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# AMBIENT VIBRATION TESTS OF FULL-SCALE STRUCTURES

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**SESSION 4 C: Dynamic Tests of Structures**

# AMBIENT VIBRATION TESTS OF FULL-SCALE STRUCTURES

by

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## SYNOPSIS

Ambient vibration testing of full-scale structures excited by wind and microtremor ground motions is discussed in terms of (1) comparison with higher level vibration generator tests; (2) comparison with earthquake-excited motions; (3) changes in ambient vibration response between pre- and post-earthquake conditions; and (4) analysis of three-dimensional building models. Information is given on modern methods of ambient test measurements based on magnetic tape recording and electronic analog-digital conversion.

## INTRODUCTION

Parameters of fundamental engineering importance in the dynamic analysis of structures are the natural frequencies of vibration and the damping in the various modes(1,2,3). Since these parameters determine the behavior of structures during strong ground shaking until yielding becomes significant, it is important to develop experimental procedures for measuring them in full scale structures.

Engineering structures are usually large and require large forces for their excitation. One is therefore led to utilize dynamic loadings which may arise naturally. Larger loads created by strong winds or earthquakes can also be used to study the response at higher excitation levels. Most of the wind and background noise loadings, however, represent low level excitations(4-7) when compared with structural design loads. Though the use of these low level excitations has not been completely ignored in the past(8) it has gained considerable attention in the past few years with the advent of superior instrumentation(5-12). The advantages of these tests over forced vibration measurements(13,14) are that they are quick, easy to perform and can be conducted by a small group of people. Also, with improved methods of analysis, excellent data on three-dimensional oscillations(15) can be obtained.

Since the frequencies during large earthquakes show marked differences from those ascertained by pre-earthquake low amplitude vibration tests, pre- and post-ambient testing of structures gives valuable data on the overall reduction in structural stiffness caused by large deformations. This paper, therefore, attempts to present the state of the art in ambient vibration testing of structures through an outline of studies made on four typical modern buildings.

## DESCRIPTION OF MEASURING EQUIPMENT

Seismometers with velocity type transducers are usually used in ambient vibration tests. The natural period of these instruments is close to one second and the damping is adjusted to 0.7 of the critical

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value. Amplification of all frequencies higher than about 1 cps is nearly a constant with a 6 db per octave fall off for lower frequencies. This low frequency fall off can be used to advantage in the study of tall structures with fundamental periods close to two seconds or longer, for the low frequency modes do not dominate the records, thus facilitating the study of some of the higher modes of vibration.

The transducer output is amplified through a signal conditioner having a maximum amplification of 350,000. When used with a velocity transducer, output voltages proportional to velocity, displacement or acceleration can be obtained depending on the frequency ranges of interest.

The amplified signal is recorded on a low noise FM-tape recorder with high tape speeds (15 ips) to reduce wow and flutter. The analog data are then converted to digital form on an analog-digital converter. During each measurement a direct visual display on ink recorders is made. This permits the digital data blocks to be edited before the spectral analysis proceeds, and assists in monitoring the measurements during the field tests.

Various sources of error may arise at different points in the measurement chain. The generator constant of the transducer may vary by about 1-2% depending on the level of excitation and the frequency content of the signal. The amplification process may introduce noise voltages and FM modulation-demodulation errors in the tape recording equipment may occur. Noise in the analog to digital conversion of data can be more effectively reduced through improved resolution of the converter rather than through increased sampling rates[16].

## FIELD PROCEDURES, DATA ANALYSIS AND INTERPRETATION

Most ambient or shaker excited building vibration tests assume that the structure can be approximated by a damped, linear, discrete or continuous system whose properties vary with reference to a line. In some cases[4] measurements indicate that floor structures are sufficiently stiff so that the above assumption of a one-dimensional line model is acceptable. In the experimental studies, it is then assumed that building vibrations can be expressed as a superposition of modes associated with discrete frequencies. This approach requires a simultaneous measurement of motion at a minimum of two different floor levels.

Typically, two simultaneous velocity recordings are made in each run. One of the transducers (the reference instrument) is left in place while the other is shifted up and down or sideways along a line suitable for the defining of a mode that is to be measured. The recorded data are converted to digital form and low pass filtered[6,9] to remove any aliasing effects in the computed spectrum. The sampling frequency which governs the Nyquist frequency of the time series is chosen so as to be capable of retrieving information up to the desired frequency limit. Generally an instrument correction[16] is also applied to compensate for the frequency characteristics of the data acquisition chain. The data are next Fourier analysed and the ratio of the Fourier spectral amplitude at any floor to that at the reference floor is determined. This ratio is proportional to the mode shape amplitude at the floor for a given frequency of vibration.

