U.S.-JAPAN COOPERATIVE RESEARCH ON
R/C FULL-SCALE BUILDING TEST
PART 4 DYNAMIC CHARACTERISTICS OF THE BUILDING

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SUMMARY

This paper presents the structural dynamic properties which were obtained from vibration tests on the full-scale seven story R/C building. Four types of dynamic tests were carried out five times throughout all test programs and consisted of earthquake responses, microtremor vibrations, and free and forced vibration tests. It is shown that an increase in natural period and damping ratio was associated with the increase of response displacement. The distribution of equivalent story stiffness was changed from a triangular to a uniform shape as the test proceeded. In addition, some results of the inelastic dynamic response analysis were shown.

INTRODUCTION

In order to determine the structural dynamic properties such as natural periods of vibration, mode shapes, and damping ratios, vibration tests on the full-scale seven story R/C building were carried out five times throughout all test programs. Four types of dynamic tests were executed in this test. The forced vibration tests were made by use of two exciters so that the translational and torsional vibrations were generated. In addition, the inelastic dynamic response analysis was done by considering effects of strain rate and stress relaxation during the pseudo-dynamic tests.

TEST PROGRAM AND PROCEDURE OF VIBRATION TEST

The vibration test (VT) was carried out five times, labelled VT-1 through VT-5, at the following stage of all test programs (Ref. 1);

VT-1 at the beginning of the first phase
VT-2 at the end of the first phase
VT-3 after repair and before installing nonstructural elements
VT-4 at the beginning of the second phase
VT-5 at the end of the second phase

In the vibration test four types of dynamic tests were carried out;

a. Observation of natural earthquake responses (EQ)
b. Observation of microtremor excited vibrations (VT-M-1∿5)
c. Free vibration tests (VT-F-1∿5)
d. Forced vibration tests (VT-G-1∿5)

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The free vibration tests (VT-F) were executed by "pull-back and quick release" method. This test was repeated seven times with applied tension between 0.5 and 3.5 tons in each VT-F test. In torsional vibration tests, the sweep up technique around the torsional natural frequency was adopted because of very low level excitations.

INSTRUMENTATION AND MEASUREMENTS

The forced vibration tests were made by employing two rotating eccentric weight exciters. One was a big exciter (Exciter 1). The other was a small exciter (Exciter 2). The translational vibration was generated by Exciter 1 in longitudinal or transverse direction, while the torsional vibration was produced by Exciter 2. The characteristics of the exciters and the adopted values of unbalanced moment are listed in Table 1.

The instrumentation system consisted of structural response transducers, amplifiers associated with integral circuits, a magnetic-tape recorder, and oscillographs. The transducer was a velocity and electromagnetic pickup, whose natural frequency and critical damping ratio were 1 Hz and 0.67, respectively. The recorded signals were the absolute displacements through integral circuits. Fig. 1 shows the locations of exciters installed on the roof and the measurement locations of pickups in longitudinal (NS) direction.

VIBRATION TEST RESULTS

Accurate values of the natural frequency and critical damping ratio could be obtained from resonance curves in forced vibration tests. The damping ratio was derived with the half-power (bandwidth) method. The records of torsional vibrations were analyzed by means of the fast Fourier transform (FFT), which was also applied to the spectral analysis of the records of an earthquake response and microtremor excited vibrations.

The building was subjected to an earthquake with a magnitude of 5.0 on January 28 of 1981. Fig. 2 shows the strong-motion accelerograms obtained on the roof. The Fourier spectra of them are shown in Fig. 3. The natural periods and damping ratios in longitudinal (NS), transverse (EW) and torsional directions are summarized in Table 2. Typical examples of the results of spectral analysis and resonance curves are depicted in Figs. 4 and 5 corresponding to test VT-M-2 and VT-G-2, respectively.

