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FORCED VIBRATION TESTING

OF A

REHABILITATED MULTISTORY BUILDING

(Volume I)

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This report describes a series of steady state harmonic forced vibration tests conducted on a multistory building before and after it was rehabilitated for seismic safety. The lateral resistance added to the building significantly increased the natural frequencies of vibration. Inplane floor slab deformations were significant in both tests. The deformation was greater in the pre-rehabilitation state. The North-South and the Torsion modes both indicated inslab floor deformations. Response was measured at 5, 25 and 45 feet from the building on the surface of ground. The soil response was measurable and indicates that an analytical model of the system must be a soil/building model and interaction during an earthquake is probable.

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TABLE OF CONTENTS

SUMMARY

This report describes a series of steady state harmonic forced vibration tests conducted on a multistory building before and after it was rehabilitated for seismic safety.

The lateral resistance added to the building significantly increased the natural frequencies of vibration. The results were:

Prior to Rehabilitation

North-South	3.5 to 3.7 Hz	(3% g max accel.)
East-west	3.9 to 4.1 Hz	(3% g max accel.)
Torsion	4.8 to 4.9 Hz	(4% g max accel.)

After Rehabilitation

North-South	4.9 Hz	(1% g max accel.)
East-West	6.1 Hz	(0.6% g max accel.)
Torsion	5.7 to 6.1 Hz	(1% g max accel.)

Inplane floor slab deformations were significant in both tests. The deformation was greater in the pre-rehabilitation state. The North-South and the Torsion modes both indicated inslab floor deformations.

Response was measured at 5, 25 and 45 feet from the building on the surface of ground. The soil response was measurable and indicates that an analytical model of the system must be a soil/building model and interaction during an earthquake is probable.

LIST OF TABLES

LIST OF TABLES (cont'd)

LIST OF FIGURES

LIST OF FIGURES (cont'd)

LIST OF FIGURES (cont'd)

I. DESCRIPTION OF THE STRUCTURE

A. Building Prior to Rehabilitation

North Hall is located on the University of California, Santa Barbara campus at the south-east corner of the intersection of Ocean Road and Campus Road (see Figure 1). The building is a three story reinforced concrete structure with plan dimensions of 240 feet by 34 feet. Figure 2[1] shows the typical floor plan of the building. Figure 3 shows the east-west direction elevation and Figure 4 shows the north-south direction elevation of the building. The structure is separated from the adjacent building on the east side by a seismic joint (see Figure 2)

There are twenty interior columns and twenty exterior columns in the structure. All interior columns in the building are 10 inches by 14 inches with four #9 bars and #2 ties every 10 inches. A typical exterior column is shown in Figure 5. There are four #10 bars and four #8 bars from the ground to the second floor; four #8 bars and four #6 bars from the second floor to the roof.

The floor slab is 2½ inches thick throughout the building. Each floor has ten girders running in a north-south direction and each girder is connected to a column. The floor slab and girder form a T section. A typical section is shown in Figure 6.