Since the effectiveness of this testing procedure depends on the accuracy of the recorded motions at the reference level, it is necessary to ensure a high signal to noise ratio at that key station. To do this, the reference point is usually chosen so that it does not lie near any of the nodes of the mode shapes of vibration that are being studied.

When choosing the frequencies[9] at which the ratios are to be taken it may not be desirable to pick exactly the peak values of the spectra. It may happen that two translational modes, or a translational and a torsional mode, may have very close frequencies and the problem of separating the modes may become troublesome. In such cases, a point away from the peak might be selected in such a way that it is as far as possible from the other frequency in question. On the other hand it must be remembered that picking a mode amplitude at a frequency differing by more than a few percent from the natural frequency in question may lead to serious perturbations of the actual mode amplitudes[18]. Therefore when two modes happen to have very close frequencies a special method of analysis may be required. The identification of natural frequencies is considerably simplified by a simultaneous study of cross spectral amplitude as well as cross spectral phase plots[6,15].

Torsional modes of vibration can be recovered by placing two instruments on the same floor in diagonal corners and appropriately summing their outputs so as to recover predominantly the torsional motions[9].

## BRIEF DESCRIPTION OF THE FOUR STRUCTURES STUDIED

Building A[5] consists of a twenty-two story ductile moment resisting steel frame (180 ft x 70 ft in plan), separated by a seismic joint from a two-story U-shaped structure which surrounds it.

Building B[9] is a thirty-nine story moment resisting steel frame with a story height of 13 ft 1 in. The tower is structurally separated from the parking structure by a joint allowing two inches of horizontal movement.

Building C[4] is a nine story reinforced concrete building 75 ft x 69 ft in plan having a central core wall and two shear walls in the N-S direction.

Building D[1] is a symmetrical nine story steel frame with plan dimensions 220 ft x 40 ft. Typical floor height is 16 ft. The large length to width ratio of this structure indicates interesting dynamic features.

## COMPARISON OF AMBIENT AND HIGHER LEVEL VIBRATION TESTS

As the amplitudes involved in ambient vibration tests are of the order of 10 microns, a natural question is whether these low amplitude motions involve the major structural elements in essentially the same way as larger motions.

Figure 1 indicates such a comparison between ambient and forced vibration test results for Building A. The open circles refer to the ambient test while the full circles refer to the forced vibration test. The nature of the load distributions on the structure in the two types of test are quite different. Shaker tests essentially involve a point source of sinusoidal excitation whereas ambient loads are distributed over the structure. The frequencies and the mode shapes calculated[5,17] show that except for the fifth N-S (4.03 cps) and torsional mode (4.61 cps) frequencies measured from ambient tests are either the same as or higher than those determined from the forced vibration tests. On an average, ambient tests show frequencies about 4% higher than those obtained by the shaker experiment. A comparison of the various mode shapes indicates systematic differences mainly occurring at the upper floor levels. The divergence is largest at the top of the building and generally leads to higher modal amplitudes from shaker than from ambient tests. This phenomenon, which is more pronounced for higher modes[18], is attributable to modal interference, and is a consequence of the concentrated source of excitation being at a frequency only slightly different from the resonant frequency. Average percentage differences in the mode shape amplitudes relative to the peak ambient vibration amplitudes are about 2% for the fundamental mode and increase to about 20% for the fifth mode.

Mode shapes and fundamental frequencies of vibration obtained from ambient and higher level excitation tests of Building C are shown in Fig. 3. Typical acceleration amplitudes during the ambient test were $10^{-8}$ g while those for the forced vibration test were $10^{-2}$ g, a difference of six orders of magnitude. Unlike Building A, the present comparison of forced and ambient tests does not indicate any systematic changes in frequency for changes in amplitude of about six orders of magnitude. The mode shapes of vibration for the first modes in both directions are in excellent agreement. Small systematic changes probably caused by modal interference[18] are detectable in the second E-W mode.