DISCUSSION OF TEST RESULTS

COMPARISON AMONG NATURAL PERIODS IN INITIAL ELASTIC RANGE

The translational natural periods and damping ratios in initial elastic range of the building were obtained from four dynamic tests, single load application test (FLL-1) and frame analysis (Ref. 1). These results in NS direction are summarized in Table 3. The correlation between the dynamic tests (VT-M-1, VT-F-1 and VT-G-1) and the earthquake record (EQ) is excellent with respect to the natural periods.

RELATIONSHIP OF NATURAL PERIOD VS. DISPLACEMENT AMPLITUDE

The relationship between fundamental natural period and displacement amplitude of vibration at the roof in NS direction is shown in Fig. 6. This figure includes the results of free vibration by the pseudo-dynamic test (PDT). The increase in fundamental natural period was associated gradually with the increase of response displacement except for test VT-1. In test VT-1, the natural period was almost constant within the range of displacement amplitude of 1 millimeter at the roof. In each test of VT-2 through VT-5, the fundamental natural periods derived from test VT-F and VT-G were longer by 3 to 16 percent and by 8 to 21 percent respectively than those obtained from the microtremor measurement (VT-M).

CHANGE OF NATURAL PERIODS THROUGHOUT FORCED VIBRATION TESTS

The comparison among resonance curves in NS and EW directions procured from each VT-G test are shown in Fig. 7. Fig. 8 represents the change of natural periods throughout all VT-G tests. In the NS direction, the fundamental natural period derived from test VT-G-2 to VT-G-5 increased by 2.1, 1.5, 1.2, and 2.2 times that from test VT-G-1, respectively. It is clear from the change of natural periods that the stiffness of the building was affected significantly by the epoxy repair and installing nonstructural elements. The ratio of the fundamental to the second natural period was 0.256 in test VT-G-1 and increased to 0.292 in test VT-G-5. It seems that the vibrational system of the building shifted from a flexural to a shear system because of failure in the shear wall at the first story.

MODE SHAPES

The translational mode shapes of the building in NS and EW directions are summarized in Fig. 9. Fig. 10 shows the comparison among vertical mode shapes at the roof level resonating at the fundamental natural frequency in NS and EW directions. The change of translational mode shapes seems to show that the system of vibration of the building shifted from a flexural to a shear system as the test proceeded.

RELATIONSHIP OF CRITICAL DAMPING RATIO VS. DISPLACEMENT AMPLITUDE

The relationship between the damping ratio and maximum displacement amplitude of vibration at the roof in NS direction, obtained from test VT-F-1 through VT-F-5, is shown in Fig. 11. The increase in damping ratio was associated gradually with the increase of displacement amplitude except for test VT-F-1. This increase may result mainly from the increase of hysteretic damping. The damping ratio procured from test VT-F-4 are about 1.5 times as much as those derived from the other tests. It is apparent from this result that the damping ratio of the building was remarkably influenced by installing the nonstructural elements.

EQUIVALENT STIFFNESS

The equivalent stiffness of an equivalent SDOF system of the building in NS direction, derived from all VT-G test, is shown in Fig. 12. The change of equivalent stiffness, as a matter of course, corresponds well to that of fundamental natural periods.

The equivalent story stiffness of the building in NS direction is shown in Fig. 13. This stiffness is derived from the fundamental natural frequency and the first mode shape in NS direction which were obtained from all VT-G test. The distribution of equivalent story stiffness along the height of the building was a triangular shape in test VT-G-1, while that of the damaged building was changed to a nearly uniform shape in test VT-G-2. The repaired building in test VT-G-3 showed a significant recovery of the original stiffness particulary in the lower three floors. The nonstructural elements particularly increased the stiffness (test VT-G-4) in the upper floors. The damage introduced by pseudo-dynamic testing (PDT) greatly reduced the stiffness of the structure, but at the first story the reduction in the phase II test (VT-G-5) was only approximately one-half of that noted for the original structure (VT-G-2).