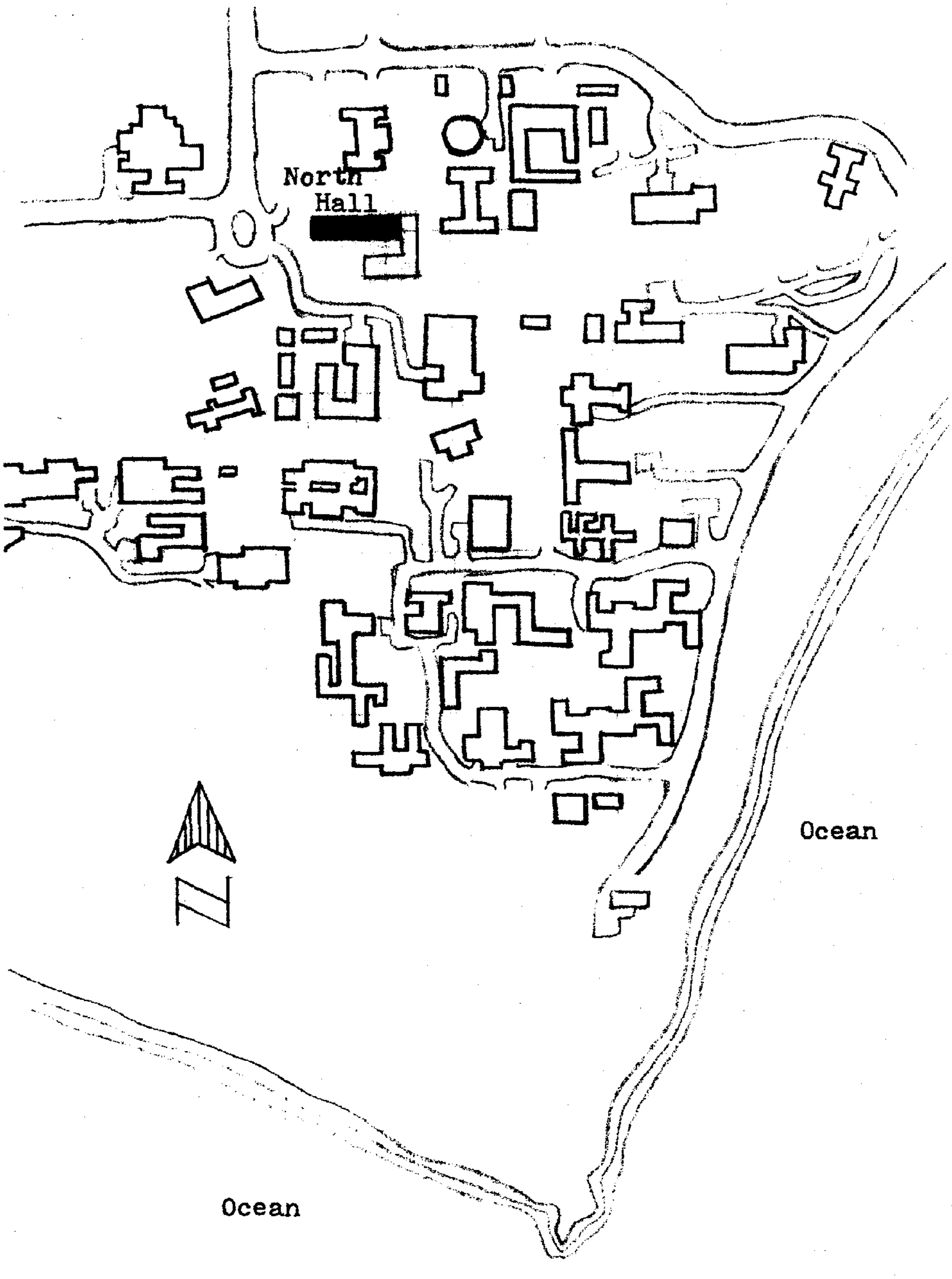


Fig. 1 U.C.S.B. Campus Map

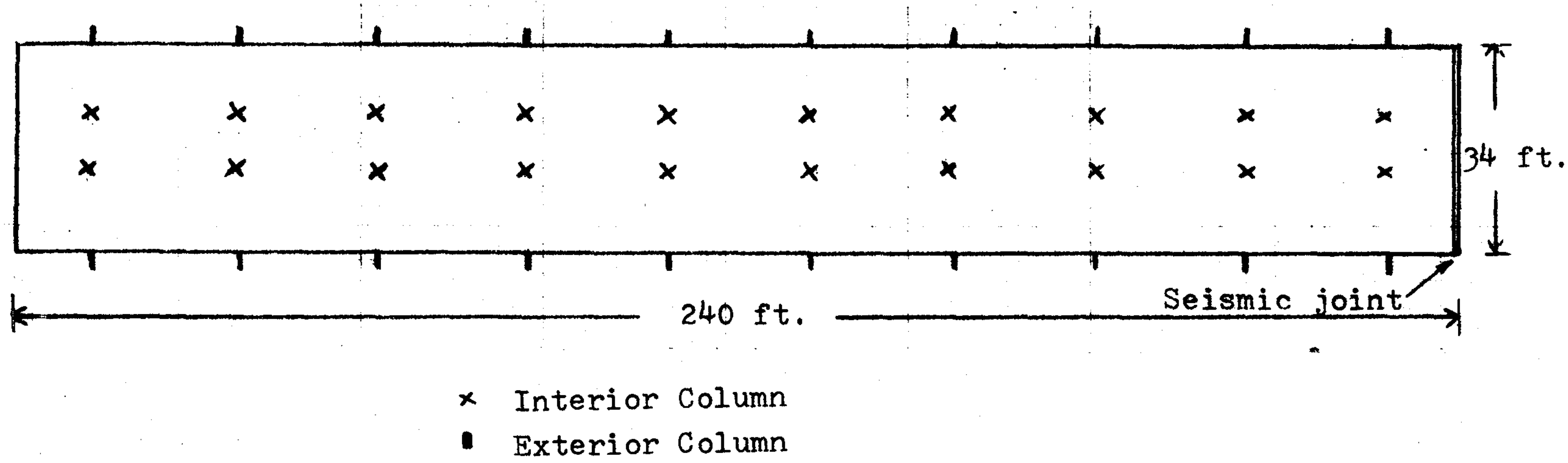


Fig. 2 Typical Floor Plan Before Correction

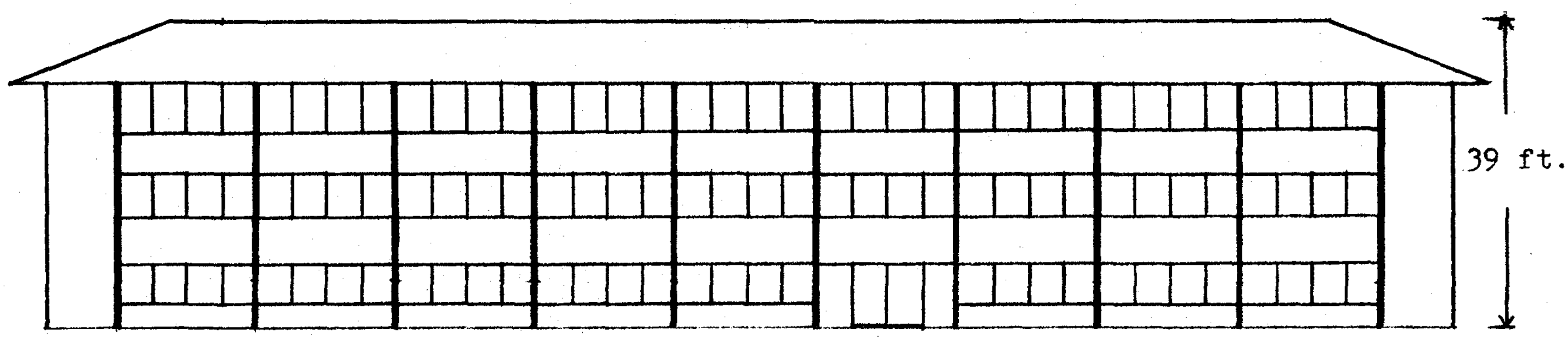


Fig. 3 East-West Elevation

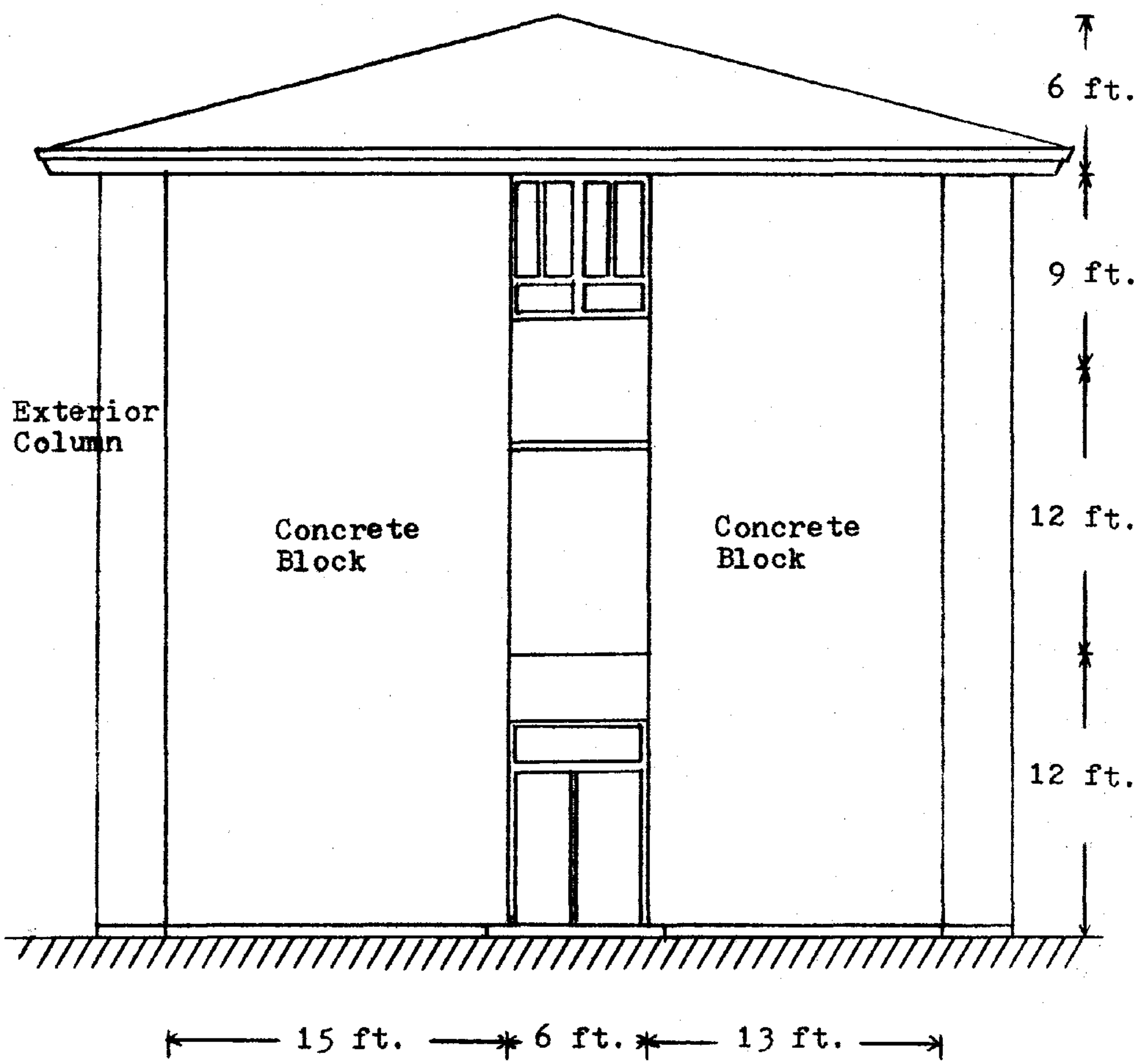


Figure 4. North-South Elevation

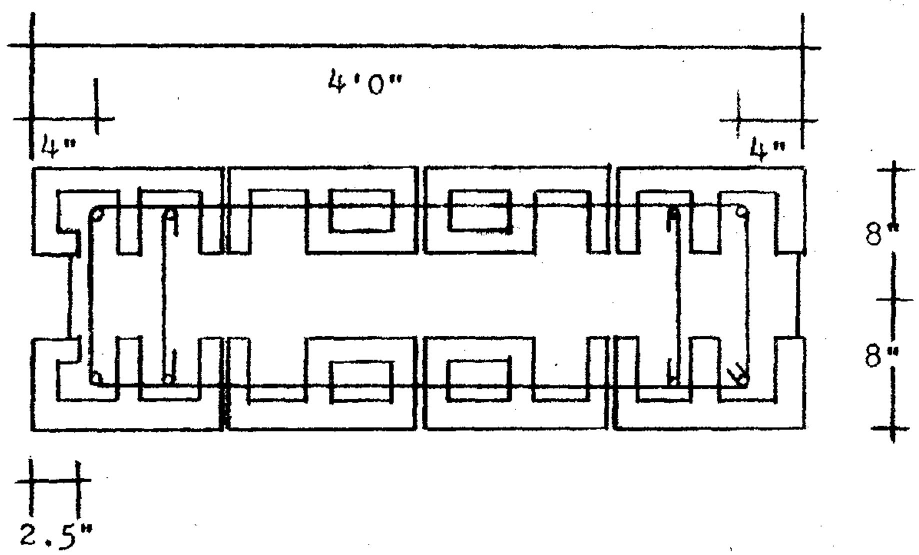


Fig. 5 Typical Exterior Column Detail

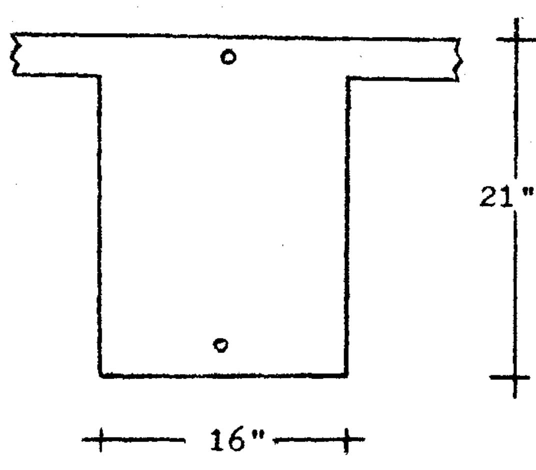


Fig. 6 Typical Girder Cross Section

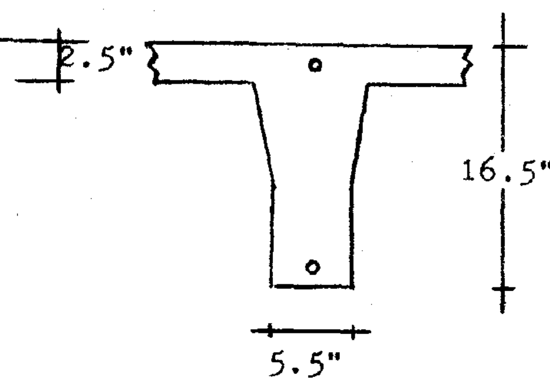


Fig. 7 Typical Beam Cross Section

Girders are also connected to each other by T beams running in an east-west direction on each floor. A typical section is shown in Figure 7. These beams together with the floor slab function as a T section.

The roof forms an angle of 32.2 degrees with the ground and it slopes up from both sides. The roof has the same type of construction as the floor slab except that it has more beams in an east-west direction (see Figure 8) and it has an angle with the ground.

At the ends of the building there are concrete block shear walls both in the east-west and the north-south direction. All together there are eight shear walls (four in the north-south direction and four in the east-west direction). All shear walls have a thickness of 7 5/8 inches. In the north-south direction there are two shear walls having a width of 12½ feet and another two shear walls that are 14½ feet wide. In the east-west direction there are three shear walls each having a width of 12 feet and one that is 3 feet and 4 3/8 inches wide. (see figure 2)

Concrete mix for the walls and footing have a minimum compressive strength of 2500 psi at 28 days. For the columns, floor beams and roof framing the minimum compressive strength is 3000 psi at

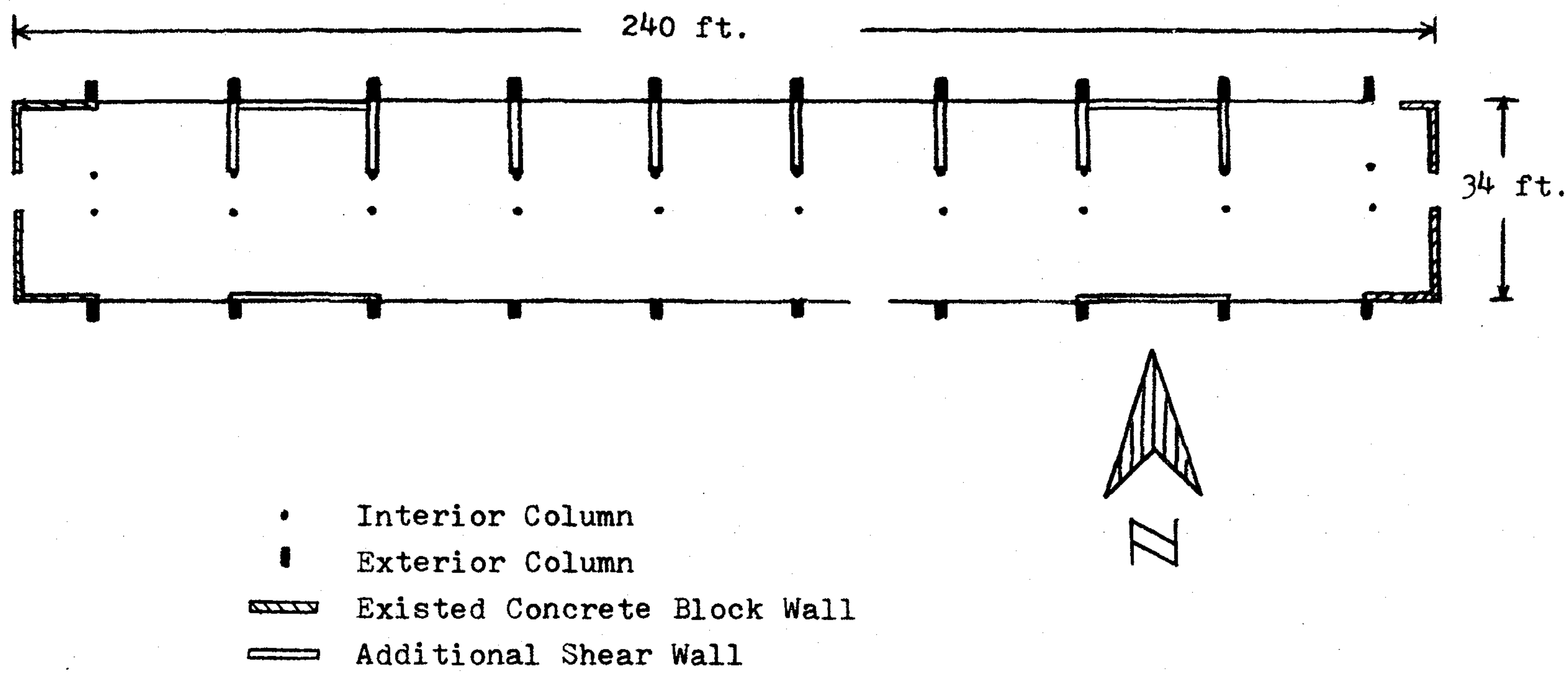


Figure 8 .Floor Plan After Seismic Correction

28 days. For the floor slab it is 1,500 psi at 28 days. All the reinforcing steel is intermediate grade deformed bars meeting the requirements of A.S.T.M. A-15 and A-305, with an allowable stress of 20,000 psi.

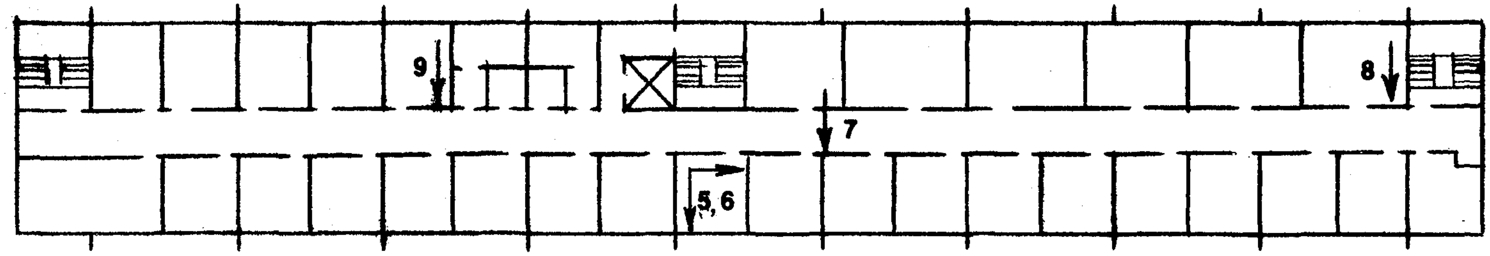
B. Building After Rehabilitation

All dimensions for the floor plan and elevation plan of the building are unchanged. The modification consisted of replacing some steel stud walls and windows with concrete shear walls to increase the stiffness of the building. Therefore there are eight additional concrete shear walls in the north-south direction each of width 12.5 feet and four additional shear walls in the east-west direction each of width 24 feet (see Figure 8)[2].

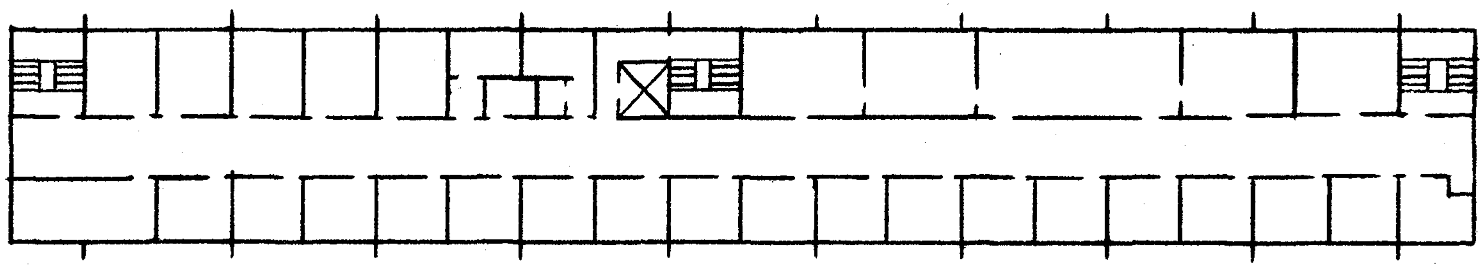
All concrete in the modification has a compressive strength of 3,000 psi at 28 days. Reinforcing steel is grade 60 for #4 bars and larger, grade 40 for #3 bars and smaller. All structural steel is A36. The rehabilitation was completed on May 13, 1976.

C. Seismic Instrumentation

Strong motion instruments were installed for future seismic study. All together nine instruments were installed and locations are shown in Figure 9.



Third Floor Plan
(note: 7 in attic)



Second Floor Plan

First Floor Plan
(note: 1 is vertical)

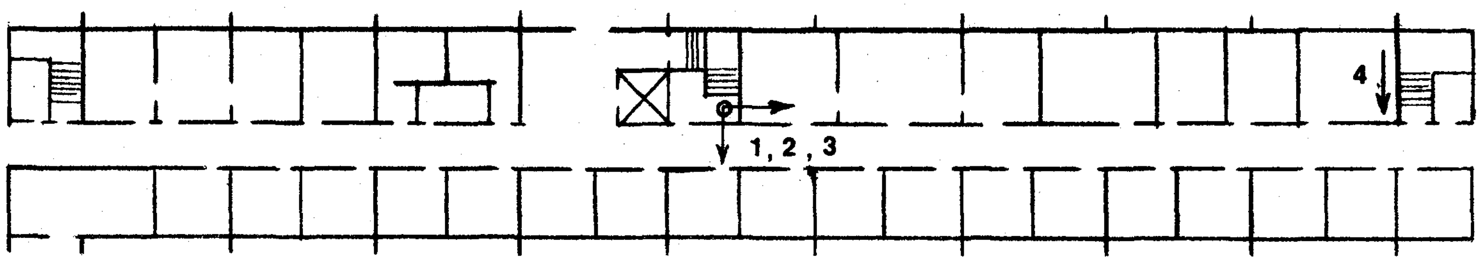


Figure 9. Strong Motion Instrumentation

II. TEST EQUIPMENT AND PROCEDURE

A. Equipment

The test equipment can be separated into two parts. One part is for the vibration system used to create the inertia force on the structure and the other part is the recording system.

The vibration system includes the Hewlett Packard electronic counter, vibration generator control units and the harmonic vibrators. The electronic counter indicates the speed of the shaker and is used to obtain the forcing frequency of the system. Control units and harmonic vibrators were developed by the California Institute of Technology under the sponsorship of the State of California Office of Architecture and Construction with advice from a special committee of the Earthquake Engineering Research Institute. The details of the design and operation are discussed by Hudson[3,4]. The control units and shakers consist of a master and a slave unit. The units can work separately or can be run synchronized in or 180° out of phase. The harmonic vibrator employs two counter-rotating weights which rotate about a vertical axis in order to generate a sinusoidal inertia force in one direction only. The centrifugal forces from the rotating masses will add in one direction and cancel in the perpendicular direction. The force level can be adjusted by changing the rotating masses or by changing the frequency since the centrifugal force is proportional to the mass and the square of the frequency.

