FUNDAMENTAL STUDY ON THE EVALUATION OF THE DYNAMIC BEHAVIOR OF STEEL STRUCTURES

by

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SYNOPSIS

The purpose of this study is to investigate the nonlinear dynamic response of steel structures subjected to an intense earthquake. To accomplish this objective, the authors have developed a new research technique for finding the nonlinear response of actual structure without assuming the mathematical model. The outline of this system and the results of the analysis are described herein. At the same time, the damage of steel structure accumulated during a severe earthquake is examined carefully by means of the "X-ray diffraction method". It is shown that this nondestructive method can offer a powerfull tool to evaluate the damage of steel structure.

1. INTRODUCTION

It is widely recognized that the structures, once being subjected to an intense earthquake, may often lose linearity and are stressed into a large plastic deformation. But the nonlinear response characteristics and the failure machanism of actual members have not sufficiently made clear up to now, inspite of the experimental and numerical studies of many researchers in this field. This situation can be thought to be derived from the facts as follows.

In an experimental study, usually one cannot help adopting rather simple load controlling systems such as cyclic, or incremental loading.etc. mainly due to the technical and ecomomical limitations. However such a loading system seems to be too simple to simulate the effects of the severe random excitations. Consequently, the improvement of testing technique is thought to be one of the most important subjects in this approach.

On the other hand, one of the largest problems in the numerical approaches in the fact that some simplified analytical models such as bilinear, Ramberg-Osgood function.etc. are to be adopted for the nonlinear hysteretic loops, although the hysteretic behavior of the actual structures is not so simple as to be expressed through such a mathematical model. So that we cannot avoid these fundamental problems in order to investigate the real dynamic behavior of strucrures more accurately, and we believe it one of the most important subjects for the future study of earthquake engineering to overcome these limitations in approach. From the aforementioned point of view, following two problems are chosen as the main subjects of this study.

1) To estimate the dynamic response based on the actual hysteretic behavior of structures.
2) To evaluate the seismic damage of steel members more accurately.

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To achieve these objectives, the authors have developed two kinds of new research techniques. These are the "On-line simulation system" and the "X-ray diffraction method". This paper describes the general ideas of these approaches and discuss the results of the dynamic destructive test using the full scale structural members.

2. SIMULATION BASED ON THE ON-LINE SYSTEM

2.1 PRINCIPLE OF THE ON-LINE SIMULATION SYSTEM

The on-line simulation system is composed of a differential analyzer, an 8-bit microprocessor, electro-hydrauric testing machine and a full scale steel structural member as shown in the block diagram in Fig.1. In this system, the restoring force term in the equation of motion is given by the reaction of a real strucrural member measured by a load transducer, and is feed back to the computation circuit of the differential analyzer. So that this system can be regarded to be a hybrid computer whose nonlinear element is substituted by the testing machine and a specimen.

One of the most important differences between the shaking table tests and this on-line system will be as follows. In the former system, acceleration signals are put into the specimen, but in the on-line system, displacement signals filtered by the nonlinear equation of motion are to be applied to the specimen. This fact facilitates the performance of the system and the reliability of the reproduced waves can be improved very much.

In the authors' system, the simulation of structures with different natural period of vibration can be realized simply by varying the time scale factor of the hybrid computer. An 8-bit microprocessor has been adopted to vary the output speed of the acceleration data written in the memory. After the circle test, the accuracy better than 0.03% has been obtained, so that this electrical system is satisfactory for the accuracy of the experiment.

2.2 ASSUMED STRUCTURAL FRAME AND THE EXPERIMENTAL MODEL

A single-degree-of-freedom frame shown in Fig.2a is considerd to be the analytical model in this study, and the test piece adopted is illustrated in Fig.2b. Basic parameters of this frame are assumed to be as follows.

i) The columns are infinitely rigid and both feet are pin-connected.
ii) The axial load in the columns are disregarded.