## PRE- AND POST-EARTHQUAKE AMBIENT VIBRATION RESPONSE

The frequencies and mode shapes of vibration of Building B prior to and after the San Fernando, California, Earthquake of February 9, 1971 are given in Fig. 2. Reduction in the natural frequencies in the N-S and E-W directions as well as in torsion are observable. The average percent reduction in the N-S frequencies is about 19%, in the E-W about 15%, and in torsion about 17%. This percentage reduction in frequency is almost a constant for all the modes of any one kind (i.e., either N-S, E-W or torsion). The ratios of the higher frequencies to the fundamental frequency in the N-S direction from both pre- and post-earthquake ambient testing follow closely the sequence 1,3,5,7,9 · · · indicating that the overall N-S structural response in these tests remained predominantly of the uniform shear beam type[9]. A constant percentage reduction in all the frequencies can then be attributed to a roughly constant reduction in rigidity all along the height of the structure. Pre- and post-earthquake response are also shown for Building C (Figs. 3 and 4). As seen from Fig. 4, Building C has undergone a series of ambient vibration tests. The percentage reductions in the first and second E-W mode are 13.8% and 9.3% respectively while in the stiffer N-S direction a frequency change of only 4.75% is indicated. The fundamental E-W period since the San Fernando main shock seems to show a gradual decrease. Ambient vibration tests in February after the main shock indicated a fundamental E-W period of 0.8 secs (Fig. 3) whereas a smaller aftershock in March indicated a fundamental period of about 0.75 secs. Later in the same month ambient tests indicated a period of 0.77 secs. Recent man-excited ambient tests indicate a period of 0.73 secs. The mode shapes determined from post- and pre-San Fernando ambient tests (Fig. 3) indicate little change in the first N-S and both E-W modes.

## COMPARISON OF AMBIENT VIBRATION TESTS WITH EARTHQUAKE RESPONSE

Figure 4 indicates the NS and EW transfer functions of Building C computed from the basement and roof records obtained during the San Fernando earthquake[19]. Both components of ground motion were studied yielding fundamental periods in the N-S and E-W directions. The figure indicates marked shifts in the frequencies from those measured in the ambient or forced vibration tests. The broad peaks at about 1.7 cps in the N-S direction and at 1.0 cps in the E-W direction (Fig. 4) seem to represent the integrated effect of gradual shifts in the fundamental frequencies of the structure for different levels of excitation. To study this effect further, transfer functions were computed for 8 sec "window lengths" of both N-S and E-W records, starting from the beginning and displacing the window each time by 2 secs. The fundamental periods in the E-W direction are shown plotted in Fig. 7 versus the time corresponding to the center of each window. The first 8 secs of the E-W component of motion (Fig. 7) show a fundamental frequency of 1.32 cps which quickly reduces to 1 cps and remains thereat up to about 16 secs at which time the response shows a much lower amplitude. The transfer function at this time indicates a "double peak", the higher frequency peak being more predominant. As the window shifts out of this rather low response zone the fundamental frequency drops back to 1 cps and remains there till the rather quiescent segment of response between about 44 secs to 54 secs sets in. The frequency jumps back then to 1.33 cps. Later excitations cause the frequency to drop back to 1.0 cps and gradually increase to about 1.23 cps for the window centered at 80 secs. A similar behavior of the N-S component of motion is shown for the first two modes in Fig. 6. Figure 5 shows the transfer functions obtained from an analysis of the complete records at basement and roof in Building D. Changes in the fundamental frequency at these large levels of excitation together with measurements of the pre- and post-earthquake responses of the structure are clearly indicated.

## TWO-DIMENSIONAL TESTING OF STRUCTURES

In the testing of most structures it is generally assumed that their behavior will be similar to continuous or discrete mass line models, the floor slabs acting as rigid members. However for structures having a high length to width ratio, such as Building D, at least a two-dimensional testing procedure, if not a three-dimensional procedure, may be required. Forced vibration testing aimed at obtaining three-dimensional modes will generally be far more time consuming than ambient tests and will require repetitious response determinations for different shaker positions.

Higher dimensional vibrations involve the added complexity that corresponding to any one mode in the vertical direction, the building could theoretically vibrate at an infinite number of modes in the horizontal direction. This is clearly indicated in Fig. 8. For example at frequencies 2.90 cps, 3.6 cps and 4.9 cps the mode shape as seen in any vertical N-S plane would be a "second mode" of vibration. Differences in the nature of vibration of the floor slabs however arises, the floor slabs vibrating as free-free beams at 3.6 cps and 4.9 cps.