The recording system includes accelerometers, strip chart recorders, a magnetic tape recorder and various kinds of cables and connectors. The accelerometers sense the acceleration of the building at the location at which they are placed. Accelerometers used during the tests were Statham A4-0.25-350 10V max. ± 0.25g., Statham A4-0.25-35 10V max. ± 0.5g., and Statham A5-2-350 9V max. ± 2g. accelerometers. Two Sanborn Model 321 Dual Channel Carrier Amplifier stripchart recorders were used to record the accelerometer signals. The response was also recorded on a 4 channels Hewlett Packard 3960 Instrumentation Recorder in order to have a permanent record and also to study the phase relationship for different channels.

A calibration plate, levels, and accelerometer mounting blocks were used to calibrate all accelerometers.

B. Procedure

Before the actual testing, the force level of each test and the direction and locations of the vibration generators and accelerometers should be pre-determined in order to investigate the building systematically. Appendix A gives all such test details.

As for the actual testing, investigators have to set up everything properly. For example, one has to mount and level the harmonic vibrators, connect all parts of the system, calibrate all recorders, and make sure all cables are long enough so that the accelerometers can be moved to various locations.

Before and after each set of tests a static calibration must be performed. Static calibration is done by putting accelerometers on the calibration plate so one can obtain a reading of 0.0 g. and $\pm$ 0.1 g. for each accelerometer. These readings are used in data reduction and one can also check whether the accelerometers are functioning properly.

With the readings obtained from static calibration, double-checking can be done by means of a dynamic calibration test. Since any location in the building at a particular instant of time should have a unique motion, a dynamic calibration can be performed by putting all accelerometers at the same location to check whether one is obtaining the same response level from each accelerometer.

The actual testing starts after all the preliminary work is done. Actual testing can be run with one harmonic vibrator running or two harmonic vibrators running synchronously. If the two shakers are placed symmetrical to the torsional center of the building and are made to run in phase, then the torsional response can be minimized. If only one shaker is running and it is not at the torsional center, then one will have the response from both the translational and torsional mode. Therefore, it is advantageous to carry out the test with two shakers running synchronously.

For each direction (i.e. major axis, minor axis and torsional) a frequency sweep is performed with no weight in the harmonic vibrator in order to locate the natural frequency of that particular direction. Then one can perform frequency sweeps with different combinations of weights in order to study how the response varies under different inertia forces.

After the natural frequency has been obtained, a series of tests are run with harmonic vibrators running at that natural frequency. By moving accelerometers to various locations in the building, The mode shape can be defined. An accelerometer can be placed across the seismic joint or an accelerometer can be placed some distance away from the building to study the soil impedance. While doing the tests mentioned above, one should always keep one accelerometer as the reference accelerometer. With the reference accelerometer one can compare the relative response at different locations from test to test.

III. DATA REDUCTION

Before the actual data reduction one has to read off the results from the paper record. The peak to peak distance multiplied by the attenuation factor will yield a set of numbers. From static calibration those numbers can be related to acceleration level for every channel. Then the response for each test can be calculated.

After the actual accelerations of the test have been obtained, a response curve can be constructed for each channel during each frequency sweep by plotting responses vs. frequency. The investigator can identify natural frequency easily by determining the frequency corresponding to the peak of the response curve.

Damping can be estimated by the half power band-width method[5]. The method consists of measuring the frequency band width Δw of the response curve between amplitudes of 0.707 times the peak amplitude at the natural frequency w_d. For a single degree of freedom system excited with constant sinusoidal force, the damping is given by the following relation:

$$\xi_{hp} = \frac{\Delta w}{2\,w_d}$$

Due to modal interference, the response curve may not be symmetrical. Therefore, an alternate method for evaluating damping was also used. The method is very similar to half-power bandwidth method and will be referred as semi-half-power bandwidth method. The method measures the minimum frequency band width w_{min} of the response curve between the peak amplitude at the natural frequency , w_d, and 0.707 times the peak amplitude. Then damping value is given by the following relation:

$$\xi_{min} = \frac{\Delta w_{min}}{w_d}$$

A mode shape can be determined from the response of the building at various locations when the building is vibrating at its natural frequency. Since one can not measure the response at all locations in order to define the mode shape at the same time, one has to normalize the response with respect to the reference accelerometer for each test. By doing so, the response from location to location relative to one another can be obtained.

Since peak to peak values instead of center to peak values are measured from the recording charts, all responses obtained will be twice the actual value. However, this will not affect the results of damping and mode shape, because when dealing with damping and mode shape, one is dealing with the ratio of responses, not the actual responses.

IV. DESCRIPTIONS AND RESULTS OF THE FIRST TEST SERIES

The first test series on North Hall were conducted on June 27 and 28, 1975. Altogether twenty-eight tests were run: six of them were run on June 27 and twenty-two of them were run on June 28. All tests were numbered. Test numbers consisted of three parts. The first part indicated the year the test was run. The second part indicated the day the test was run. The third part indicated the test number during that particular day. All the test details are included in appendix A.

During the first test series, two harmonic vibrators were mounted symmetrically to the mid-point of the third floor and a quarter of the total length from the ends. Depending upon the purpose of the test, vibrators were run in or 180° out of phase. Two shakers were used for every test. The reference accelerometer was placed at the west quarter point of the third floor. All other accelerometers were placed at the ends, quarter points and mid-point of each floor, depending on each different test. Accelerometer no. 4 was placed across the seismic joint in the adjacent building during test 75-28-12, 75-28-13, 75-28-19, 75-28-20, and 75-28-21 to study the function of the seismic joint.

Since the range of the forcing frequency is limited by the maximum allowable frequency of the harmonic vibrator, we can only reach the first natural frequency in the major axis, minor axis and torsional directions. All information about higher modes is incomplete and inconclusive.

A. Natural Frequency

1. Minor Axis (the north-south direction):

Three sets of frequency sweeps were run in the north-south direction. Tests 75-27-2 and 75-27-3 complete a frequency sweep and they were run with empty baskets. Test 75-27-4 was run with one small weight in each basket. Test 75-28-6 was run with three small weights in each basket. All accelerometers were placed on the third floor during a frequency sweep. A typical response curve is shown in Figure 10. A summary of the results is given in Table 1. Complete information is contained in Appendix B.

As shown in Table 1, for each frequency sweep, every channel yielded the same natural frequency. Tests 75-27-2,3 give 3.66 Hz as the natural frequency. Test 75-27-4 gives 3.60 Hz and Test 75-28-6 gives 3.51 Hz. the natural frequency decreased as force level increased

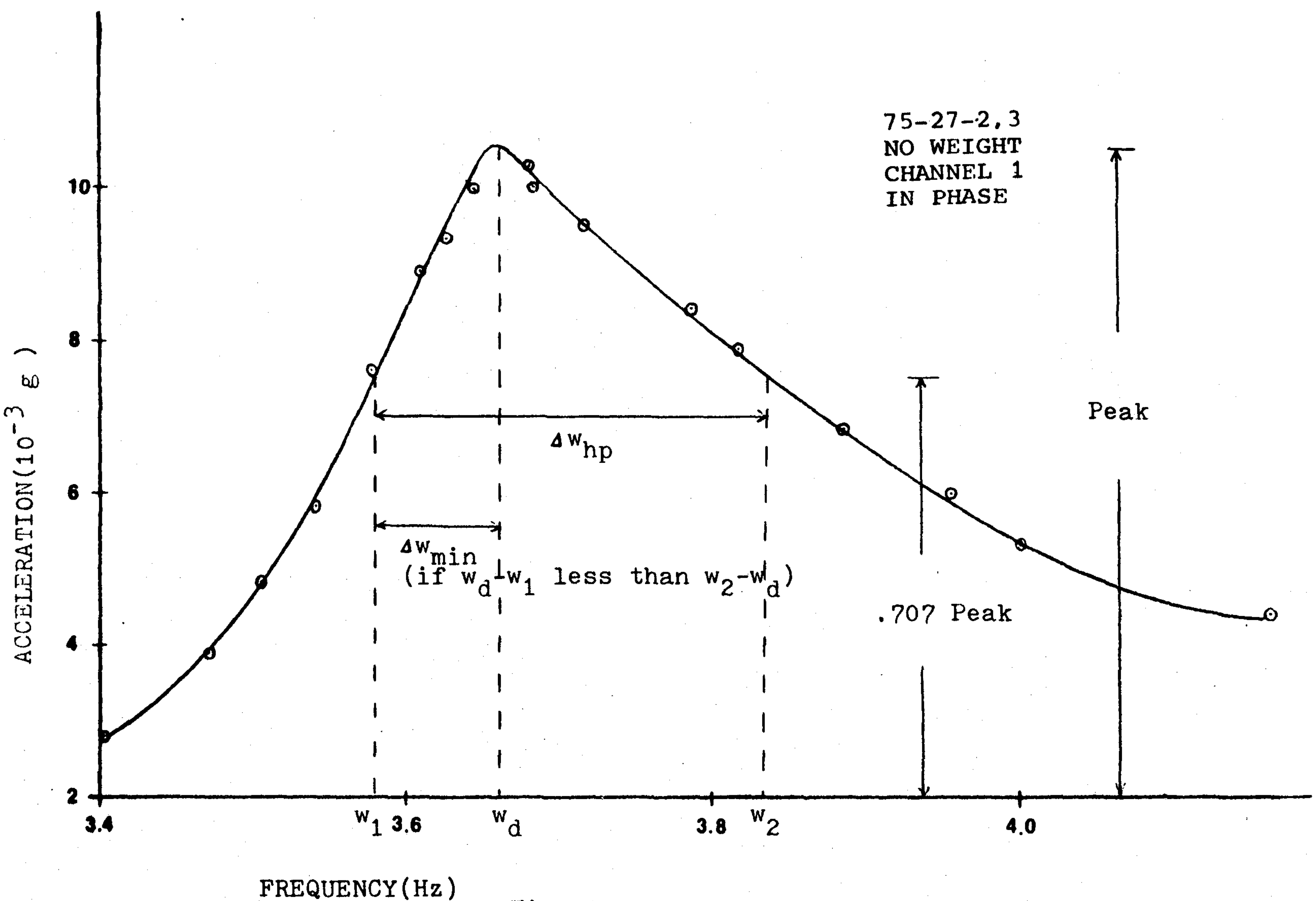


Fig. 10 Typical Frequency Response Curves Before Correction (Minor Axis)

TABLE 1. MINOR AXIS NATURAL FREQUENCY AND DAMPING

SET-UP: ↑2 ↑3 ↑1 ↑4 SHAKERS IN PHASE

TEST NO.	75-27-2,3				75-27-4				75-28-6			
# OF WEIGHTS	NONE				ONE-SMALL				THREE-SMALL			
CHANNEL	1	2	3	4	1	2	3	4	1	2	3	4
w_n	3.66	3.66	3.66	3.66	3.60	3.60	3.60	3.60	3.51	3.51	3.51	3.51
Peak	10.6	5.9	10.4	8.2	18.2	10.0	17.0	13.0	30.4	20.4	30.4	23.1
ζ_{hp}	7.2	8.8	7.2	6.8	7.0	7.4	7.3	7.7	7.7	5.6	5.8	8.1
ζ_{min}	4.8	4.7	4.5	4.7	3.8	4.1	4.5	5.0	5.0	4.0	4.6	5.4
$\bar{w}_n$	3.66				3.60				3.51			
$\bar{\zeta}_{hp}$	7.5				7.3				6.8			
$\bar{\zeta}_{min}$	4.7				4.3				4.7			
Max Acceler.	3.04 % g											

which can be explained by a softening of the system.

2. Major Axis (the east-west direction):

Three frequency sweeps were performed in the east-west direction. Tests 75-28-19, 75-28-20 and 75-28-21 were run without added weights, with two small weights and with four small weights in each basket respectively. All accelerometers were placed at the mid-point of different floors except accelerometer no.4 which was placed across the seismic joint on the second floor.

From preliminary studies, it was found that all responses obtained from channel 4 were just some random and low amplitude motions which implies that the seismic joint caused the buildings to move independently. A summary of all results is given in Table 2. A typical response curve is shown in Figure 11 and the complete information is contained in Appendix C.

From Table 2 every channel yields the same natural frequency for each frequency sweep. Test 75-28-19 gives 4.14 Hz as natural frequency, 75-28-20 gives 4.01 Hz and 75-28-21 gives 3.91 Hz. The system also exhibited the phenomenon of a softening system.

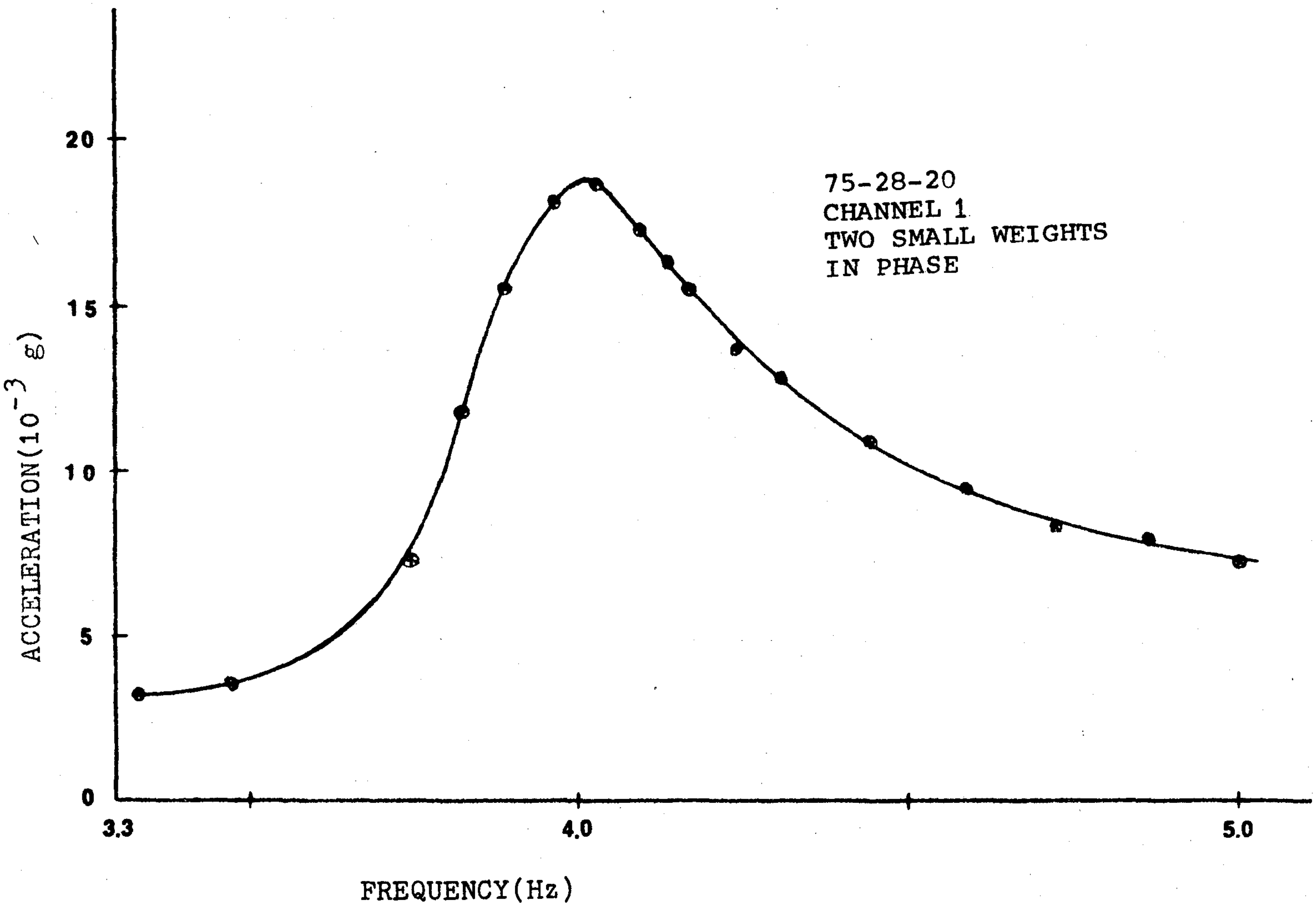
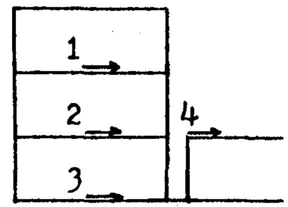


