NON-STATIONARITIES OBSERVED IN STRONG MOTION ACCELEROGRAMS AND THEIR EFFECTS ON EARTHQUAKE RESPONSE OF STRUCTURES

by TADAO MINAMI[I], TEIJI TANAKA,[II] YOSHITAKA SONODA[III] and YUTAKA OSAWA[IV]

SYNOPSIS

Simulated accelerograms are generated to study the effects of non-stationary features appearing in strong motion earthquake records to the non-linear response of structures. Response displacements and plastic work consumed in simple structures during strong motion earthquakes are calculated for three different restoring force models. In some cases, considerable discrepancies have been observed in the response spectra for different types of accelerograms which possess similar Fourier spectra but different patterns of amplitude distribution. Significant effects of non-stationarities, however, have not been recognized for relatively stable hysteretic models.

INTRODUCTION

It has been pointed out through damage investigations of structures that some kind of structure suffers destructive damage while another kind of structure being not far apart remains safe and sound during strong motion earthquakes. The situation is reversed on other occasions. In many cases, except for lucky situations where the failure mechanism can be detected using strong motion earthquake records obtained at the base of structures, this large difference in earthquake damage cannot be explained well solely from aseismic capability of structures.

Random nature of earthquake ground motions suggests that individual wave forms may have destructive effects for a certain structure and less harmful effects for other structures, especially when the structural response exceeds the elastic limit considerably. In order to clarify the interrelationships between structural behavior and seismic wave forms, 24 strong motion accelerograms observed at four stations in northern Japan are studied first with special emphasis on non-stationary nature of the ground motions. Earthquake response analyses of simple structures with different restoring force models are then carried out for several groups of simulated accelerograms which may reflect some fundamental non-stationary characters of recorded ground accelerations.

The difference in seismic wave forms plays an important role in some ill conditioned cases which may represent low strength and/or non-ductile structures. Quantitative relationships between input accelerations and earthquake response of this kind of structures should be studied in more detail.

NON-STATIONARITIES OBSERVED IN STRONG MOTION ACCELEROGRAMS

Strong motion accelerograms of 24 earthquakes obtained at four observation stations in northern Japan (Hachinohe, Miyako, Kushiro and Hiroo) are analized to study the amplitude (energy) distribution patterns over time-frequency domain. Fig 1 a), b) show typical examples of running window Fourier spectrum (RWFS) being averaged over two horizontal components. The RWFS contains a few

---

I Assistant, II Lecturer, III Graduate Student, IV Director, Earthquake Research Institute, Univ. of Tokyo

peaks running vertically at the natural frequencies of the ground, which have been determined by means of the average Fourier spectrum of earthquake motions together with microtremor observations and S-wave travel-time measurements [1]. Location and length of the peaks, however, varies from one record to another and they even disappear in some extreme cases due to the different source mechanism and path characteristics for travelling seismic waves. It is generally observed that complex features in the earlier part of the accelerograms are simplified considerably with a remaining few peaks in the latter phases. These characteristics are commonly seen in the strong motion earthquake records at other places, e.g., El Centro 1940 and Taft 1952 whose RWFS are illustrated in Fig. 2 a), b), respectively.

To see the comparative spectral pattern, Fourier spectral ratios between the early and latter portions of records at each observation site, the area below the spectra being normalized to unity, are calculated. Average spectal ratios at each site, shown on logarithmic scale in Fig 3, take a constant value, although individual ratios take different patterns.