## CONCLUSIONS

Ambient vibration testing is an easy, quick and efficient way of studying the linear response of structures. Results from ambient and forced vibration tests show good argument. Though pre- and post-ambient testing of structures gives valuable data on the overall reduction in structural stiffness caused by damaging earthquakes, structural frequencies during large earthquakes show marked differences from those ascertained by pre-earthquake low amplitude vibration tests. Ambient vibration testing has been shown to be an invaluable tool for the study of two or three dimensional vibrations of extended structures.

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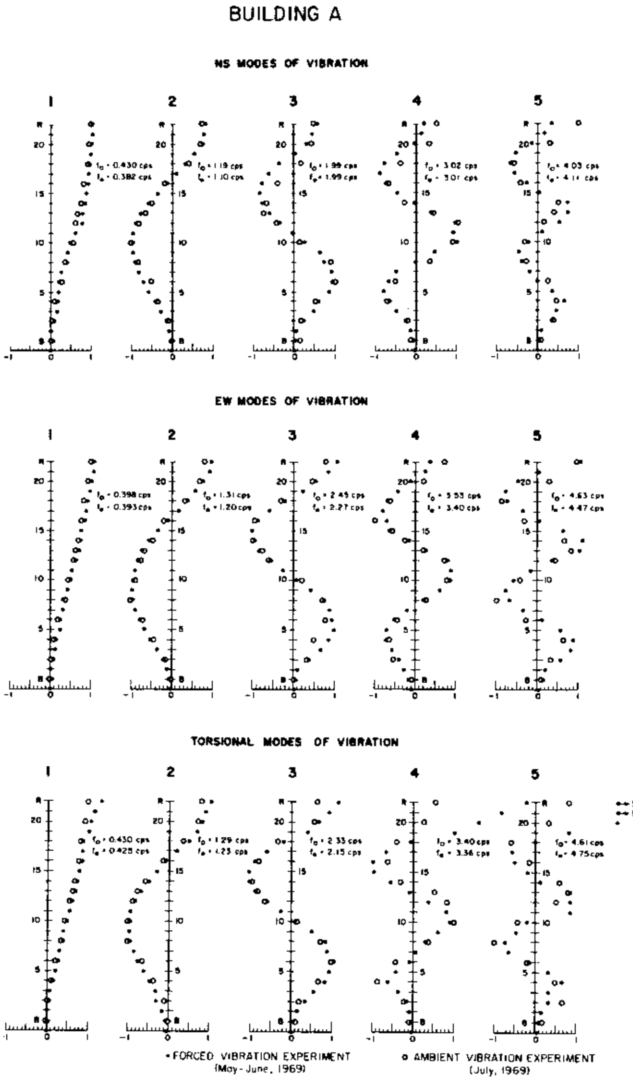