Fig. 11 Typical Frequency Response Curves Before Correction (Major Axis)

TABLE 2. MAJOR AXIS NATURAL FREQUENCY AND DAMPING

SET-UP:



SHAKERS IN PHASE

TEST NO.	75-28-19				75-28-20				75-28-21			
# OF WEIGHTS	NONE				TWO-SMALL				FOUR-SMALL			
CHANNEL	1	2	3	4	1	2	3	4	1	$\bar{2}$	3	4
w_n	4.14	4.14	4.14	----	4.01	4.01	4.01	----	3.91	3.91	3.91	----
Peak	8.0	4.40	0.65	----	18.8	10.2	2.33	----	29.4	15.8	3.78	----
ξ_{hp}	10.2	9.2	16.2	----	8.7	10.2	9.2	----	10.2	9.2	10.9	----
ξ_{min}	5.8	6.3	7.3	----	7.0	7.5	6.2	----	6.7	6.1	8.4	----
$\bar{w}_n$	4.14				4.01				3.91			
$\bar{\xi}_{hp}$	11.8				9.4				10.1			
$\bar{\xi}_{min}$	6.4				6.9				7.1			
Max Acceler.	2.94% g											

3. <u>Torsional</u>:

Again, three frequency sweeps were performed. Tests 75-28-1, 75-28-2 and 75-28-16 were run with no weight, one small weight and two small weights in each basket respectively. Test 75-28-16 was run with shakers in phase to investigate the effect on the torsional natural frequency. A typical response curve is shown in Figure 12 and a summary of the results is given in Table 3. All information about these tests is contained in Appendix D.

From Table 3, Test 75-28-1 and 75-28-2 still give the same kind of results as in major and minor axes. Every channel gives the same natural frequency for each frequency sweep and natural frequency decreases as driving force increases. The natural frequency obtained from Test 75-28-1 is 4.86 Hz and from Test 75-28-2 is 4.79 Hz. Test 75-28-16 yielded natural frequencies ranging from 4.77 Hz to 4.82 Hz with an average value of 4.8 Hz which is higher than Test 75-28-2. Even the natural frequency obtained from Test 75-28-16 is expected to be lower than Test 75-28-2 since the force level is higher during Test 75-28-16. The changes in the natural frequency may be caused by that shakers was in phase.

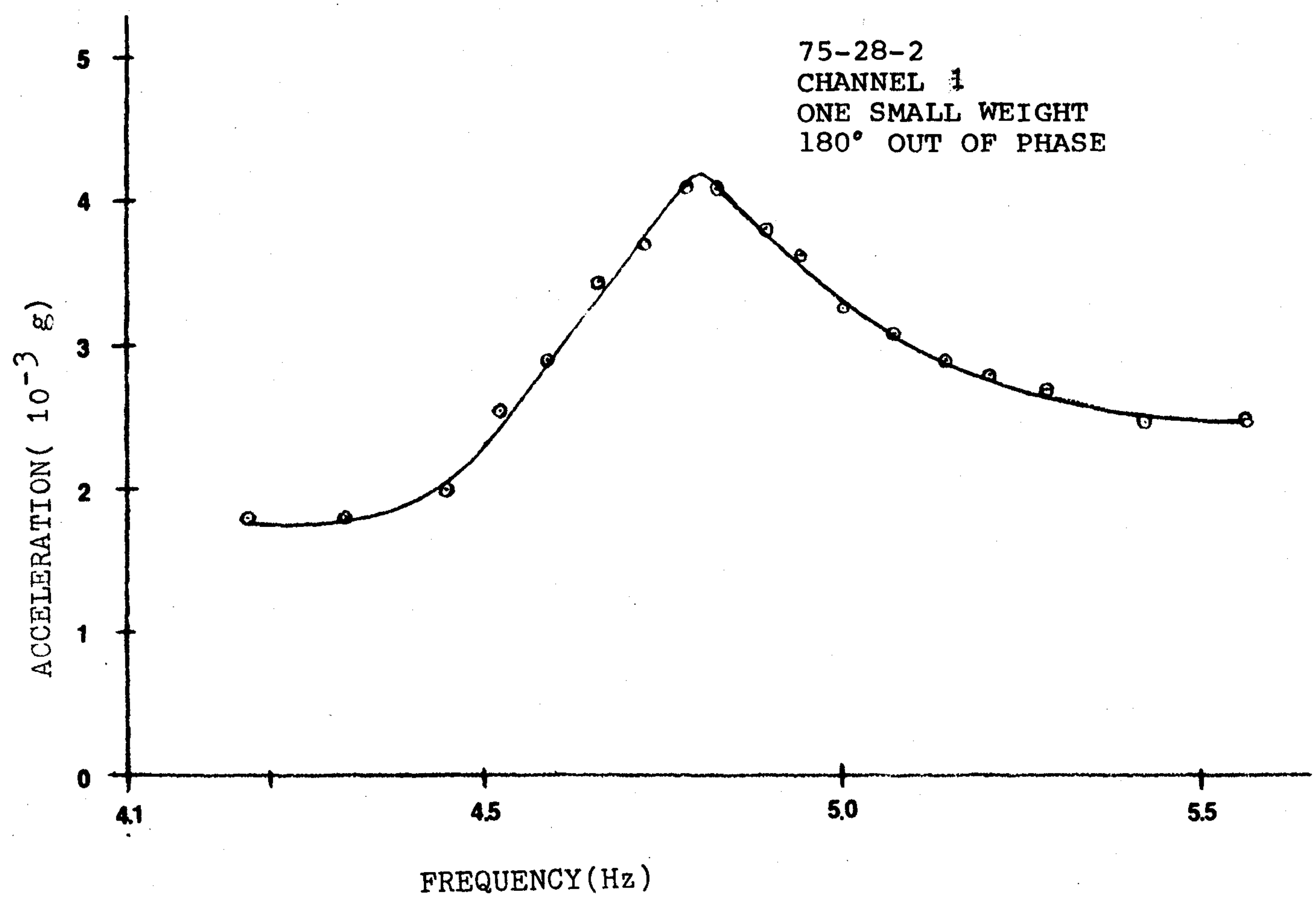


Fig.12 Typical Frequency Response Curves Before Correction (Torsional)

TABLE 3. TORSION NATURAL FREQUENCY AND DAMPING

SET-UP: ↑2 ↑3 ↑1 ↑4

TEST NO.	75-28-1				75-28-2				75-28-16			
# OF WEIGHTS	NONE				ONE				TWO			
PHASE	180 OUT				180 OUT				IN			
CHANNEL	1	2	3	4	1	2	3	4	1	2	3	4
w_n	4.86	4.86	4.86	4.86	4.79	4.79	4.79	4.79	4.82	4.81	4.81	4.77
Peak	2.3	17.4	5.4	4.9	4.1	30.7	12.9	19.6	5.7	44.3	19.8	28.8
ξ_{hp}	14.0	11.7	10.6	9.4	11.5	11.6	8.9	9.1	11.2	12.8	9.4	9.2
ξ_{min}	9.1	6.2	9.1	9.1	8.6	6.4	7.6	8.6	9.5	6.9	9.3	7.8
$\bar{w}_n$	4.86				4.79				4.80			
$\bar{\xi}_{hp}$	11.4				10.3				10.7			
$\bar{\xi}_{min}$	8.4				7.8				8.4			
Max Acceler.	4.43% g											

Test 75-28-16 was run with shakers in phase and at frequencies close to torsional natural frequency. Since it is impossible to have the shakers exactly symmetrical about the center of rigidity of the building, the torsional mode would, therefore, still be excited with shakers in phase. However, the translational mode would affect the response more than if the test was run with shakers out of phase.

B. Damping

1. Minor Axis (the north-south direction):

Damping values were obtained from the same frequency response curves as the natural frequency was obtained from and used the methods mentioned in the previous section. All results are also listed in Table 1 and a more complete set of information is contained in Appendix B.

For the half-power band method, damping value has the range from 5.6 % to 8.8 % with an average value of 7.2 %. Tests 75-27-2,3 have the range from 6.8 % to 8.8 % with an average value of 7.5 %. Test 75-27-4 has the range from 7.0 % to 7.7 % with an average value of 7.3 %. Test 75-27-6 has the range from 5.6 % to 8.1 % with an average value of 6.8 %. Overall coefficient of variation is 0.125. Coefficient of variation for Tests 75-27-2,3 is 0.117, Test 75-27-4 is 0.038 and Test 75-27-6 is 0.194. So Test 75-27-4 gives a better result with a damping value of 7.3 % by the half-power band method.

Damping obtained by the second method has an overall range from 3.8 % to 5.4 %. Tests 75-27-2,3 had 4.5 % to 4.8 %. Test 75-27-4 had 3.8 % to 5.0 % and Test 75-27-6 had 4.0 % to 5.4 %. The average for overall is 4.6 %, for Tests 75-27-2,3 is 4.7 %, for Test 75-27-4 is 4.3 %, and for Test 75-27-6 is 4.7 % The coefficient of variation is 0.102 for overall, 0.026 for Tests 75-27-2,3, 0.123 for Test 75-27-4 and 0.128 for Test 75-27-6. So Tests 75-27-2,3 should yield a better result with damping value of about 4.7 %.

2. Major Axis (the east-west direction):

Damping values were obtained from the frequency response curve of Test 75-28-19, 75-28-20, and 75-28-21. All results are shown in Table 2 and complete information is contained in Appendix C.

Damping evaluated by using the half-power band method has the range from 8.7 % to

16.2 % for overall results , 9.2 % to 16.2 % for Test 75-28-19, 8.7 % to 9.2 % for Test 75-28-20 and 9.2 % to 10.9 % for Test 75-28-21. Average value is 10.4 % for overall results, 11.8 for Test 75-28-19, 9.4 % for Test 75-28-20 and 10.1 % for Test 75-28-21. Coefficient of variation is 0.216 for overall results, 0.320 for 75-28-19, 0.079 for 75-28-20 and 0.083 for 75-28-21.

Using the second method, damping has the range from 5.8 % to 8.4 % for overall results, 5.8 % to 7.3 % for 75-28-19, 6.2 % to 7.5 % for 75-28-20 and 6.1 % to 8.4 % for 75-28-21. Average value is 6.8 % for overall results, 6.4 % for 75-28-19, 6.9 % for 75-28-20 and 7.1 % for 75-28-21. Coefficient of variation is 0.121 for overall results, 0.115 for 75-28-19, 0.091 for 75-28-20 and 0.171 for 75-28-21.

3. <u>Torsional</u>:

Frequency response curves obtained from Tests 75-28-1, 75-28-2 and 75-28-16 were used to calculate the damping. All results are shown in Table 3 and all complete information is contained in Appendix D.

Damping value obtained from the half-power band method has the range from 8.9 % to 14.0 % for overall results, 9.4 % to 14.0 % for Test 75-28-1, 8.9 % to 11.6 % for 75-28-2 and 9.2 % to 12.8 % for 75-28-16 with an average value of 10.8 % for overall results, 11.4 % for 75-28-1, 10.3 % for 75-28-2 and 10.7 % for 75-28-16. Coefficient of variation is 0.152 for overall results, 0.174 for 75-28-1, 0.144 for 75-28-2 and 0.157 for 75-28-16.

Damping calculated by the second method has the range from 6.2 % to 9.5 % for all results, 6.2 % to 9.1 % for 75-28-1, 6.4 % to 8.6 % for 75-28-2 and 6.9 % to 9.5 % for 75-28-16. Coefficient of variation is 0.146 for all results, 0.174 for 75-28-1, 0.136 for 75-28-2 and 0.153 for 75-28-16.

C. Mode Shape

1. Minor Axis (the north-south direction):

Tests 75-28-7, 75-28-8, 75-28-11, 75-28-12, 75-28-15 and 75-28-16 were run to define the mode shape in the north-south direction. All tests were run with one small weight in each basket at 3.61 Hz. Locations of accelerometers are contained in Appendix A. The reference accelerometer was placed at the west quarter point on the third floor.

Test 75-28-15 was run to check major axis and minor axis coupling. All accelerometers were placed on the third floor. Accelerometer no. 1 was in the north-south direction and accelerometer no. 2,3, and 4 were in the east-west direction. Accelerometer no. 1 was located at the west quarter point and accelerometer no. 2,3, and 4 were located at the west end, west quarter point, and east quarter point, respectively. During the test, accelerometer no. 1 had experienced an acceleration of 0.0159g. and accelerometer no. 2,3, and 4 had 0.00071g., 0.00096g., and 0.00125g., respectively. Since the acceleration in the minor axis direction is much higher than in the major direction, the response in the major axis direction is not significant.