GENERATION OF NON-STATIONARY ARTIFICIAL EARTHQUAKE ACCELEROGRAMS

For the purpose of investigating the effects of non-stationarities in earthquake ground motions, five groups (A, B, C, D, E) of simulated accelerograms of 30 sec duration are generated by the concept of evolutionary power spectrum [2]. Each group consists of six sample waves of the same spectral pattern which contains three peaks at the frequencies of 1.0, 2.0 and 4.0 Hz. The location of the latter two peaks are fixed for all groups, while the first one is shifted systematically as illustrated in Fig 4. The intensity time function shown in the same figure together with the amplification spectrum of slightly damped (0.1 critical) simple oscillator is used as the standard design patterns for all the peaks in the first four groups of accelerograms, while in the last group high intensity phases (with constant intensity level) at 1.0 Hz last twice as long. All the 30 simulated accelerograms in total are scaled individually according to Housner's spectral intensity [3], so that the integrated velocity response spectrum over 0.1 - 2.5 sec with 0.2 fraction of critical damping may become equal to that of El Centro 1940 earthquake.

Average Fourier spectra of the full length accelerograms in each group are plotted in Fig 5. It is observed that spectral patterns are somewhat similar even for group E, the high intensity phases of which are considerably longer than the others at the frequency of 1.0 Hz, although the amplitude distribution in a particular time interval is designated different from one group to another.

NON-LINEAR RESPONSE SPECTRA

Response spectra of three different restoring force models are calculated for all the simulated accelerograms to verify the effects of their non-stationary character on the structural response. Hysteretic rules employed in the models, which are designated as the trilinear siffness degrading model, origin-oriented model and slip model, are schematically illustrated in Fig 6 a), b), c), respectively. The first model is to be applied to wooden, steel and reinforced concrete structures whose plastic deformation and failure mechanism are controlled mainly by the flexural capability; the second model representing relatively britle reinforced concrete structures whose limitting state is determined primarily by the shearing strength; and the last model to simulate prestressed concrete and other structures whose non-linear behavior is strongly affected by axial loads and bond slippage.

For the purpose of comparison, the following model parameters have been assumed for all models.

$$k_c = 0.25\ k_y, \quad k_2 = 0.333\ k_1, \quad k_3 = 0.001\ k_1$$

Yielding seismic coefficients are changed from 0.1 to 1.0 by increments of 0.1.

Two measures of structural damage, i.e., maximum displacement response and plastic work done by the hysteretic behavior of structures, are adopted in this study to reflect some features of plastic drifts and hysteretic cycles in the entire response history [4]. All the computed results are averaged for six simulated accelerograms of each spectral pattern previously mentioned (Fig 4).

Average displacement spectra of linear systems are shown in Fig 7 for comparison purposes together with the total input energy spectrum which is defined conventionally as integrated product of input accelerations and incremental response displacements. Some examples of non-linear response spectra are shown in Figs 8 - 10 for the trilinear stiffness degrading, origin-oriented and slip models, respectively.

DISCUSSION OF RESULTS

Linear displacement spectra exibit no significant discrepancies among different groups of simulated accelerograms especially in the periods less than 0.6 - 0.7 sec, which is a consequence of fixed peak patterns used in generation processes of accelerograms. The discrepancies and fluctuations in total input energy spectra, being greater than those in displacement spectra, indicate sensitive nature to frequency components contained in the ground accelerations.

Non-linear displacement spectra of origin-oriented and slip models show greater fluctuation and scattering than those in linear cases while those of trilinear stiffness degrading models increase monotonically with small deviation even for low strength levels. Especially in slip hysteretic models extremely large discrepancies among five groups of accelerograms are observed, for example, at the period of 0.4 sec in the case $k_y = 0.8$ where the average reponse displacement for group C is more than six times greater than that for group E (Fig 10). There seems to exist in this particular model with relatively low strength, critical periods below which the response suddenly diverges.

Plastic work spectra, which partly reflect effects of hysteretic cycles experienced in the entire time history of response fluctuate much more than displacement spectra. Their spectral shapes change not only with the hysteretic models but also with different levels of yielding strength execpt for the trilinear stiffness degrading models with higher strengths than $k_y = 0.3$. The average spectral values over the periods 0.1 - 1.0 sec tabulated in Table 1 are, however, almost constant both for different groups of accelerograms and different yielding strength with a slight trend of increase from the groups A, B, C to D and E in this order, except for slip models with low strength levels.