Figure 1

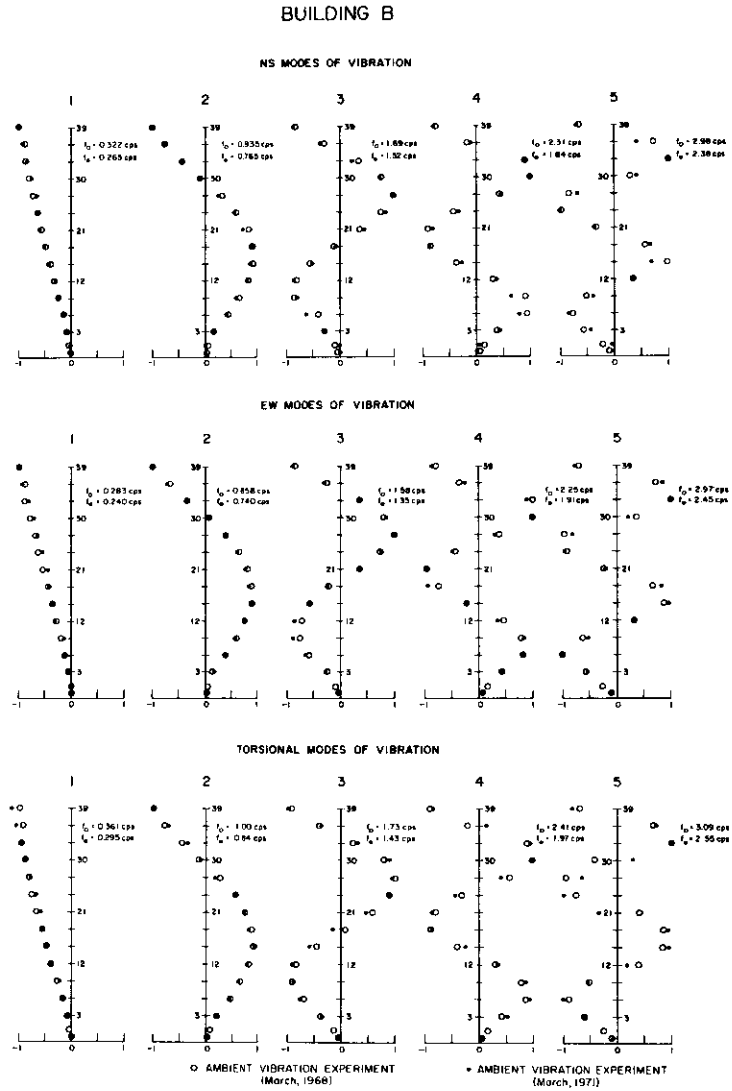



Figure 2

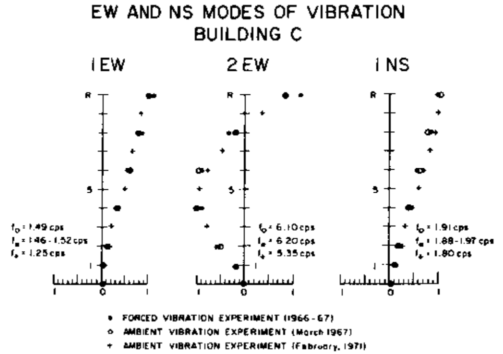



Figure 3

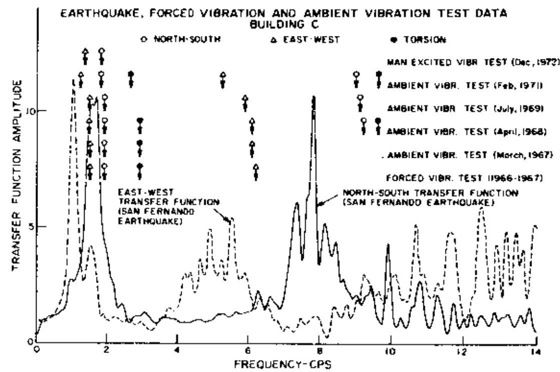
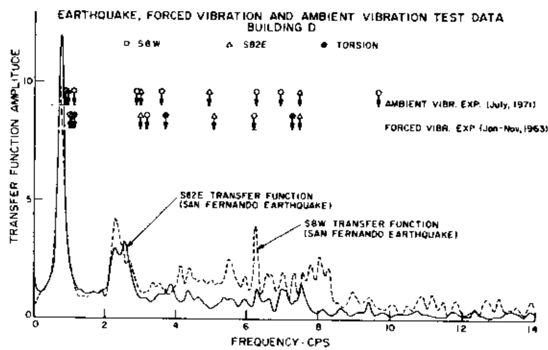



