as a shaking table test does, if the restrictions on the computation speed and other instrumentations are removed.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support of the Ministry of Education, Japanese Government, Grant in Aid for Scientific Research, No.57850186, which made this work possible. Also the authors would like to express their appreciation to Prof. K.Udagawa, Mr.Y.Shimawaki, and Mr.H.Kondo for their supports during this study.

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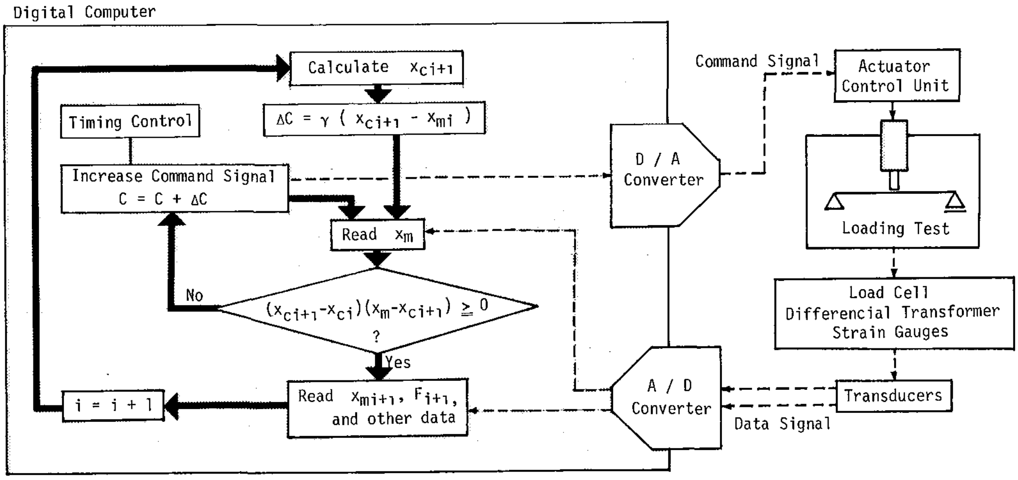
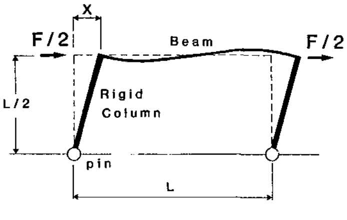
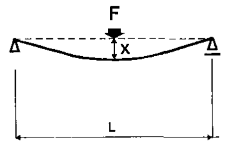


Fig.1 BLOCK DIAGRAM OF *RAPID* COMPUTER-ACTUATOR ON-LINE SYSTEM



(1) Analized Frame



(2) Simple Beam Test

Fig.2 ANALIZED FRAMES AND TEST BEAMS

Table 1 SUMMARY OF ON-LINE TESTS

Frame Code	Test Code	t_m/t_c	$\ddot{x}_{0max}$	k_e	M	T	x_{max}	
A	AP	24.0	320.0	8.0	0.05066	0.5	4.66	-3.48
B	BE1	22.0	25.6				0.58	-0.53
	BE2	5.2	25.6				0.50	-0.44
	BP	4.4	320.0				4.69	-3.31
C	CP	5.4	960.0		0.01824	0.3	4.41	-9.29

$\ddot{x}_{0max}$: Peak Amplitude of Input Excitation (cm/sec^2)
t_m : Actual Time t_c : Time in Computation
k_e : Elastic Stiffness Measured (ton/cm)
M : Mass in Computation (ton·cm/sec^2)
x_{max} : Peak Displacement Response in Computation (cm)
T : Natural Period in Computation (sec)

Table 2
MECHANICAL PROPERTIES
OF STEEL MATERIAL USED

	Tension Test			Bending Test	
	$\dot{\varepsilon}$	σ_Y	σ_B	$\dot{\varepsilon}$	σ_Y
Flange Material	22*	3.12	4.44	68	3.12
	330	3.34	4.51	68	3.17
	350	3.27	4.49	690	3.30
	2800	3.56	4.66	650	3.39
	2900	3.68	4.69	17000	3.77
				17000	3.91
Web Material	12*	3.82	4.82	48	3.97
	58	3.84	4.85	48	4.06
	410	4.17	4.98	12000	4.25
	3000	4.50	5.19	12000	4.62
	3900	4.55	5.35		
	4300	4.32	5.08		