CONCLUDING REMARKS

Non-linear earthquake response of structures depents much on the hysteretic properties of prototype models especially for those in the short period range, say, of less than 0.6 - 0.7 sec. For relatively unstable models with low yielding strength, it also varies with the input accelerations of different amplitude distribution patterns in such a way that the relative magnitude of response for different groups of accelerograms changes with structures of different periods. These facts may in part explain the large discrepancies in structural damage observed during strong earthquakes

Some combination of maximum displacement response and plastic work done by the repetition of hysteretic loops may well serve as proper criteria of possible structural damage. The former is insensitive but the latter is sensitive to the amplitude distribution of the ground accelerations in both the frequency and time domains.

REFERENCES

[1] T. Tanaka and S. Yoshizawa, "Vibrational Characteristics of the Ground as Derived from Strong Motion Earthquake Records", 4th Japan Earthquake Engineering Symposium, 1975

[2] H. Takizawa, "private communication"

[3] P. C. Jennings, G. W. Housner and N. C. Tsai, "Simulated Earthquake Motions", Report Earthquake Engineering laboratory, Calif. Inst. Tech., 1968

[4] B. Kato and H. Akiyama, "Energy Input and Damages in Structures Subjucted to Severe Earthquakes", Trans. Architectural Inst. Japan, No.235, 1975

Type of Models	k_y	Group A	Group B	Group C	Group D	Group E
Trilinear Stiffness Degrading Models	0.2	46	51	54	65	59
	0.4	47	49	51	57	53
	0.6	47	49	51	57	53
Origin-Oriented Models	0.2	17	18	16	15	18
	0.4	17	18	20	23	20
	0.6	10	12	15	17	16
	0.8	9	9	9	12	11
	1.0	8	9	10	11	9
Slip Models	0.4	218	563	561	413	728
	0.6	53	64	56.	41	73
	0.8	48	44	56	50	36
	1.0	34	33	39	39	28

Table 1 Average Plastic Work Energy (cm^2/sec^2)

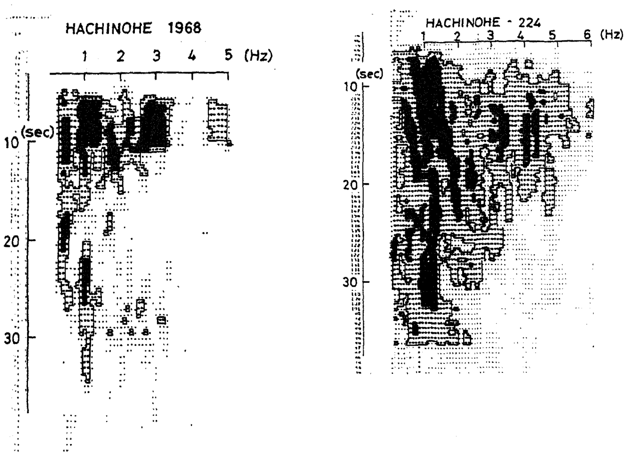

Fig 1 Examples of RWFS (Japan)

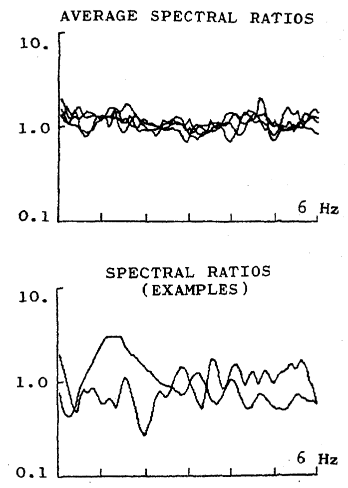

Fig 3 Spectral Ratios

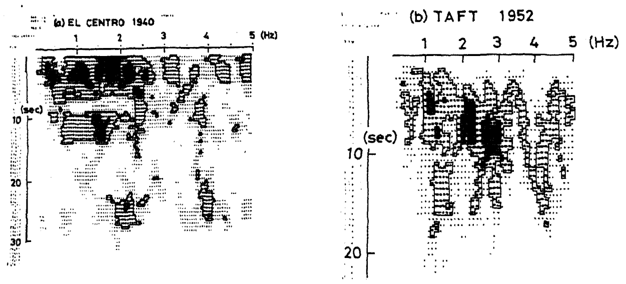

Fig 2 Examples of RWFS (U.S.A)