The reference accelerometer had an acceleration value ranging from 0.0154g. to 0.0166g. All responses measured at various locations were normalized with respect to the response of the reference accelerometer of the same test. The normalized mode shape is listed in Table 4 and shown in Figure 13.

2. <u>Major Axis</u> (the east-west direction):

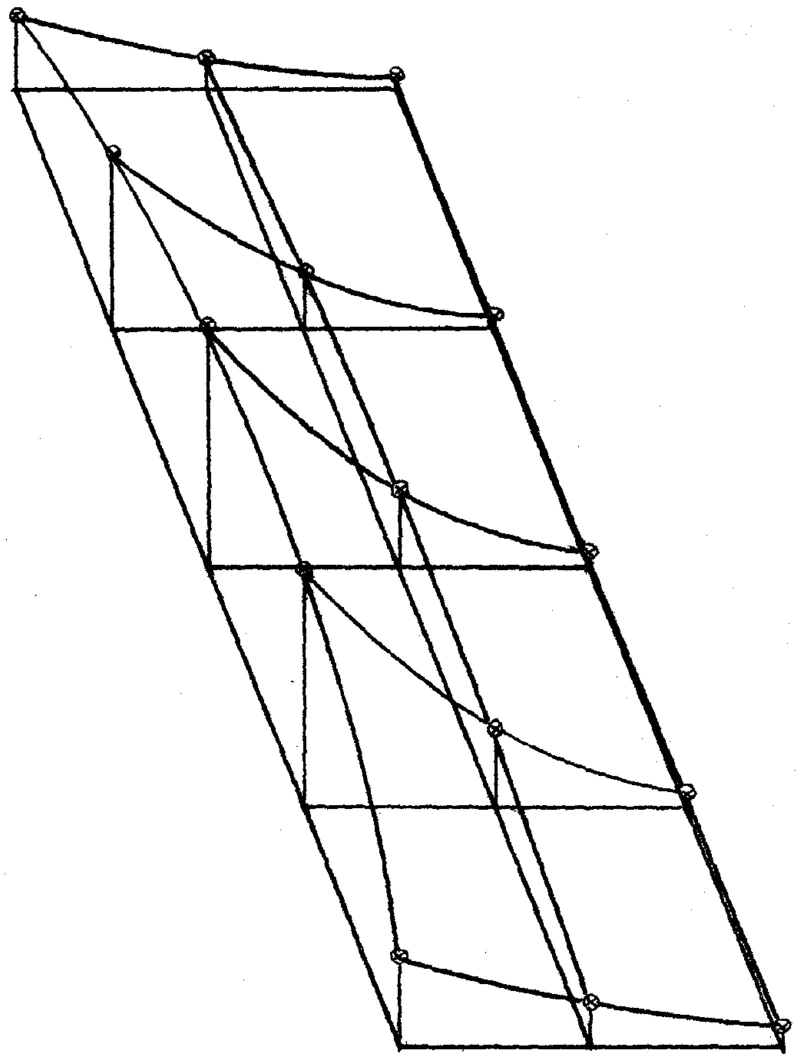


Fig. 13 Minor Axis Mode Shape Before Correction

TABLE 4

The North-South Mode Shape
(Before Correction)

	West End	West Quarter Point	Mid-Point	East Quarter Point	East End
3rd Level	0.37	1.00	1.00	0.73	0.30
2nd Level	0.19	0.31	0.31	0.23	0.13
1st Level	0.08	0.04	0.08	0.04	0.06

Mode shape in the major axis direction was obtained by taking the responses of each floor at the natural frequency from the frequency response curves. Three frequency sweeps, Tests 75-28-19, 75-28-20 and 75-28-21 with different load combinations were run in the major axis direction, so three mode shapes were obtained.

For each test, responses were normalized with respect to the response of the third level. Test 75-28-19 was run with no weight in the basket and had 0.008g. acceleration on the third floor. Test 75-28-20 was run with two weights in each basket and had 0.0188g. acceleration. Test 75-28-21 was run with four weights in each basket and had 0.0294g. acceleration. All three mode shapes are listed in Table 5 and plotted in Figure 14.

With different load combinations, the response level changed quite considerably. But, the mode shapes after normalization as shown in Table 5 are almost identical to one another, which is expected.

3. Torsional:

Tests 75-28-6, 75-28-9, 75-28-10, 75-28-13, 75-28-14 and 75-28-17 were run to

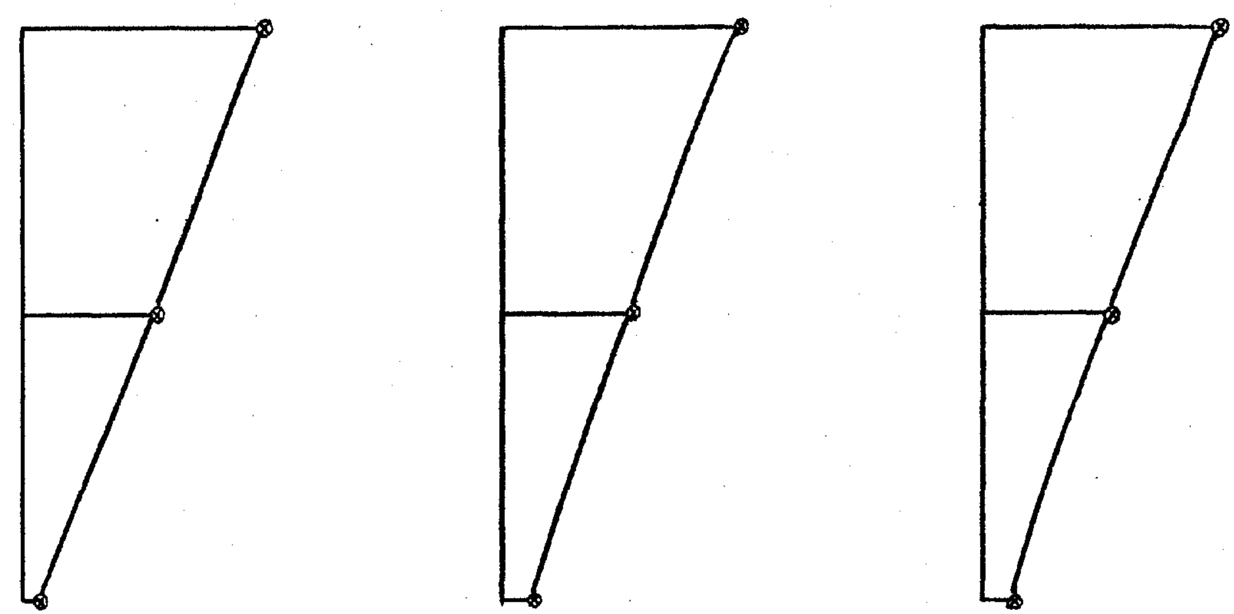


Fig. 14 Major Axis Mode Shape Before Correction

TABLE 5

The East-West Mode Shape
(Before Correction)

Test No.:	75-28-19	75-28-20	75-28-21
Weight:	None	Two	Four
3^{rd} Level:	1.0	1.0	1.0
2^{nd} Level:	0.55	0.54	0.53
1^{st} Level:	0.08	0.12	0.12

define the torsional mode shape. All the locations of accelerometers are listed in Appendix A. All tests were run with one weight in each basket at 4.79 Hz. The reference accelerometer was located at the west quarter point of the third floor.

Test 75-28-17 was run to check coupling of torsional and major axis direction. The set-up was the same as that of Test 75-28-17 mentioned earlier. Accelerometer no. 1 through 4 experienced an acceleration of 0.01455g., 0.00114g., 0.00096g., and 0.00063g., respectively. So the motion in major axis direction was insignificant to affect the torsional testting.

The reference accelerometer measured acceleration from 0.01427g. to 0.01455g. during all tests. All responses were normalized with respect to the response of the reference accelerometer of the same test. The normalized mode shape is shown in Table 6 and Figure 15.

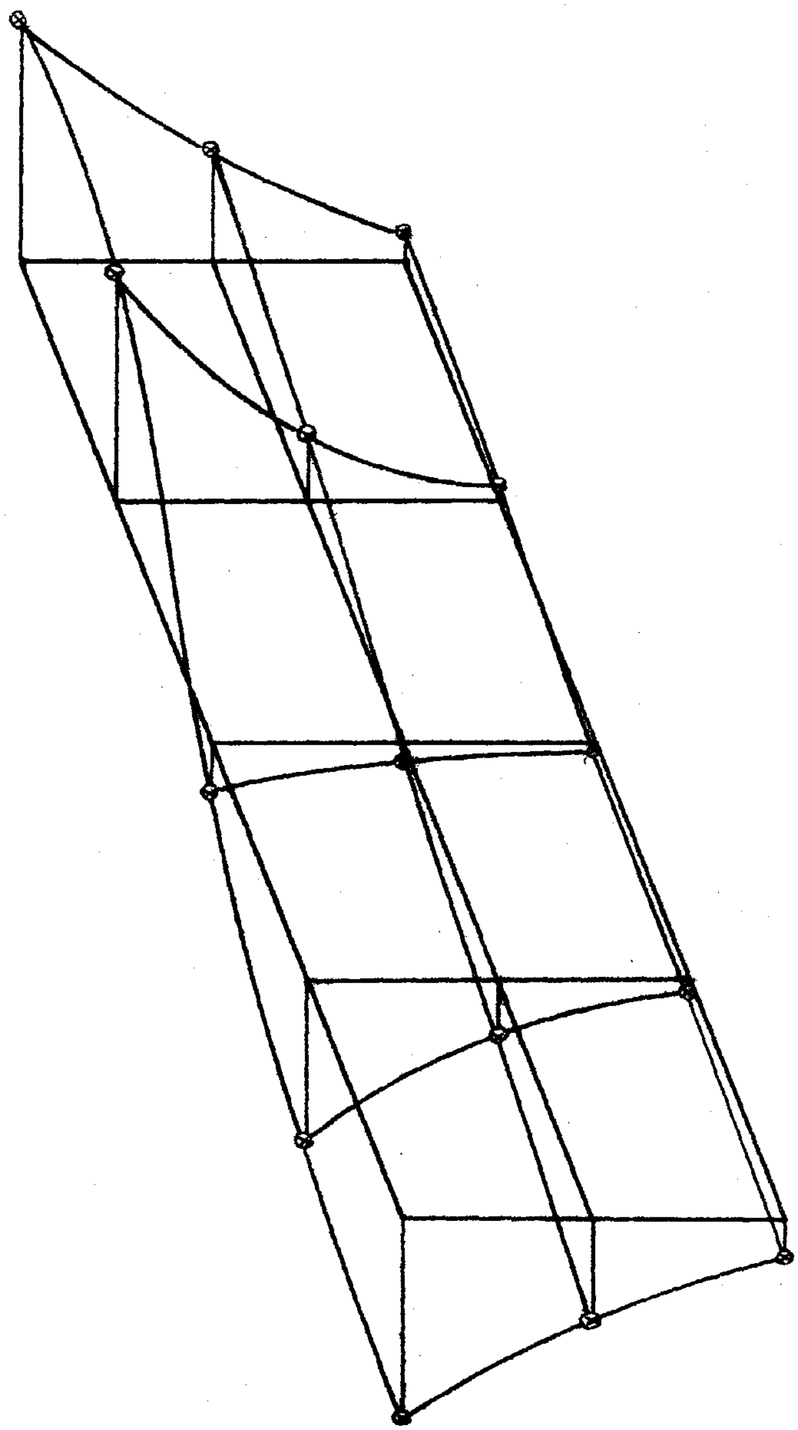


Fig. 15 Torsional Mode Shape Before Correction

TABLE 6

The Torsional Mode Shape
(Before Correction)

	West End	West Quarter Point	Mid- Point	East Quarter Point	East End
3rd Level	+1.21	+1.0	+0.29	-1.39	-1.45
2nd Level	+0.62	+0.33	+0.12	-0.42	-0.67
1st Level	+0.24	+0.06	+0.04	-0.08	-0.15

V. DESCRIPTIONS AND RESULTS OF THE SECOND TEST SERIES

The second test on North Hall after the seismic rehabilitation was performed on September 3 and 4, 1976. September 3 was spent in setting up test equipment and calibrating all the instruments; no test was run. Fifteen tests were run on September 4. All tests were numbered in the same way as in the first test series. All the test information is contained in Appendix E.

During the second test series, two harmonic vibrators were mounted at the same locations as in the first test series. However, only one vibrator was used for each test; so the frequency sweep in the minor axis direction would yield both translational (minor axis) and torsional response. The reference accelerometer was placed at the west quarter point of the third floor. All other accelerometers were placed at the locations of interest for each test.

Again, accelerometer no. 4 was placed across a seismic joint in the adjacent structure during Test 76-4-11 to study the function of the seismic joint. Some tests were run with an accelerometer placed outside the building to study the soil impedance. Test 76-4-4 was run with the vibrator shaking in the major axis direction and accelerometer no. 4 was placed next to the building, 25 feet away from the building and 45 feet away from the building in the east-west direction at the mid-point of the south side of the building. Test 76-4-13 was run with the vibrator shaking in the minor axis direction at both the minor axis and torsional natural frequency. During the test all accelerometers were in the north-south direction. Accelerometer no. 2,3, and 4 were placed at the east, south and west sides, respectively, and were five feet away from the building for the first set-up; twenty-five feet away for the second set-up.