$\dot{\varepsilon}$: Strain Rate (μ strain/sec)
σ_Y : Yield Stress (ton/cm^2)
σ_B : Tensile Strengtn (ton/cm^2)
* : regarded as Quasi-static in Fig.4

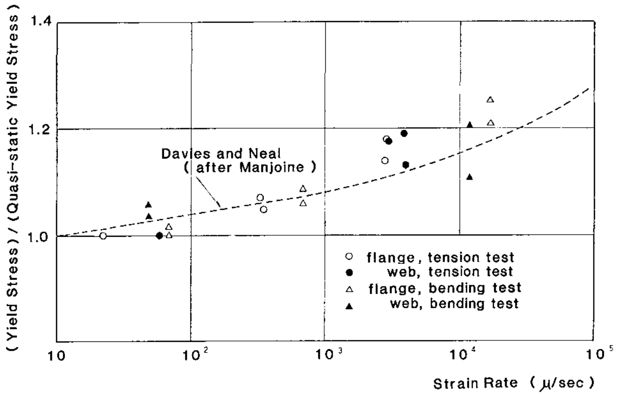
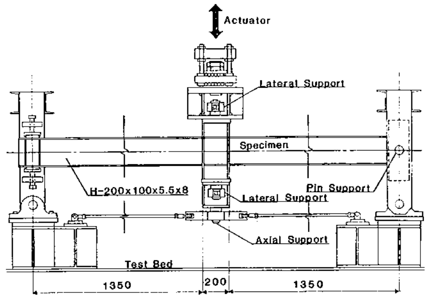
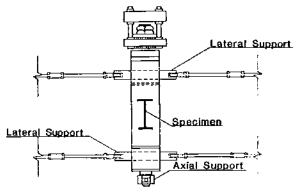


Fig.4 INCREASE OF YIELD STRESS DUE TO STRAIN RATE



(1) Front Elevation



(2) Side View

Fig.3 TEST SETUP

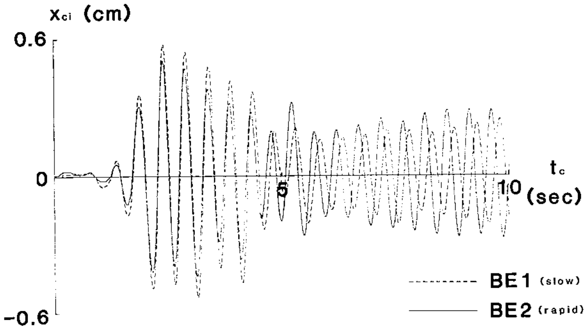
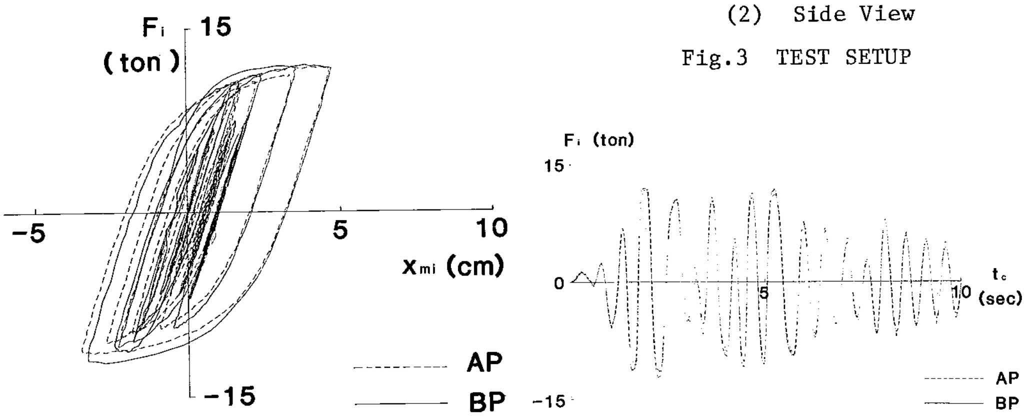
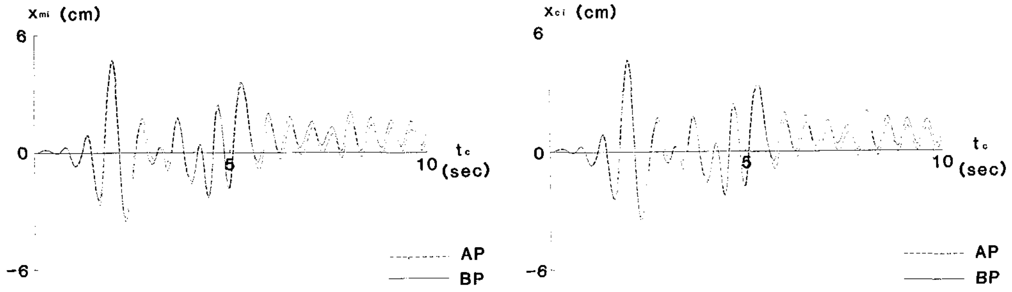