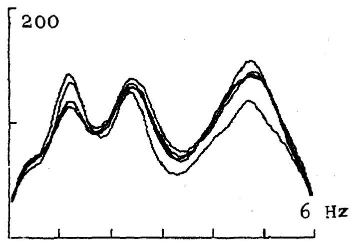

Fig 4 Average Fourier Spectra of Simulated Accelerograms

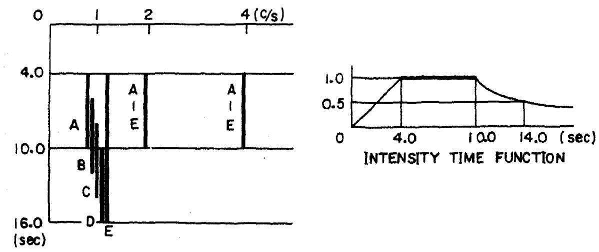

Fig 5 Design Spectral Patterns of Artificial Earthquakes

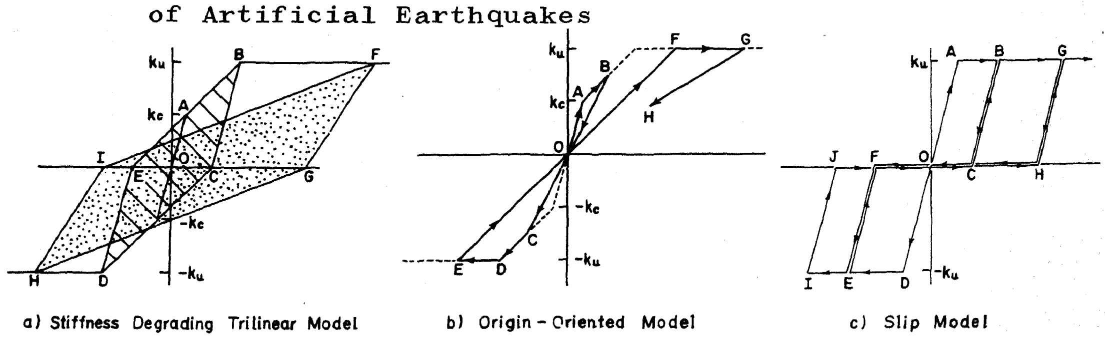

Fig 6 Hysteretic Rules of Restoring Force Models

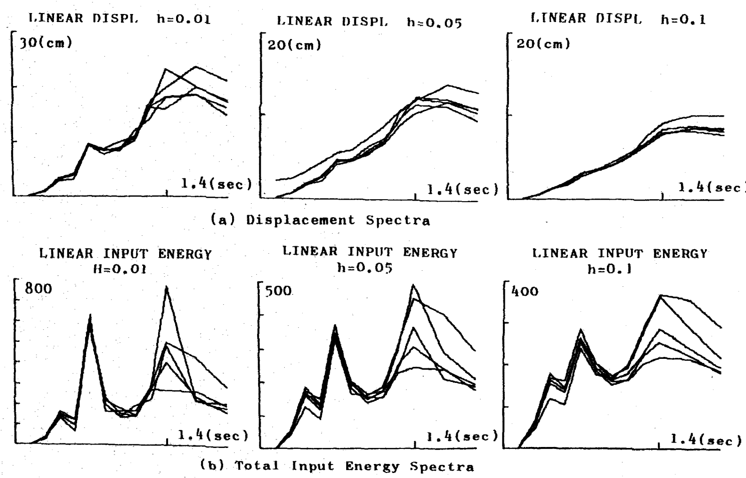