The restoring force P corresponding to the horizontal story displacement X of the top of a column is given by the concentrated load P' when the deflection of the test piece is X/2 at midspan. In this experiment, dimension of the test piece has been selected as to the condition that $I_f/I_b=LH^2/4L_b^{\ 3}$ can be satisfied. So that we can get the practical earthquake response of the frame model by using the simple beam specimen.

2.3 INPUT ACCELERATION

Recorded earthquake acceleration used in this study was the El Centro 1940 NS component. The intensity of the input acceleration accelerations have been prescribed by the yield acceleration Ay defined by the following equation

$$Ay=(2\pi/T)^2\delta y$$

where T denotes the natural period of vibration of structure, and δy means the yield displacement of the frame. The accelerograms have been prepared through a Digital-Analogue converter from the digital file. Considering the time factor of the differential analyzer, the output speed of the acceleration has been slowed down by the ratio of $2\pi\tau/T$, in which τ denotes the time constant of the differential analyzer. Damping factor of the structure has been considered to be 0.5% in this study.

2.4 RESULTS OF THE ON-LINE SIMULATION

Displacement response Fig.4 shows the results of the simulation based on the on-line method. The natural period of vibration presented herein is 0.6 sec and the ordinates are normalized by the value of the maximum response written below. Fig.4a corresponds to the case when the input acceleration level is 1.17 times the yield acceleration Ay. Under such a moderate earthquake, the plastic deformations have taken place only near the primary phase of the input motion, and the structure generally has remained elastic. Consequently, the displacement response has shown a stationary sinusoidal vibration as a whole. On the contrary, as the input accelerations were intensified as shown in Figs.4b-c, the structures have suffered large plastic deformations. Noticeable features of the nonlinear response under severe earthquake excitations have seemed to be as follows.

1) Large plastic deformations have been observed near the peak of the principal shock, and often resulted in one-side plastic drift or the residual deformations. This leads to the plastic excursion failure by the gradual accumulation of the plastic deformations even if the excitation becomes weak towards the end of the earthquake. This fact shows that the inelastic response analysis should be performed for sufficiently long durations.

2) A large plastic deformation plays an important role for the attenuation of the response.

3) As the input accelerations become intense, overall response behavior shows the tendency to approach the envelope of the input motion. This fact shows that the damaged structures become sensitive to the low frequency content of the excitations.

Restoring force characteristics The restoring force characteristics show very complex hysteresis because of the drift of the neutral axis of the response caused by the plastic deformations and the change in response amplitude as shown in Fig.5. However, each of the hysteresis loops seems to be regular as is evidently seen in the hysteresis loop obtained by the static loading tests without axial load.

Fourier spectra and auto-correlations In order to examine the detailed frequency characteristics of the displacement response, Fourier spectra and auto-correlations were computed (Fig.6). The Fourier spectra show that the band-width of the response become wider as the input excitation is intensified. So that, the overall response tends to increase the irregularity and the nonstationarity as compared with the elastic response. The auto-correlation, inverse transformation of power spectrum, is advisable to evaluate the irregularity of the response. At small intensity of acceleration, the auto-correlation shows a sinusoidal vibration with gradual damping. On the other hand, at strong intensity of earthquakes, it shows such a large damping that the irregular response is obvious at glance.

3. X-RAY DIFFRACTION STUDY ON THE EVALUATION OF SEISMIC DAMAGE

3.1 BASIC CONCEPTS OF X-RAY DIFFRACTION APPROACH

If we look at the mechanical behavior such as the plastic deformation, fatigue fracture.etc. from the microscopic level, it will be nothing but the process of the deformation or the deterioration of lattice structures under various stress conditions. Therefore, it might be reasonable to evaluate the safety of steel members by a parameter which is directly related to the deterioration of metal crystalline resulting in fracture through some suitable experimental process. From the aforementioned point of view, we adopted the X-ray diffraction method for the study of earthquake engineering. Because this method is nondestructive and very sensitive to the microscopic change in crystalline materials.(1)

In this study, three kinds of X-ray diffraction techniques have been used. The macro-beam method, whose radiating area is 10-20mm^2, has been used for the residual stress measurement. Sub-macro and micro-beam method, whose diameter of X-ray beam is 1.0 and 0.16mm, respectively,have been introduced to observe the change in crystalline structures under the strain cycles.