Figure 4



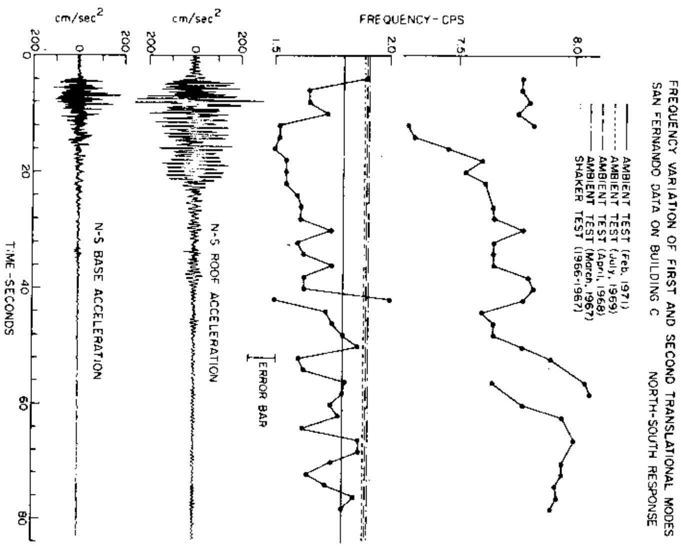




Figure 6

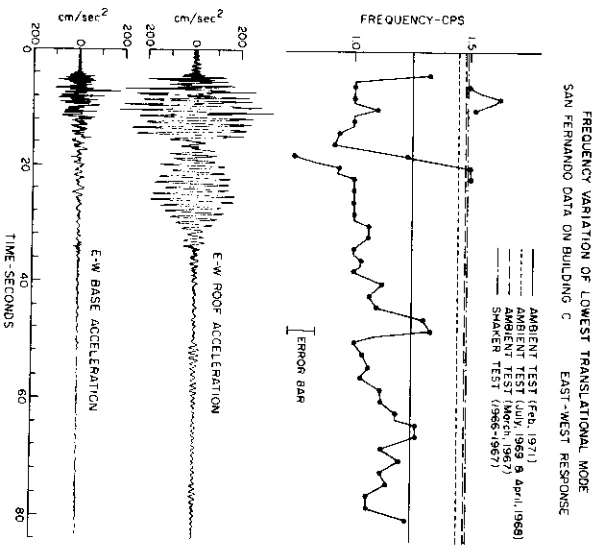



Figure 7

# TWO DIMENSIONAL N-S MODES OF VIBRATION
## BUILDING D

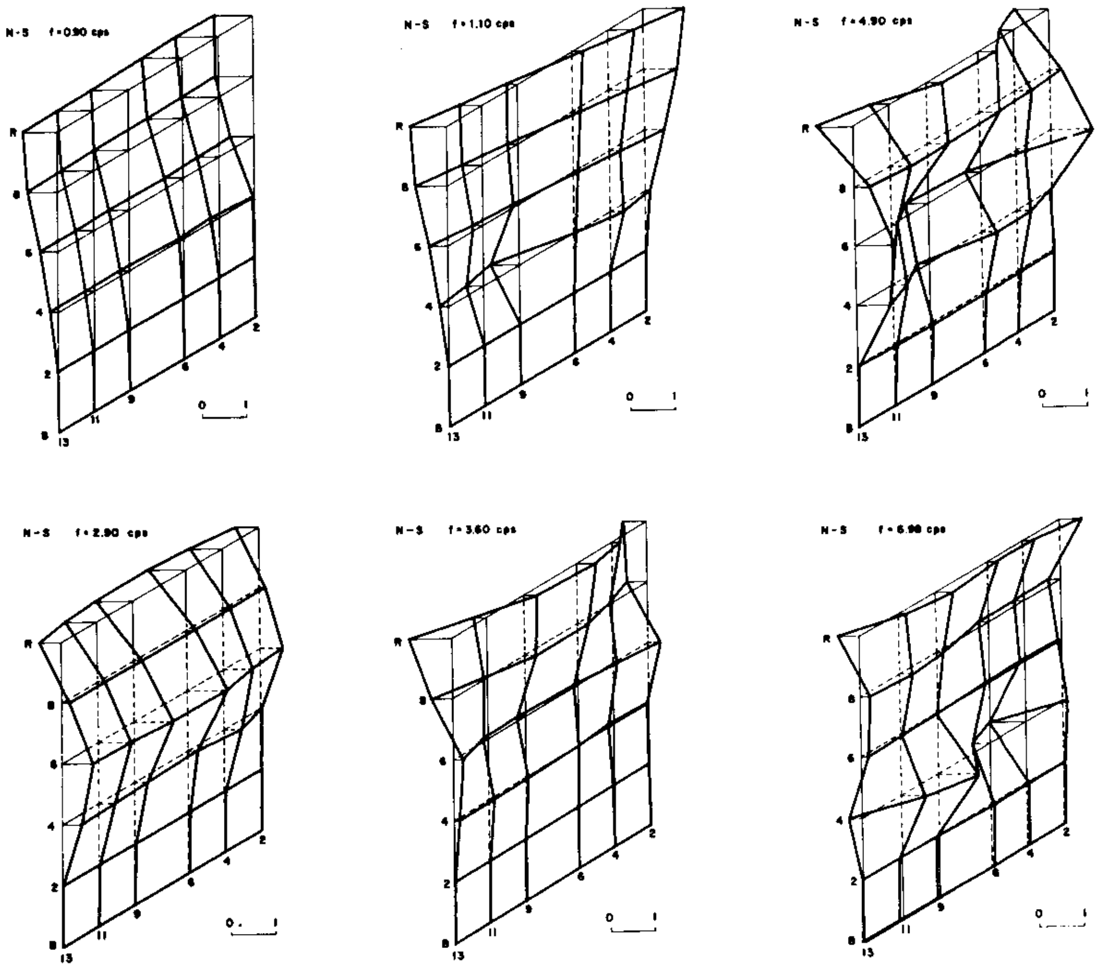



Figure 8