RESULTS OF INELASTIC DYNAMIC RESPONSE ANALYSIS

The inelastic dynamic response analyses were done by use of a lumped mass model with and without effects of strain rate and stress relaxation (Refs. 2 and 3). The modified D-Tri-linear model whose stiffness and strength are determined from the pseudo-dynamic test results in SPD-3 (Ref. 1) and Maxwell visco-elastic model were applied to the hysteresis rule. Figs. 14 (a), (b) and (c) show the results, such as the total shear force vs. relative displacement at the roof and the time history of relative displacement at the roof, obtained from the test and the analyses. These figures show that the analytical result without dynamic effects agrees approximately with the experimental one. However, a correlation between the experimental and analytical results with dynamic effects is not so well because the restoring force characteristics was changed due to effects of strain rate and stress relaxation.

CONCLUSION

The main results obtained from the vibration test especially in longitudinal (NS) direction are summarized as follows:

1) Before the pseudo-dynamic tests, that is, in the initial elastic range, the correlation among the free and forced vibration tests and the earthquake record was excellent with respect to the natural periods.

2) According to the free and forced vibration tests, the fundamental natural period of the building was 0.43 sec. before the pseudo-dynamic tests. After the pseudo-dynamic tests, repair, installing nonstructural elements, and final failure, the fundamental natural periods was 0.80∿0.91 sec., 0.57∿ 0.63 sec., 0.45∿0.52 sec. and 0.86∿0.96 sec., respectively.

3) An increase in the fundamental natural period of the building occurred gradually with the increase of response displacement except for the initial elastic range.

4) The critical damping ratio increased with the increase of response displacement except for the initial elastic range. It should be noted that the damping ratio after installing nonstructural elements was the largest among all vibration tests.

5) The equivalent story stiffness was distributed along a triangular shape before the pseudo-dynamic tests. However, this distribution was changed to a uniform shape as the damage of the building progressed.

6) In case of discussion on earthquake performance of a structure from a dynamic response analysis, it is pointed out that the dynamic restoring force characteristics should be evaluated accurately.

ACKNOWLEDGMENTS

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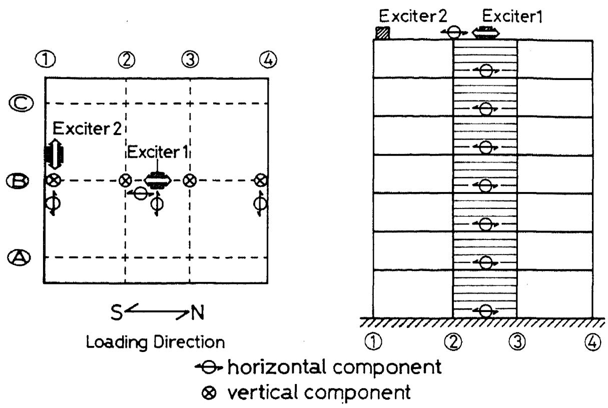


FIG. 1 LOCATION OF PICKUPS AND VIBRATION EXCITERS IN NS DIRECTION

TABLE 1 VIBRATION EXCITER CHARACTERISTICS

Characteristics	Exciter 1 (BRI-B type)	Exciter 2 (EX-4DC type)
Direction	Two horizontal	One horizontal One vertical
Maximum generated force, in tonf	10	0.1
Frequency range, in Hertz	0.2-15	2-25
Unbalanced moment, in kilogram-meters	75	0.04
Adopted unbalanced moment, in kilogram-meters	5,10,20	0.04