3.2 TEST PROCEDURES

The test pieces used in this study were fabricated by welding in order to simulate the actual strain distribution pattern near the beam-column connection as shown in Fig.3a. A series of tests have been conducted on three test pieces by varying the loading conditions as presented in Fig.7. Each block in the figure shows the relation ship between the input acceleration level and the natural period of vibration of the assumed structures. X-ray stress measurement and the sub-macro and micro-beam observations were performed on several stages of the on-line experiment for each specimen as shown in Fig.7. The total energy of the input acceleration has been roughly estimated to be in the ratio of 1:6:11 for TP1,TP2,TP3 specimen.

3.3 STRAIN DISTRIBUTION OF THE FRANGE

To determine the location of X-ray measurement, the static loading test has been performed by applying the midspan deflection comparable to the maximum story displacement obtained through the on-line simulation. Fig.8 shows the results of the test. From these figures, it is seen that the strain contours have begun to concentrate, when the deflection exceeded the elastic limit. This fact indicates the evidence of the formation of the plastic hinge resulting in the local backling.

3.4 EXPERIMENTAL RESULTS

Change in residual stress Fig.9a shows the example of the change in residual measured parallel to the direction of rolling. Details of the location of the measured points are shown in Fig.9b. The pattern of the residual stress distribution before test showed a typical convex pattern particular to the hot-rolled sections, and the maximum compressive residual stress was about 16kg/mm^2, however, the residual stress continued to decrease as the loading cycles were increased. The rate of the reduction of the residual stress showed the dependence on the amplitude and the number of the stress cycling. This fact indicates that there is a good possibility that the residual stresses measured by the X-ray method enables us to evaluate the damage caused by the earthquake motion.

Change in X-ray diffraction pattern Fig.10 presents several examples of the X-ray diffraction pattern. In these figures, each of the spots has the one to one correspondence to the reflected image of a crystal by the X-ray. So that, if a crystal is deformed under certain stress conditions, the pattern of spot changes its configuration. The outstanding features of these patterns will be summarized as follows.

Those, obtained before test, have small spots on the ring (Fig.10a). However, after experiencing an intense earthquake, those spots have begun to expand into both radial and tangential directions (Fig.10b). This tendency has become more conspicuous as the number of loading cycle was increased. The sub-macro patterns have a tendency to form a doublet pattern, and the micro-beam pattern has grown gradually by forming the sharp subdivided spots in the expanded arc (Fig.10c). The pattern obtained from the TP3 specimen, has become broader than that from TP2 specimen (Fig.10d).

Change in micro-beam parameters In order to examine the change in the diffraction pattern quantitatively, following four parameters; i.e. total misorientation, micro lattice strain, subgrain size, and excess dislocation density, have been calculated by basing on the X-ray micro-beam observations, in which excess dislocation density corresponds to the amount of the total length of the dislocations per unit volume, and the misorientation means the distortion of the crystal. Change in four parameters are shown in Fig.10, where the abscissa is the order of total energy of the input acceleration. What is evident from these figures will be outlined as follows.

All parameters have changed noticeably once experiencing an intense earthquake. For example, the subgrain size before test was about 24μ, which is almost equivalent to the average grain size of the specimen. However, it was reduced to a half after one cycle of the on-line experiment. On the contrary, the excess dislocation density before test was 1.0×10^8 lines/cm^2 per unit thickness, but it was increased about 8 times after the test. As loading cycles were increased, three parameters, except the micro lattice strain which has saturated in the early stage, have changed in a regular manner. In the case of the TP3 specimen after 11 cycles of loading, the excess dislocation density was incresed 40 times as large as that before tests and the subgrain size was reduced to a quarter.