Limited by the frequency range of the vibrator, only the first mode was obtained in all directions and had the following results:

A. Natural Frequency

1. Minor Axis (the north-south direction):

Two frequency sweeps were performed with the shaker in the north-south direction. Test 76-4-5 was run with no weight in the basket and Test 76-4-6 was run with one weight in each basket. All accelerometers were placed on the third floor during the tests. A typical respo-

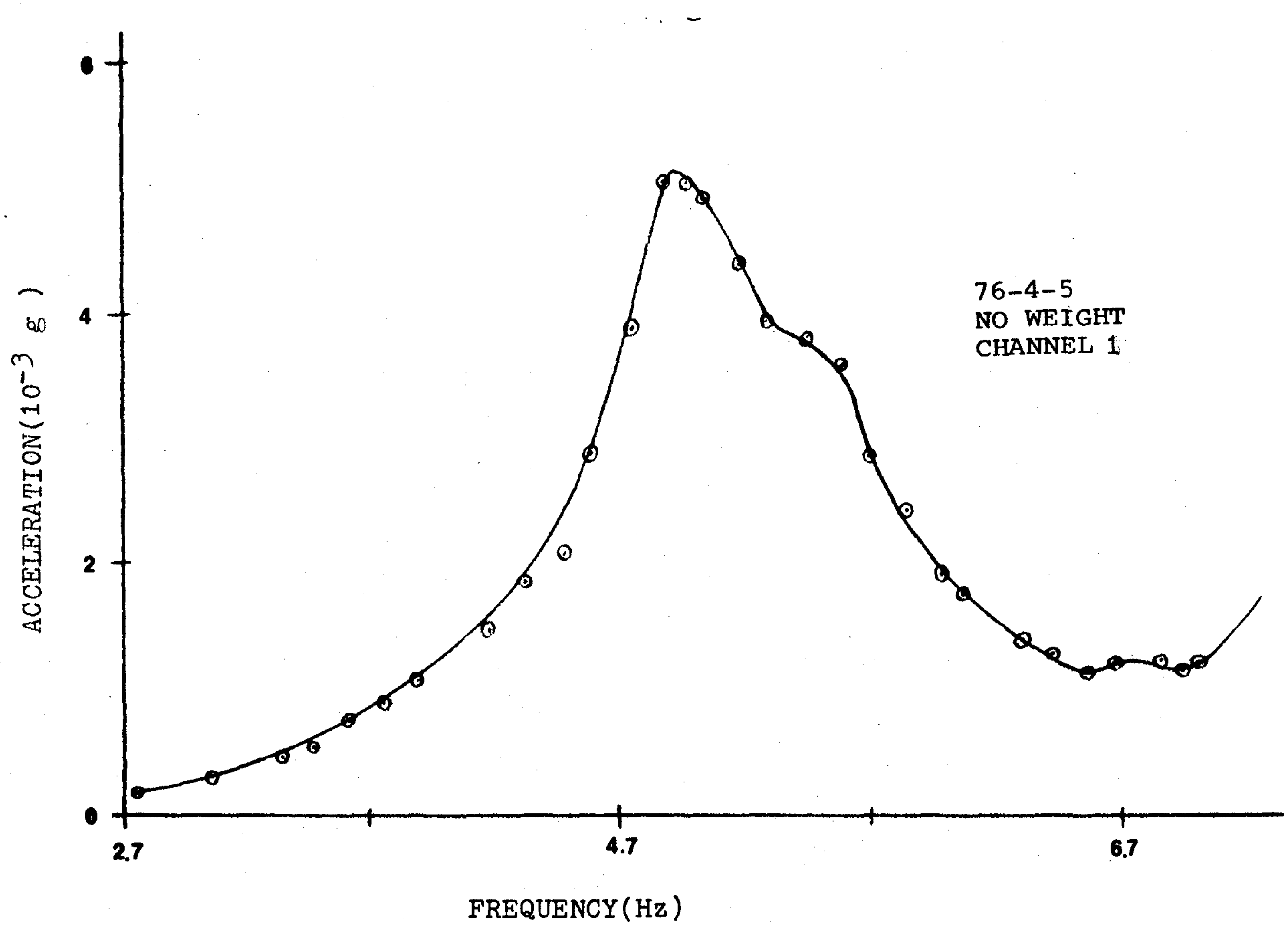


Fig. 16 Typical Frequency Response Curves After Correction (Minor & Torsional)

TABLE 7. MINOR AXIS NATURAL FREQUENCY AND DAMPING

SET-UP: ↑2 ↑3 ↑1 ↑4

TEST NO.	76-4-5				76-4-6			
# OF WEIGHTS	NONE				ONE			
CHANNEL	1	2	3	4	1	2	3	4
w_n	4.90	4.90	4.90	4.90	4.90	4.90	4.86	4.93
Peak (x 10^{-3}g)	5.3	6.0	6.6	3.4	8.6	10.0	11.1	6.1
ξ_{hp}	7.3	6.3	5.5	12.4	7.7	5.4	5.4	12.4
ξ_{min}	4.3	4.6	4.9	3.3	3.9	4.3	4.3	5.1
$\bar{w}_n$	4.90				4.90			
$\bar{\xi}_{hp}$	6.3				6.1			
$\bar{\xi}_{min}$	4.3				4.4			
Max Acceler.	1.11% g							

nse curve is shown in Figure 16 also a summary of the results are shown in Table 7 and complete information is contained in Appendix F.

From Table 7, all channels yield 4.90 Hz as natural frequency for Test 76-4-5. Channel 1 and 2 yield 4.9 Hz, channel 3 yields 4.86 Hz and channel 4 yields 4.93 Hz with an average value of 4.8975 Hz for Test 76-4-6. The spring softening phenomenon does not exist.

2. <u>Major Axis</u> (the east-west direction):

Two frequency sweeps were performed in the major axis direction. Test 76-4-2 was run with an empty basket and all accelerometers were placed at the mid-point of the third floor. Test 76-4-3 was run with one weight in each basket. Accelerometer no. 1,2 and 4 were placed in the east-west direction at the mid-point of the third, second and first floors, respectively. Accelerometer no. 3 was placed at the mid-point of the third floor in the north-south direction to check major and minor axis coupling.

A typical response curve is as before, shown in Figure 17. Summary of the results is listed in Table 8. Complete information is contained in Appendix G. From Table 8, all chan-

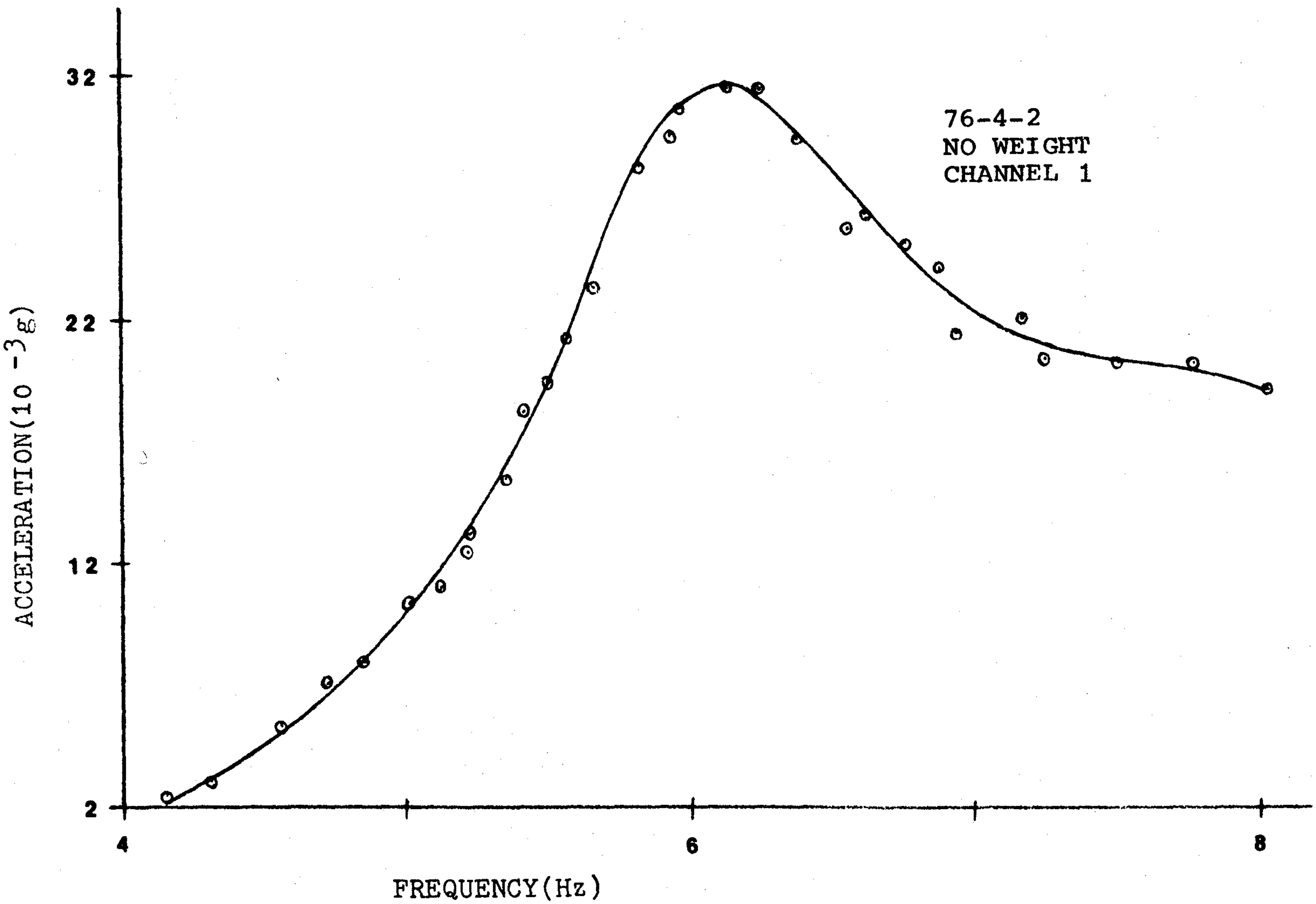
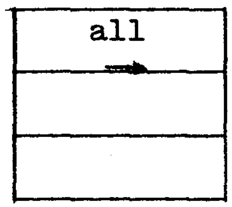


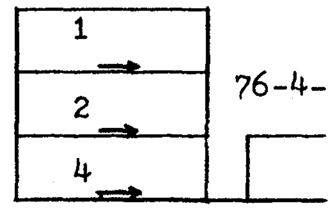
Fig. 17 Typical Frequency Response Curves After Correction (Major Axis)

TABLE 8. MAJOR AXIS NATURAL FREQUENCY AND DAMPING

SET-UP:

76-4-2:





76-4-3:

TEST NO.	76-4-2				76-4-3			
# OF WEIGHTS	NONE				ONE			
CHANNEL	1	2	3	4	1	2	3	4
w_n (Hz)	6.13	6.13	6.13	6.13	6.13	6.13	----	6.13
Peak ($10^{-3}g$)	3.2	3.6	3.4	3.3	6.3	3.7	----	1.5
ξ_{hp}	12.2	8.7	11.3	15.4	10.0	8.7	----	9.1
ξ_{min}	8.5	7.4	8.2	9.1	8.7	8.1	----	7.1
$\bar{w}_n$	6.13				6.13			
$\bar{\xi}_{hp}$	11.9				9.3			
$\bar{\xi}_{min}$	8.3				8.0			
Max Accelerat.	0.613% g							

nels for both tests give natural frequency of 6.125 Hz and Test 76-4-3 shows that major and minor axis coupling is not noticeable.

3. Torsional:

Only one shaker was used during the frequency sweep in the north-south direction. Using frequency response curves obtained from Tests 76-4-5 and 76-4-6, torsional natural frequency should be able to be identified. Summary of the results are shown in Table 9.

Channel 1 was located at the center of the third floor, so it is reasonable that torsional peak is hard to be identified. From Table 9, Test 76-4-5 yields natural frequency from 5.90 Hz to 6.10 Hz and Test 76-4-6 yields natural frequency from 5.70 Hz to 6.16 Hz.

B. Damping

1. Minor Axis (the north-south direction):

Damping values are calculated from frequency response curves of Tests 76-4-5 and 76-4-6. All results as shown in Table 7. Since the frequency response curves for channel 4 have translational and torsional peaks very close to each other, damping values evaluated by the half-power band method are ignored.

TABLE 9

Torsion

TEST NO.	CHANNEL	w_n	PEAK (x 10^{-3}g)
76-4-5	1	----	----
	2	6.10	6.30
	3	5.90	2.67
	4	5.95	3.32
76-4-6	1	----	----
	2	6.16	11.25
	3	5.84	5.11
	4	5.70	6.05

As shown in Table 7, by using the half-power band method, damping varies from 5.4 % to 7.7 % with an average value of 6.2 %. Damping from Test 76-4-5 varies from 5.5 % to 7.3 % with an average of 6.3 %. Damping from Test 76-4-6 varies from 5.4 % to 7.7 % with an average of 6.1 %. By using the second method, damping ranges from 3.3 % to 5.1 % and has an average of 4.3 %. Test 76-4-5 ranges from 3.3 % to 4.9 % with an average of 4.3 %. Test 76-4-6 ranges from 3.9 % to 5.1 % with an average of 4.4 %.

2. <u>Major Axis</u> (the east-west direction):

Damping values were obtained from frequency curves of Tests 76-4-2 and 76-4-3. All results are contained in Table 8 and complete information is included in Appendix G.

Using the half-power band method, damping ranges from 8.7 % to 15.4 % and has an average value of 10.7 %. Test 76-4-2 ranges from 8.7 % to 15.4 % and has an average of 11.9 %. Test 76-4-3 ranges from 8.7 % to 9.9 % and has an average of 9.3 %. Using the second method, damping values ranging from 7.1 % to 9.1 % with an average of 8.2 %. Test 76-4-2 ranges from 7.4 % to 9.1 % with an average of 8.3 %. Test 76-4-3 ranges from 7.1 % to 8.7 % with an average of 8.0 %.

3. Torsional:

Damping of torsional mode was not evaluated due to the shape of the frequency response curve.

C. Mode Shape

1. Minor Axis (the north-south direction):

Tests 76-4-9, 76-4-10, 76-4-11 and 76-4-12 were run with one small weight in each basket; part of each test was run at minor direction natural frequency (4.93 Hz). Together with the response obtained from frequency sweep Test 76-4-6, mode shape is defined. The reference accelerometer was located at the west quarter point of the third floor. All responses were normalized to the reference accelerometer.

Normalized mode shape is shown in Table 10 and plotted in Figure 18. The reference accelerometer had measured acceleration ranges from 0.0109 g. to 0.0111 g.