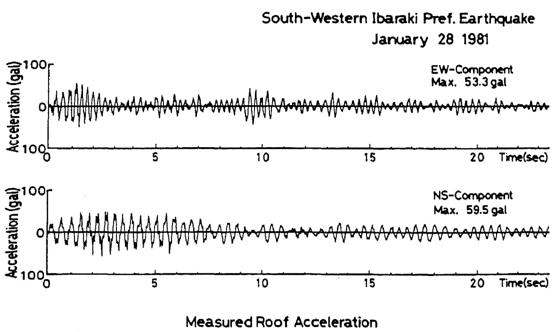


FIG. 2 ACCELEROGRAMS ON THE ROOF OBTAINED BY SMAC

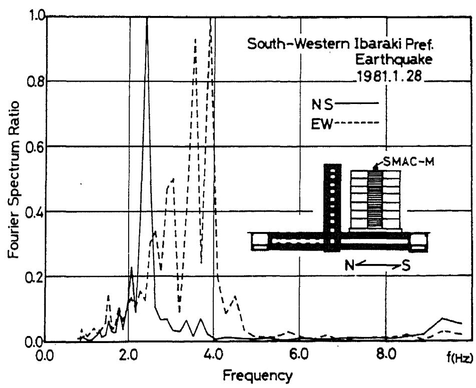


FIG. 3 FOURIER SPECTRUM RATIO OF AN EARTHQUAKE RECORD

TABLE 2 NATURAL PERIODS AND DAMPING RATIOS OBTAINED BY VIBRATION TESTS

	before P.D. Test May. 6-9 1981		after P.D. Test July 8-10 1981		after Repair Aug. 3-4 1981		after N.E. Sept. 9-12 1981		after Failure Nov. 5-7 1981	
	Period	Damp.	Period	Damp.	Period	Damp.	Period	Damp.	Period	Damp.
Micro-tremor NS 1st	0.42sec.	—	0.75sec.	—	0.55sec.	—	0.43sec.	—	0.80sec.	—
NS 2nd	0.11sec.	—	0.15sec.	—	0.13sec.	—	0.12sec.	—	0.23sec.	—
EW 1st	0.29sec.	—	0.35sec.	—	0.36sec.	—	0.36sec.	—	0.45sec.	—
EW 2nd	—	—	0.11sec.	—	0.11sec.	—	0.11sec.	—	0.14sec.	—
Free Vibration NS 1st	0.43sec.	0.021	0.80sec. ~ 0.87sec.	0.020 ~ 0.032	0.57sec. ~ 0.60sec.	0.019 ~ 0.025	0.45sec. ~ 0.47sec.	0.028 ~ 0.035	0.86sec. ~ 0.93sec.	0.019 ~ 0.032
Forced Vibration NS 1st	X X 0.43sec.	 0.019	0.83sec. 0.85sec. 0.91sec.	0.009 0.013 0.019	0.60sec. X 0.63sec.	0.011 0.013	X X 0.52sec.	 0.024	0.86sec. 0.91sec. 0.96sec.	0.015 0.013 0.019
NS 2nd	X X 0.11sec.	 0.012	0.17sec. 0.18sec. 0.20sec.	0.014 0.012 0.019	0.14sec. X o.15sec	0.012 0.016	X X 0.14sec.	 0.016	0.26sec. 0.27sec. 0.28sec.	0.010 0.019 0.014
EW 1st	0.30sec.	—	0.44sec.	0.018	0.44sec.	0.024	0.44sec.	0.020	0.53sec.	0.023
EW 2nd	0.089sec.		0.14sec.	0.013	0.14sec.	—	0.14sec.	0.013	0.17sec.	0.019
Torsion	0.23sec.	0.008	0.30sec.	—	0.29sec.	—	0.28sec.	—	0.37sec.	—
Free Vibration (P.D. Test)	0.43sec.	(1.2mm)	0.94sec. ~ 1.36sec.	(0.8mm) (150mm)	X		0.57sec.	(1.0mm)	X	