The test results show that the X-ray diffraction parameters such as the residual stress, diffraction pattern and micro-beam parameters, are very sensitive to any small changes in the mechanical property of material, and the most of the parameters are proportional to the input intensity of earthquake. Consequently, nondestructive method based on the X-ray diffraction technique provides as a powerfull tool to discuss the safety of steel structures subjected to a strong motion earthquake.

4. CONCLUDING REMARKS

In this study, inelastic behavior of a simple steel structure during an intense earthquake has been investigated by basing on the newly developed on-line simulation system and discussed the characteristics of the response of structure from various points of view. Further, the authors have introduced the X-ray diffraction method to show that this method is very advantageous in the study of earthquake engineering.

BIBLIOGRAPHY

(1) Taira.S: X-ray Diffraction Approach for Studies on Fatigue and Creep, Experimental Mechanics, Vol.13, No.11, 449-463, November 1973

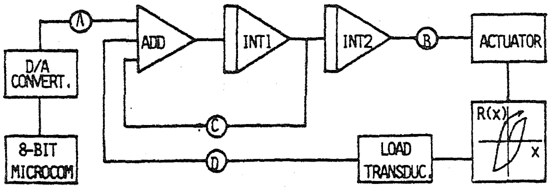
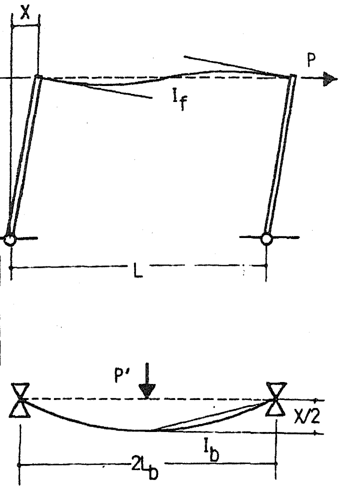


Fig.1 BLOCK DIAGRAM OF ON-LINE SYSTEM



$$\frac{I_f}{I_b}=\frac{1}{4}\frac{LH^2}{L_b^3}$$

Fig.2 STRUCTURAL FRAME & EXPERIMENTAL MODEL

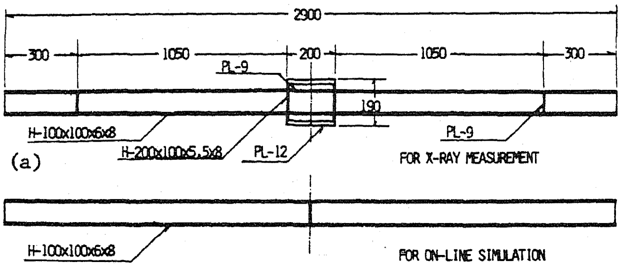
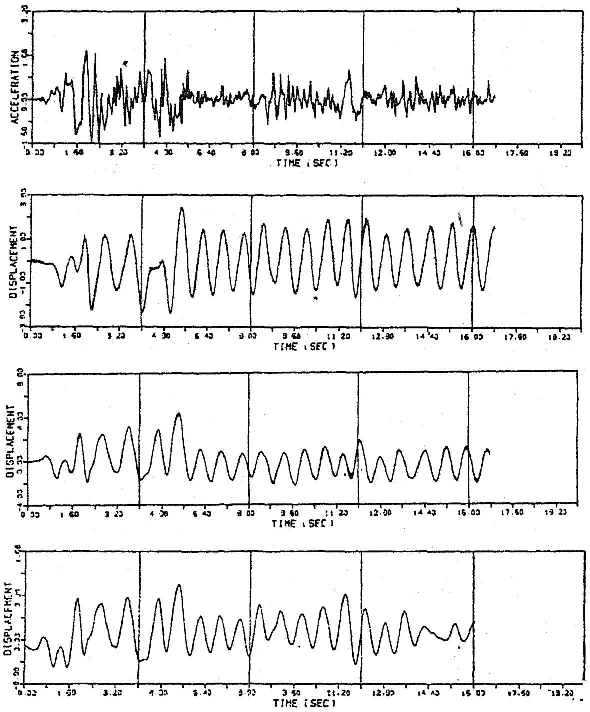