2. Major Axis (the east-west direction):

Mode shape of major axis direction is obtained from the peak acceleration of each

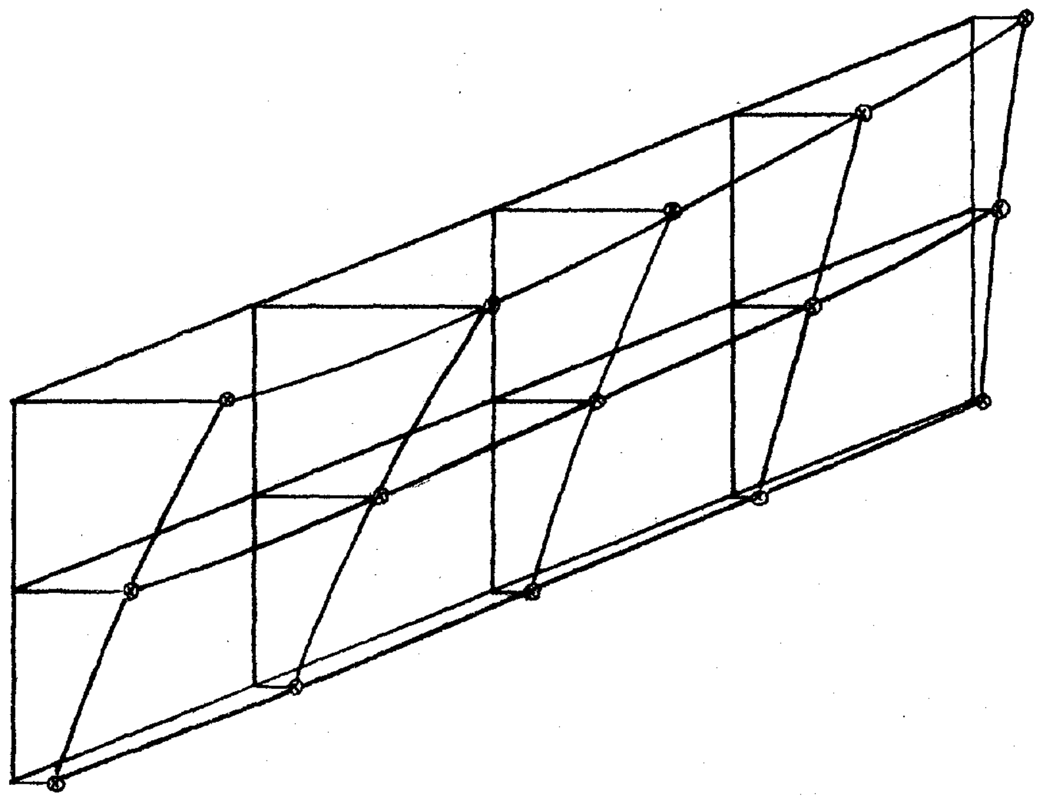


Fig. 18 Minor Axis Mode Shape After Correction

TABLE 10

The North-South Mode Shape
(After Correction)

	West End	West Quarter Point	Mid-point	East Quarter Point	East End
3rd Level	0.889	1.0	0.753	0.530	0.201
2nd Level	0.493	0.519	0.424	0.329	0.105
1st Level	0.174	0.171	0.164	0.101	0.034

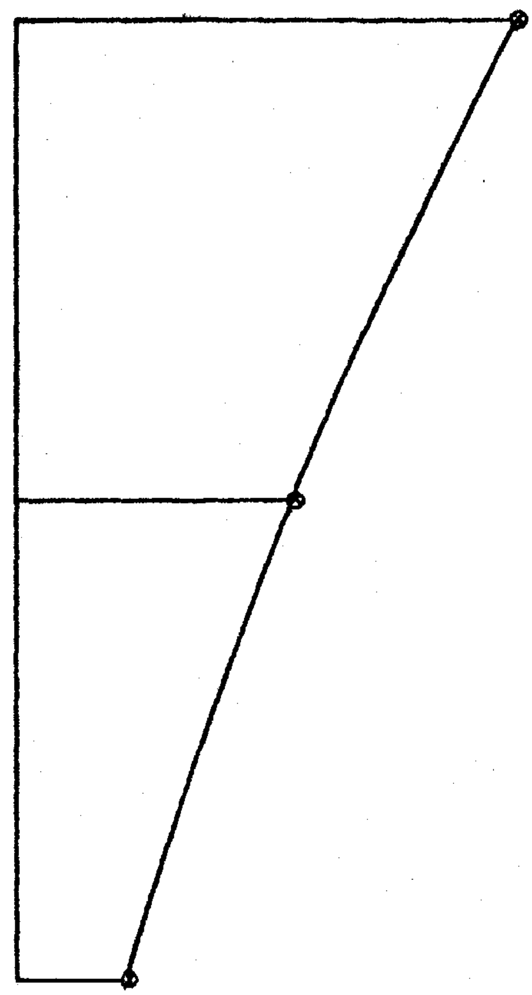


Fig. 19 Major Axis Mode Shape After Correction

TABLE 11

The East-West Mode Shape
(After Correction)

3^{rd} Level:	1.0
2^{nd} Level:	0.58
1^{st} Level:	0.24

level during Test 76-4-3. Responses are normalized with respect to the response of the top level. The top floor had peak acceleration of 0.0063 g. Normalized mode shape is shown in Table 11 and Figure 19.

3. Torsional:

During frequency sweeps, each channel yielded different torsional frequency. The accelerometer on the farthest end should have the largest response due to torsion. So the natural frequency obtained from the accelerometer at the end was used to define the torsional mode shape. Part of Tests 76-4-9, 76-4-10, 76-4-11 and 76-4-12 was run at 6.11 Hz with one weight in each basket. Together with frequency sweep Test 76-4-6, mode shape is obtained.

The reference accelerometer was placed at the west quarter point of the third floor. All responses were normalized to the reference accelerometer. The reference accelerometer experienced acceleration from 0.0044g. to 0.0050 g. during all testing. Normalized mode shape is shown in Table 12 and Figure 20.

D. Outside Building Test

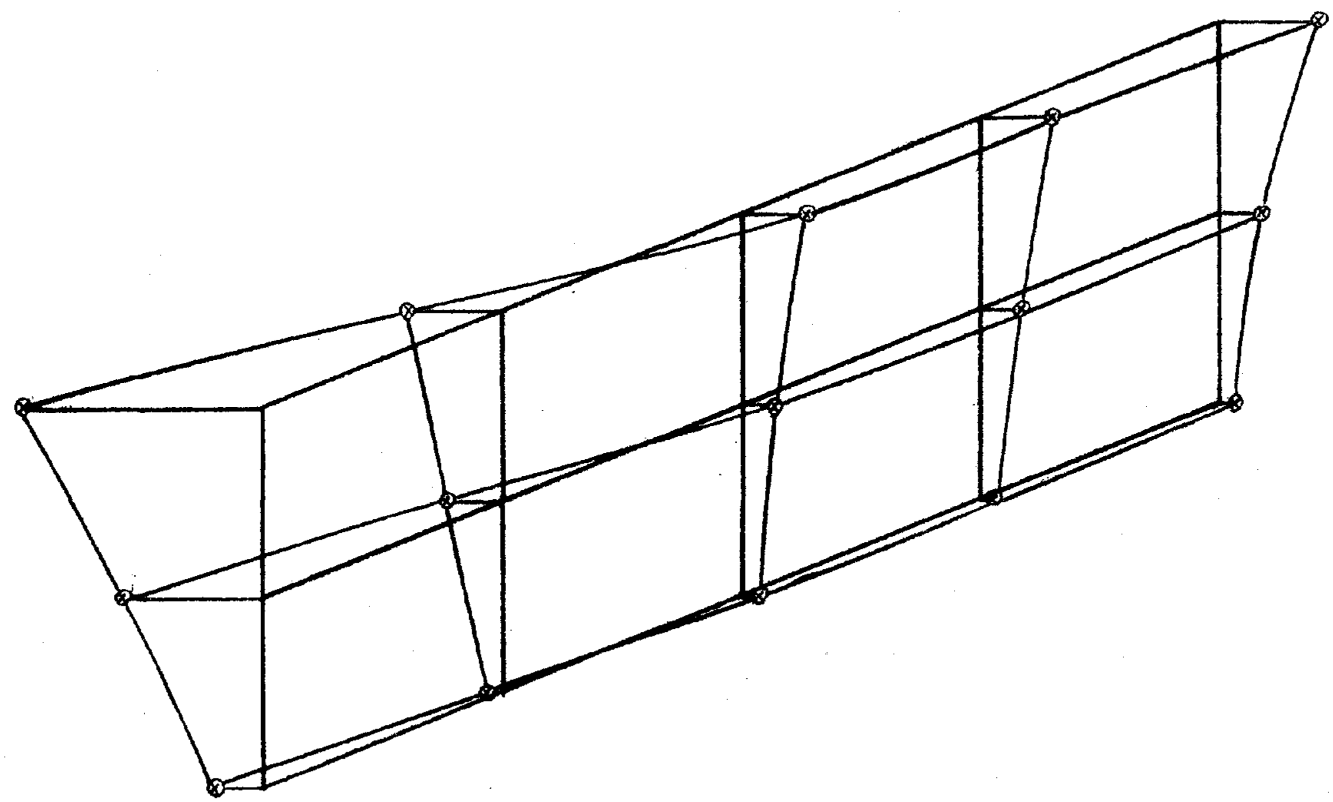


Fig. 20 Torsional Mode Shape After Correction

TABLE 12

The Torsional Mode Shape
(After Correction)

	West End	West Quarter Point	Mid-point	East Quarter Point	East End
3rd Level	2.528	1.0	-0.687	-0.742	-1.059
2nd Level	1.498	0.593	-0.347	-0.444	-0.454
1st Level	0.517	0.124	-0.141	-0.091	-0.133

Test 76-4-4 was run with accelerometer no. 4 placed at the south side next to the building, twenty-five and forty-five feet away from the building in the east-west direction. The test was run at 6.04 Hz which is close to the natural frequency in the east-west direction. As shown in Table 13, acceleration decreases from 0.0012 g. to 0.0007 g. to 0.0006 g. as distance increases from 0 to 25 to 45 feet away from the building.

Test 76-4-13 measured ground acceleration 5 and 25 feet away from the building at the east, west and south side of the building. The test was run at translational (4.93 Hz) and torsional (6.11 Hz) frequency. All accelerometers were placed in the north-south direction. Results are shown in Table 13. In all directions, results show that ground acceleration decreases as distance increases. On the south side of the building measurements were taken on a concrete slab so measured acceleration level was not as high as the other sides.

TABLE 13

Outside Building Test

	West Side		East Side		South Side			
	5 ft	25 ft	5 ft	25 ft	0 ft	5 ft	25 ft	45 ft
Minor	1.667	0.494	0.162	0^+	----	1.111	1.00	----
Major	----	----	----	----	1.189	----	0.703	0.649
Torsion	1.914	0.679	0.105	0^+	----	0.444	0.171	----

*All results are shown in units of 10^{-3}g.

VI. COMPARISON OF TEST RESULTS

Comparisons were made of the dynamic characteristics of the building before and after the seismic rehabilitation. Results are contained in Table 14 through 17 and also discussed below.

A. Natural frequency:

As shown in Table 14, The natural frequency in the minor axis direction changed from 3.595 Hz to 4.90 Hz; an increase of 36%. In the major axis direction, the natural frequency changed from 4.01 Hz to 6.125 Hz; an increase of 53%. For the torsional mode, the natural frequency changed from 4.79 Hz to 6.11 Hz; an increase of 28%.

Steel stud walls were replaced by reinforced concrete shear walls during the rehabilitation and the change in mass is negligible comparing with the total mass of the building, so the total mass remains unchanged. Assuming a single degree of freedom system, then the natural frequency $w_n=(K/M)^{\frac{1}{2}}$ and from which the changes in stiffness can be evaluated. It was found that stiffness has increased 86% in the minor axis direction, 123% in the major axis direction and 63% in the torsional direction.

B. Damping:

From Table 14, damping evaluated from half power bandwidth method has changed from 7.2% to 6.3%

<u>TABLE 14</u>

Comparison of Natural Frequency & Damping

		Before	After	Change
Minor Axis	Natural Frequency	3.595	4.90	36.30%
	Damping (A)	7.2 %	6.3 %	-12.07%
	(B)	4.6 %	4.3 %	-5.03%
Major Axis	Natural Frequency	4.01	6.125	52.74%
	Damping (A)	10.4%	10.8 %	3.56%
	(B)	6.8 %	8.2 %	19.68%
Torsion	Natural Frequency	4.79	6.11	27.56%
	Damping (A)	10.8 %	----	----
	(B)	8.2 %	----	----

Note: (A) used half power band method.
(B) used semi-half power band method.

and decreased 12.1% in the minor axis direction, changed from 10.4% to 10.8% and increased 3.6% in the major axis direction. Damping evaluate from the second method have changed from 4.6 % to 4.3 % and decreased 5.0% in the minor axis direction, changed from 6.8 % to 8.2 % and increased 19.7% in the major axis direction. Damping in the torsional direction was not evaluated for the second test series, so no comparison was made.

C. <u>Mode shape</u>:

The minor axis mode shape for before and after the seismic correction was normalized to the west-quarter point of the third floor. The renormalized mode shapes are listed in table 15 and shown in figure 21, the response for before seismic correction is relatively more symmetric to the mid point than the response after seismic correction. Responses after seismic correction at the west end are much larger than the east end which implies the east end of the building is stiffer than the west end.

The major axis mode shape for before and after seismic correction was normalized to the third level. The normalized mode shapes are listed in table 16 and plotted in figure 22 for comparison. The changes are very small.