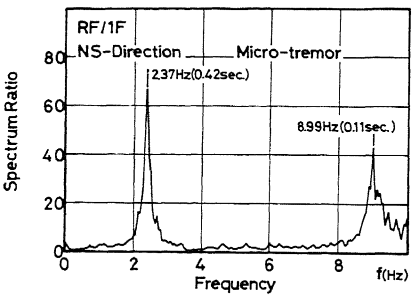


FIG. 4 FOURIER SPECTRUM RATIO OF MICROTREMORS; TEST VT-M-2

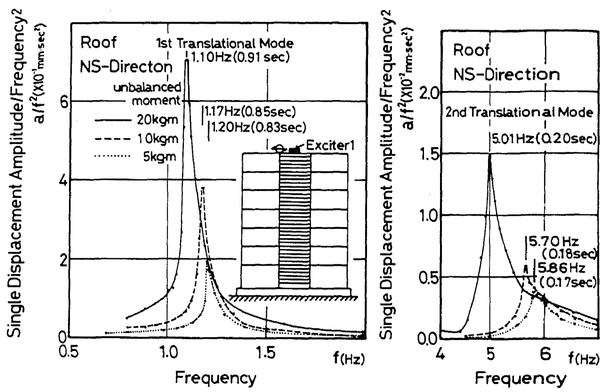


FIG. 5 RESONANCE CURVES IN NS DIRECTION; TEST VT-G-2

TABLE 3 COMPARISON AMONG NATURAL PERIODS AND DAMPING RATIOS IN LONGITUDINAL (NS) DIRECTION

	Mode Number	Earthq. Record	Free Vib. Test	Forced Vib. Test	Static Test	Frame Analysis
Natural Period (sec.)	1st	0.420	0.43	0.43	0.448	0.505 *1 (0.468)*2
	2nd	0.107	—	0.11	0.125	0.133 (0.123)
Damping Ratio	1st	0.026*3	0.021	0.019*3	—	—
	2nd	—	—	0.012*3	—	—

*1 Young's modulus is 210 t/cm².
*2 Young's modulus is 244 t/cm².
*3 Damping ratio is obtained by the half-power method.