Fig.3 DIMENSION OF TEST PIECE (mm)



(a)
MAX.=2.63 cm
T =0.6 sec
I =1.17 Ay

(b)
MAX.=4.07 cm
T =0.6 sec
I =1.76 Ay

(c)
MAX.=5.70 cm
T =0.6 sec
I =2.0 Ay

Fig.4 DISPLACEMENT RESPONSE

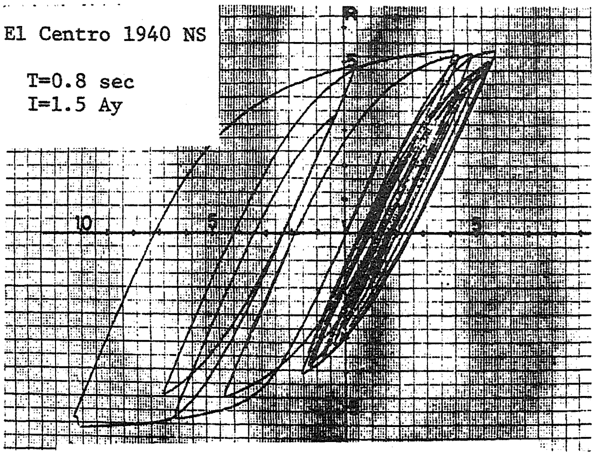


Fig.5 RESTORING FORCE CHARACTERISTICS

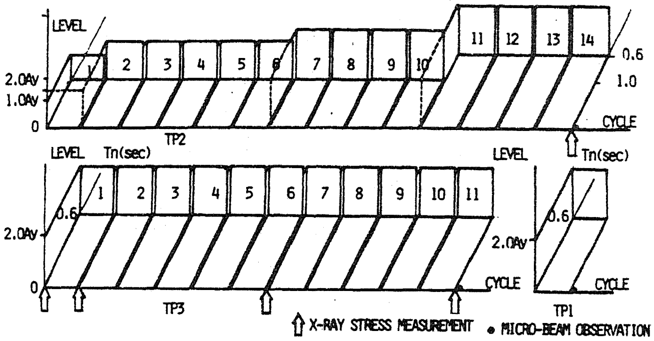
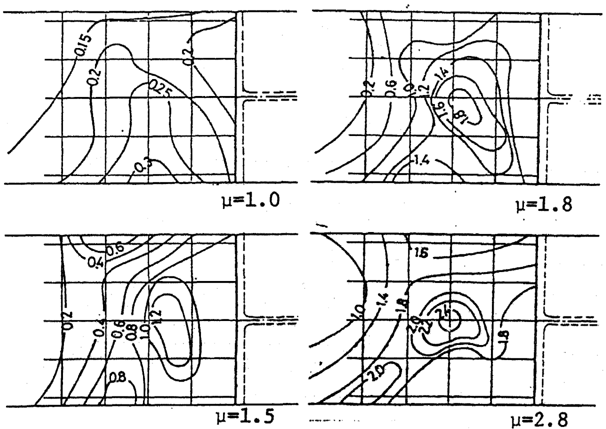


Fig.7 LOADING DIAGRAM



μ=1.0

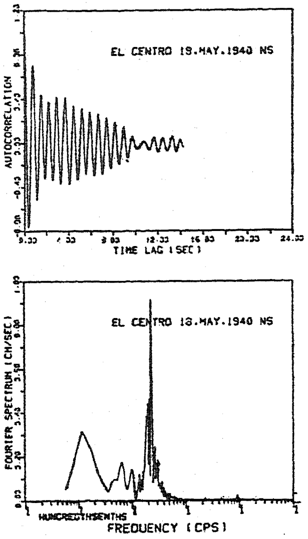
μ=1.8

μ=1.5

μ=2.8

Fig.8 STRAIN DISTRIBUTION (%)