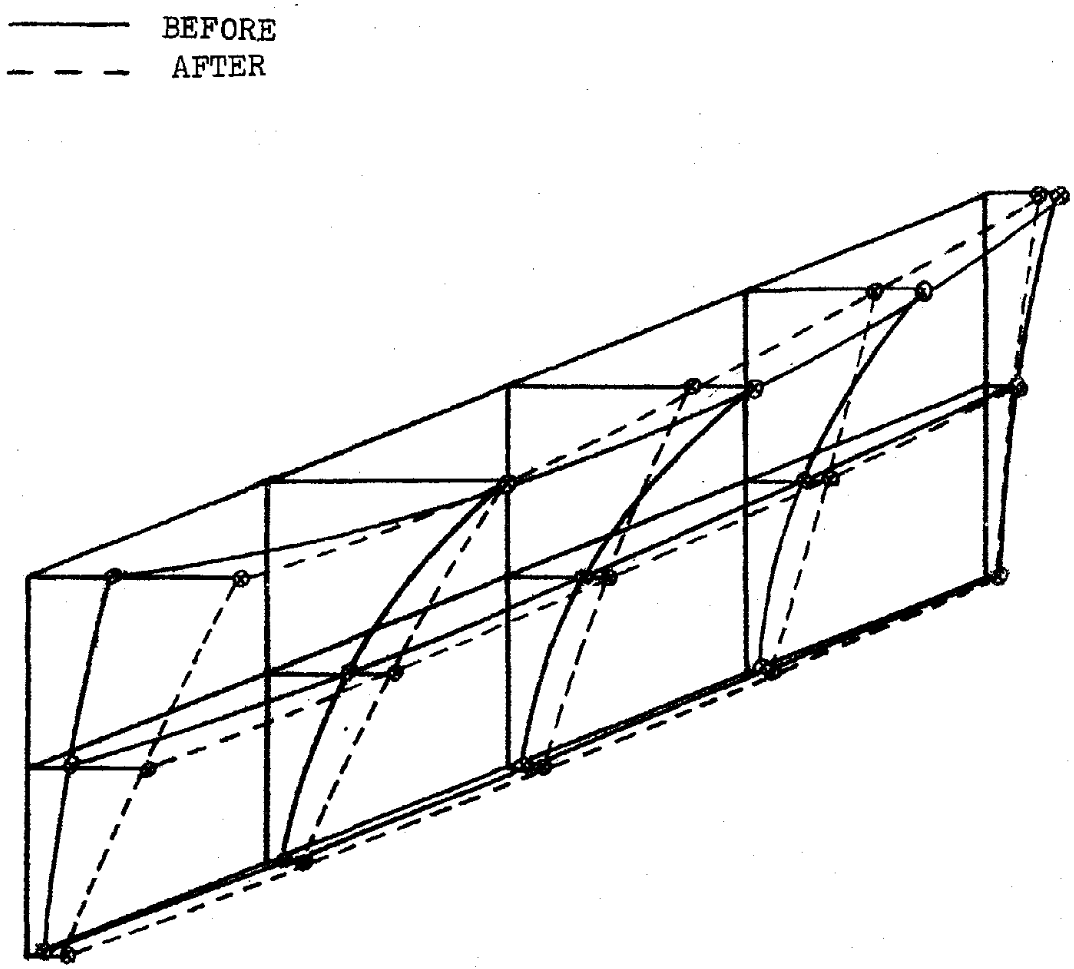


Fig. 21 Comparsion of Mode Shapes (Minor Axis)

TABLE 15

Comparison of Mode Shape
(Minor Axis)

	West End		West Quarter Point		Mid-point		East Quarter Point		East End	
	Before	After	Before	After	Before	After	Before	After	Before	After
3rd Level	0.372	0.889	1.0	1.0	1.004	0.753	0.732	0.530	0.301	0.201
2nd Level	0.197	0.493	0.313	0.519	0.311	0.424	0.233	0.329	0.130	0.105
1st Level	0.081	0.174	0.047	0.171	0.080	0.164	0.041	0.101	0.065	0.034

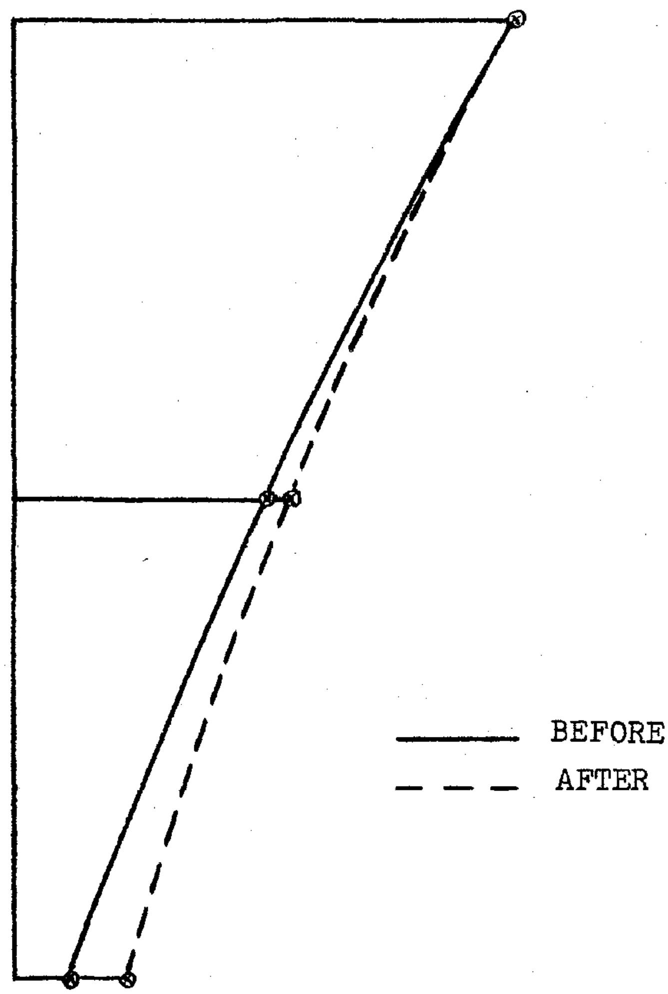


Fig. 22 Comparsion of Mode Shapes (Major Axis)

TABLE 16

Comparison of Mode Shape
(Major Axis)

	Before	After
3rd Level	1.0	1.0
2nd Level	0.540	0.58
1st Level	0.124	0.24

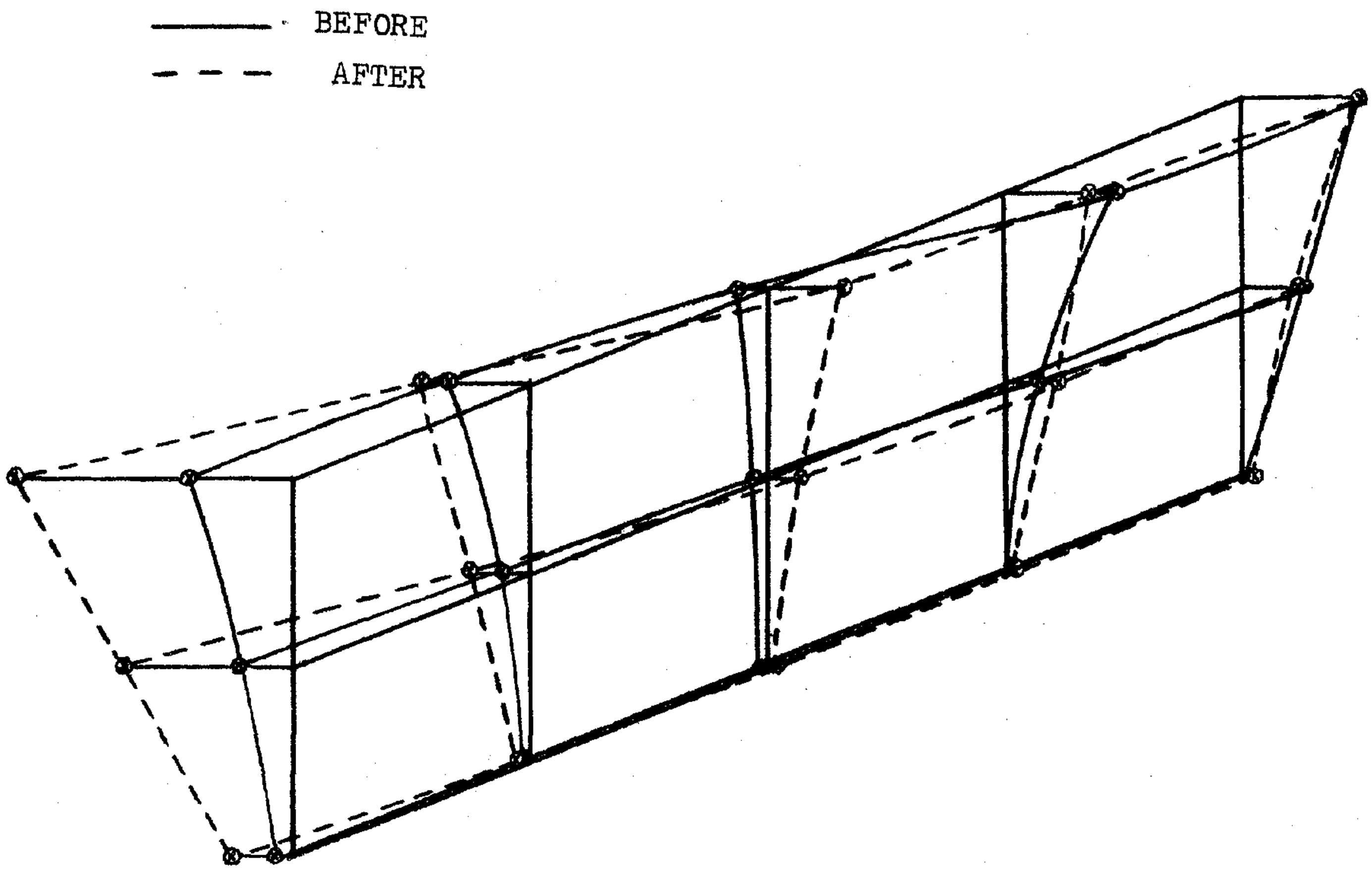


Fig. 23 Comparsion of Mode Shapes (Torsional)

TABLE 17

Comparison of Mode Shape
(Torsional)

	West End		West Quarter Point		Mid-point		East Quarter Point		East End	
	Before	After	Before	After	Before	After	Before	After	Before	After
3rd Level	-0.832	-2.387	-0.687	-0.944	-0.203	0.649	0.958	0.701	1.0	1.0
2nd Level	-0.428	-1.415	-0.229	-0.560	-0.086	0.328	0.290	0.419	0.462	0.429
1st Level	-0.171	-0.488	-0.047	-0.117	-0.028	0.133	0.058	0.086	0.109	0.126

The torsional mode shape for before and after the seismic correction was normalized with respect to the east end of the third floor. The re-normalized mode shapes are listed in table 17 and shown in figure 23. Again the response at the west end is much higher than the east end which is consistent with the results obtained for the minor axis direction.

The deformed shapes in the minor axis and torsional direction of the third floor for both before and after seismic correction is shown in figure 24 and 25. Even the deformed shapes are not the same but both show that the floor slab is not rigid in its own plane, since the deformed shape of a rigid body should be a straight line and none of the experimental results is anywhere close to a straight line.

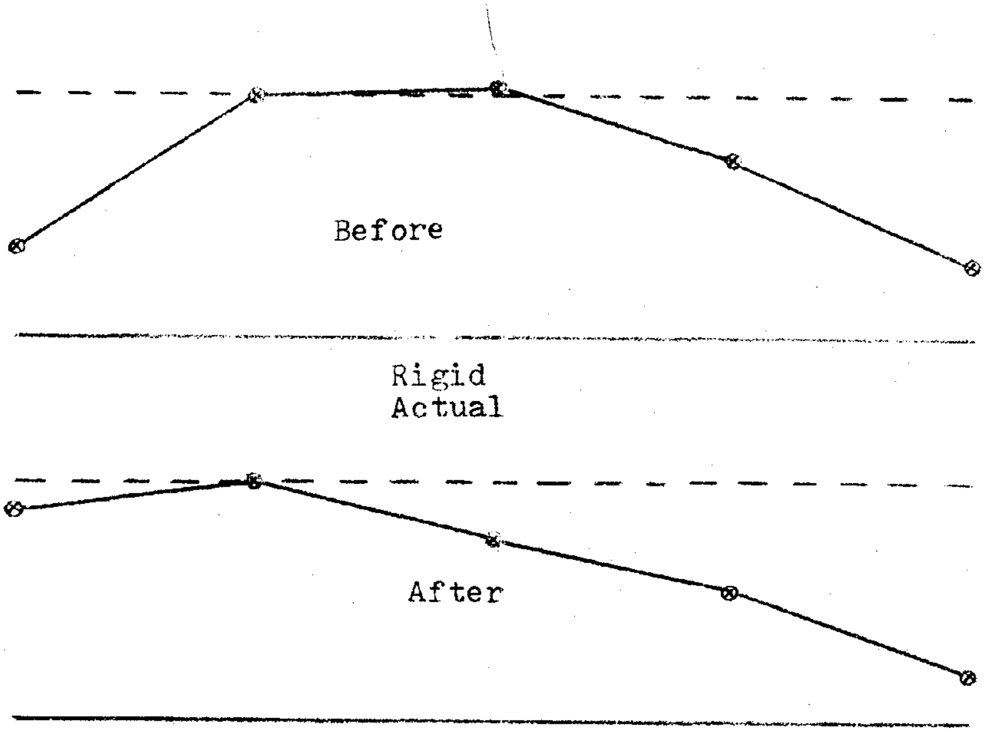


Fig. 24 Third Floor Deformed Shapes (Minor Axis)

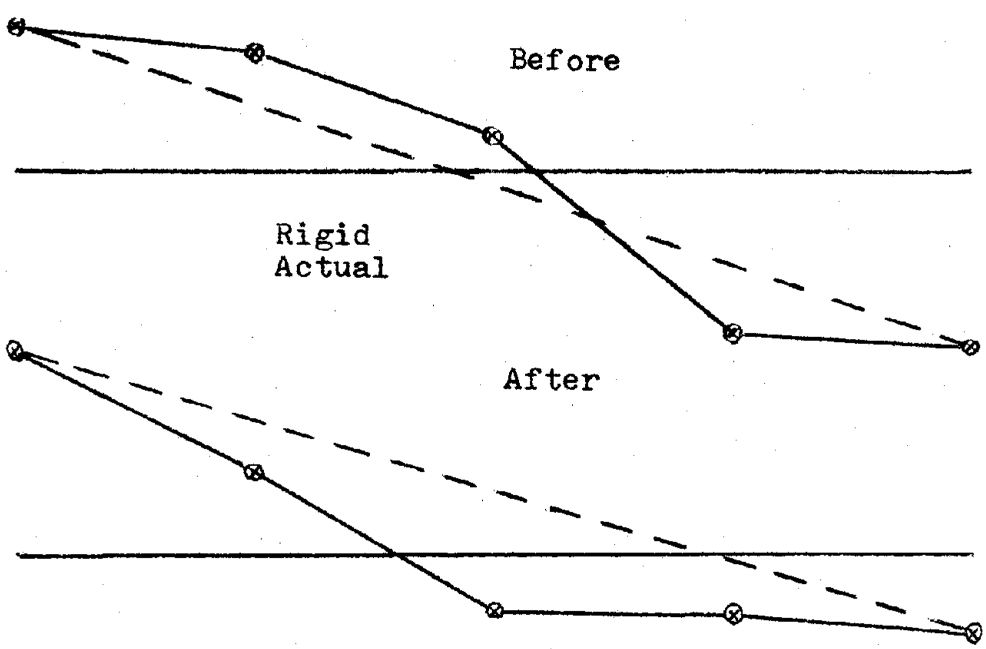


Fig. 25 Third Floor Deformed Shapes (Torsional)