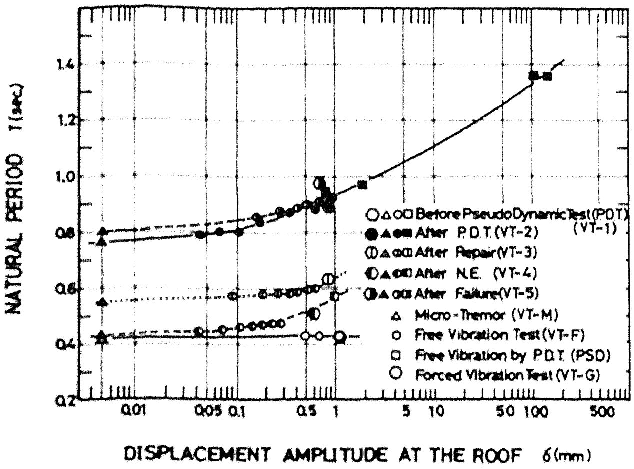


FIG. 6 RELATIONSHIP OF NATURAL PERIOD VS. DISPLACEMENT AMPLITUDE; TEST VT-1∿5

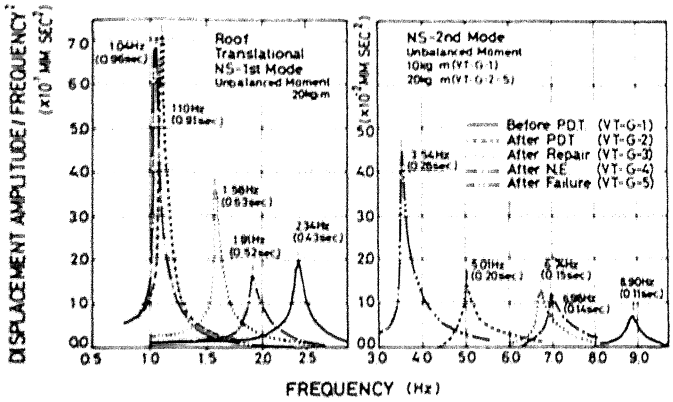


FIG. 7(a) RESONANCE CURVES IN NS DIRECTION; TEST VT-G-1∿5

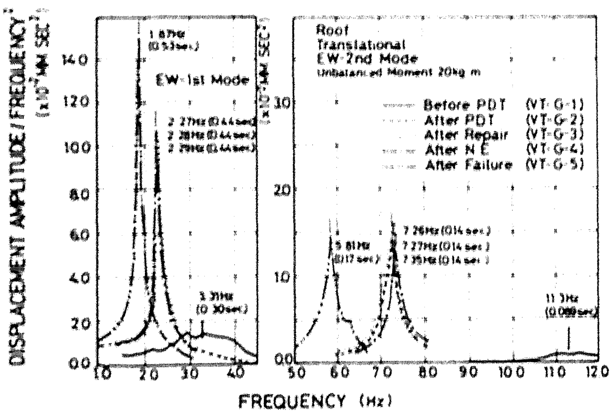
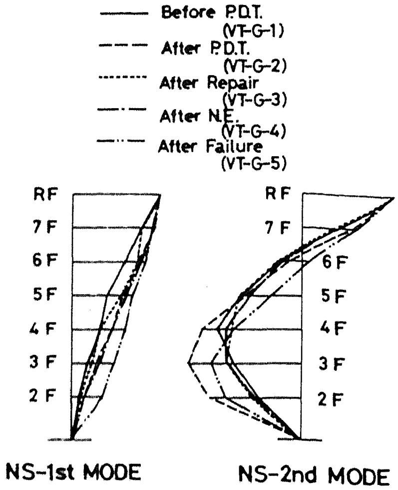
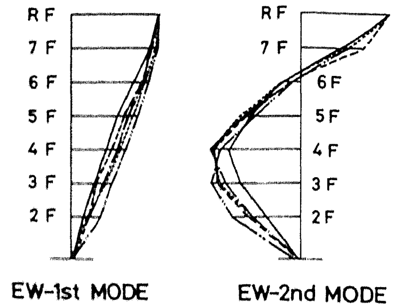


FIG. 7(b) RESONANCE CURVES IN EW DIRECTION; TEST VT-G-1∿5



(a) NS DIRECTION



(b) EW DIRECTION

FIG. 9 TRANSLATIONAL MODE SHAPES; VT-G-1∿5

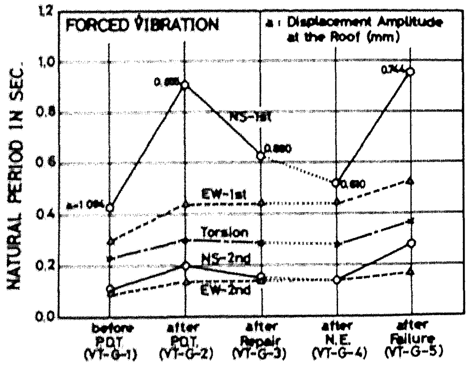
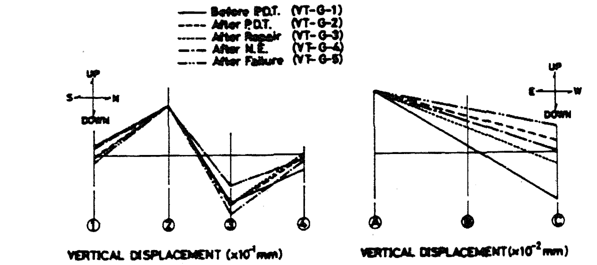


FIG. 8 CHANGE OF NATURAL PERIODS; VT-G-1∿5



	VERTICAL DISPLACEMENT (x10⁻¹mm) 1	2	3	4	VERTICAL DISPLACEMENT (x10⁻²mm) A	C
VT-G-1	0.200	1.280	-1.200	-0.560	1.01	0.77
VT-G-2	-0.050	0.920	-0.860	-0.040	4.57	0.80
VT-G-3	-0.150	2.560	-2.640	0.040	2.81	0.53
VT-G-4	-0.080	0.640	-0.760	-0.070	2.97	0.10
VT-G-5	-2.400	1.450	-8.400	-0.100	5.40	2.32