Fig 7 Response Spectra of Linear Systems

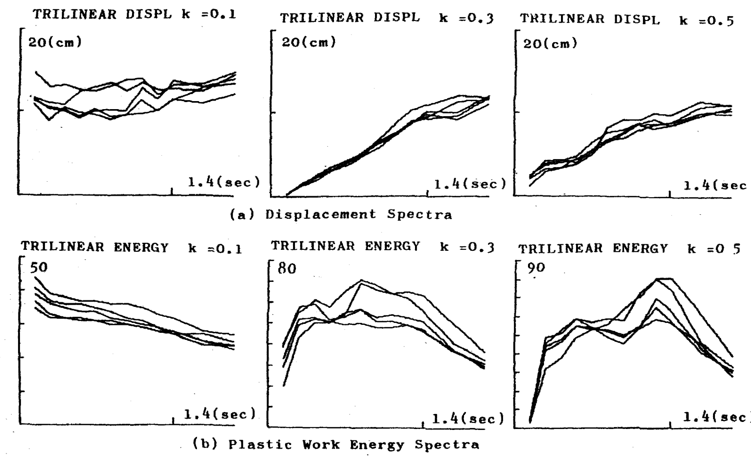

Fig 8 Non-Linear Response Spectra
(Trilin. Stiff. Degrading Model)

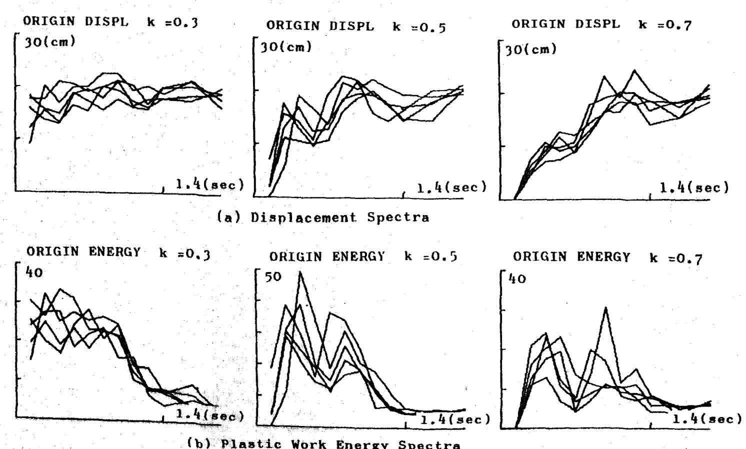

Fig 9 Non-Linear Response Spectra
(Origin-Oriented Model)

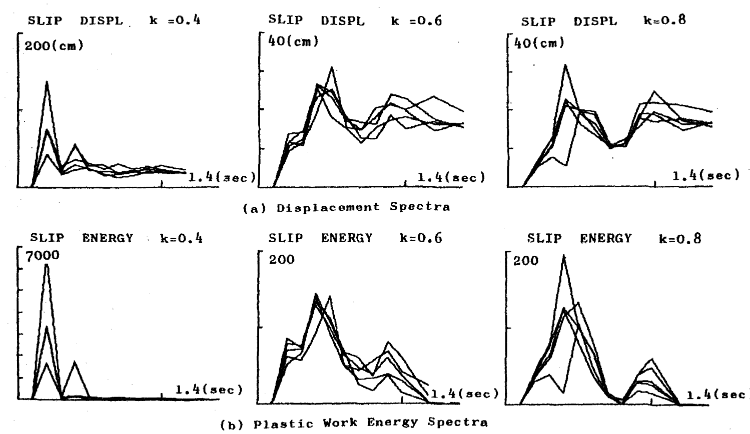

Fig 10 Non-Linear Response Spectra
(Slip Model)