T=0.6 sec, I=1.17 Ay



T=0.6 sec, I=1.76 Ay

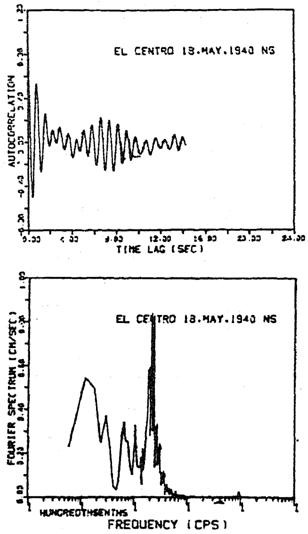


Fig.6 FOURIER SPECTRUM
&
AUTO-CORRELATION

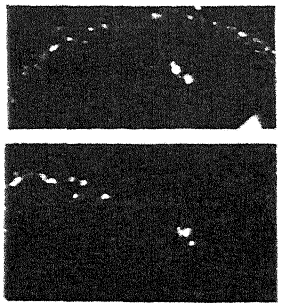


Fig.10a BEFORE TEST

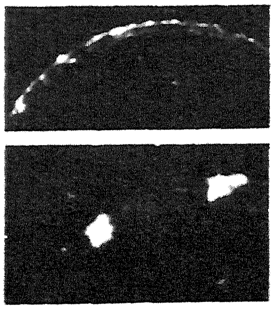


Fig.10b TP1 SPECIMEN

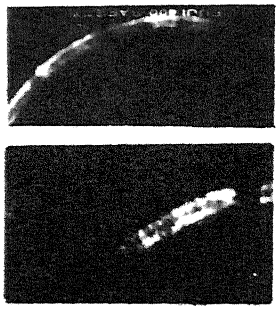


Fig.10c TP2 SPECIMEN

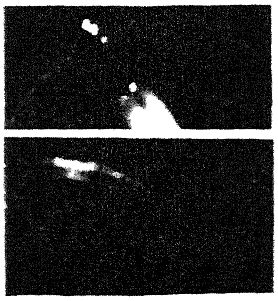


Fig.10d TP3 SPECIMEN

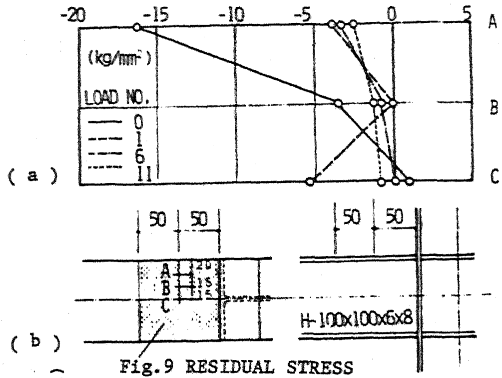


Fig.9 RESIDUAL STRESS

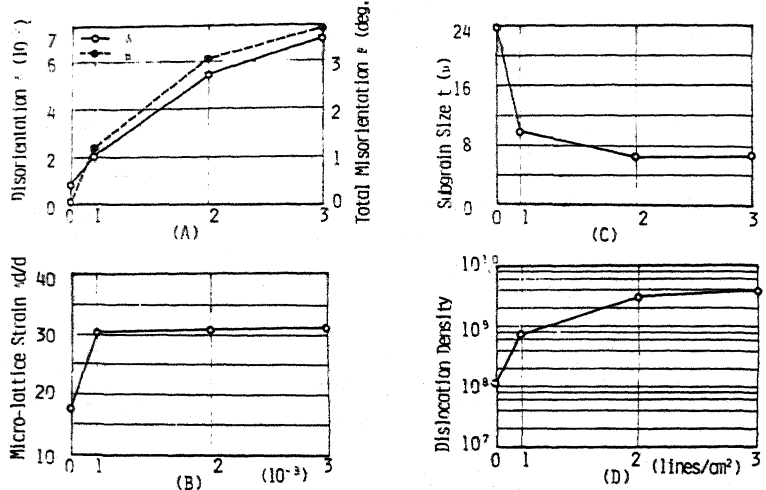


Fig.11 MICRO-BEAM PARAMETER