FIG. 10 VERTICAL MODE SHAPES AT THE ROOF LEVEL; TEST VT-G-1~5

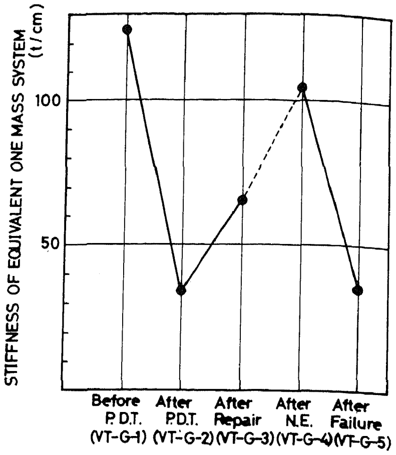


FIG. 12 EQUIVALENT STIFFNESS OF A SDOF SYSTEM

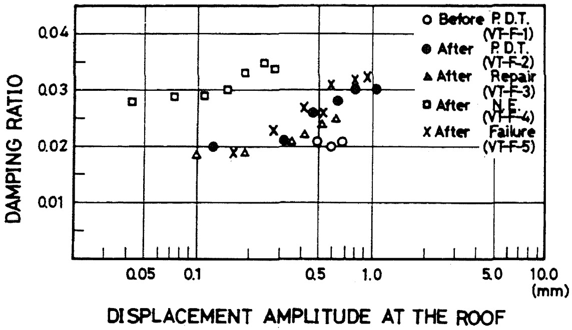


FIG. 11 RELATIONSHIP OF DAMPING RATIO VS. DISPLACEMENT AMPLITUDE; TEST VT-F-1~5

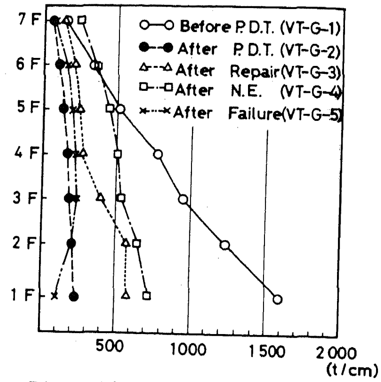
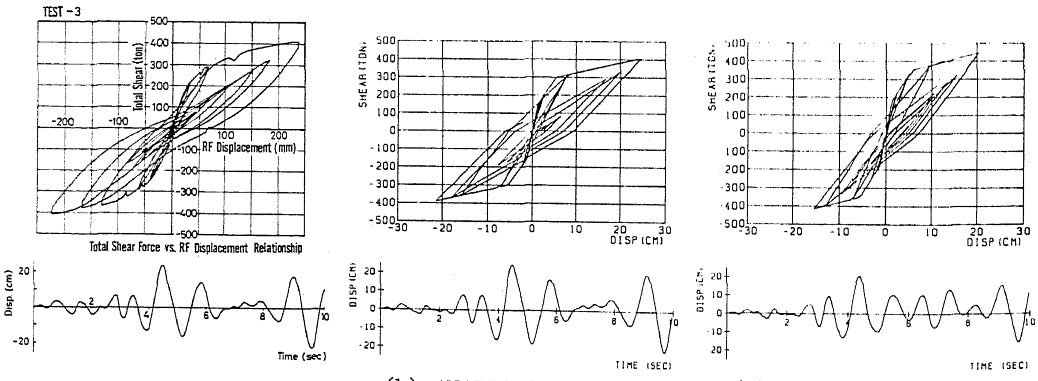


FIG. 13 EQUIVALENT STORY STIFFNESS



(a) PSEUDO-DYNAMIC TEST

(b) ANALYSIS WITHOUT DYNAMIC EFFECTS

(c) ANALYSIS WITH DYNAMIC EFFESTS

FIG. 14 EXPERIMENTAL AND ANALYTICAL RESULTS; TEST SPD-3