Fig.5 EFFECTS OF TEST SPEEDS ON ELASTIC RESPONSES (TEST BE1 AND BE2)



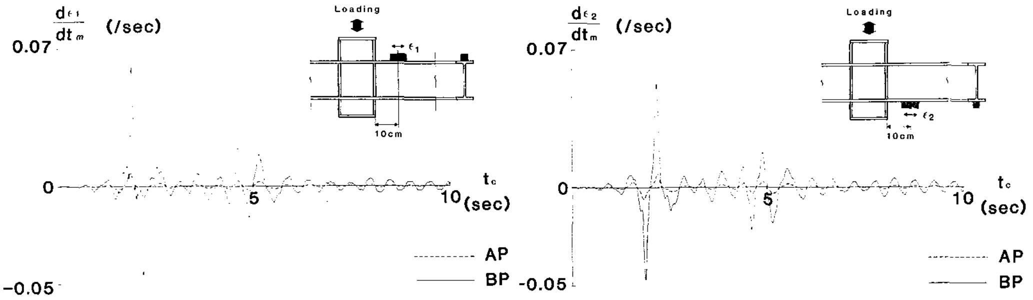
(1) Hysteresis Loops
(2) Time Histories of Restoring Forces

Fig.6 EFFECTS OF TEST SPEEDS ON INELASTIC RESPONSES (TEST AP AND BP)
(to be continued)



(3) Time Histories of Displacements Measured

(4) Time Histories of Displacements in Computation



(5) Time Histories of Strain Rates (6) Time Histories of Strain Rates

Fig.6 EFFECTS OF TEST SPEEDS ON INELASTIC RESPONSES (TEST AP AND BP)

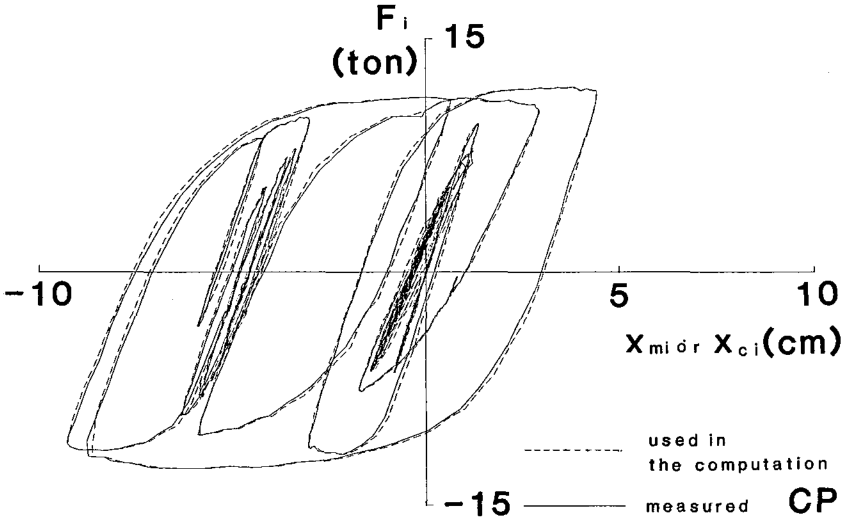


Fig.7 HYSTERESIS LOOPS IN TEST CP