ANALYSIS OF STRUCTURAL RESPONSE AND INSTRUMENTS

SUMMARY REPORT

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The large number of papers presented at this session precludes the possibility of making closing remarks about each paper. In fact, the amount of information contained in these papers is so great that it will require considerable time to read the papers and to digest the information contained in them. It will be necessary to correlate the new facts with the old, to reconcile the discrepancies, and to advance our understanding of the earthquake problem. However, the topics covered at this Session can be classified under six headings and I should like to summarize the contributions under these headings. In addition, I should like to call attention to those facts which came out during the session which seem to call for the exercise of caution in the application of earthquake engineering, and I shall wave the danger flag over these facts.

Nonlinear Oscillator under Earthquake-Type Excitation.

A large number of papers dealt with this topic. These were concerned with the maximum displacements of the oscillator and the displacement spectra, with the energy dissipated during the vibrations and the equivalent viscous damping. The relation of the maximum displacements and the energy dissipation to the spectra of the linearly elastic systems was studied. The significance of these studies on the single-degree of freedom oscillator is that they build up our understanding of the nonlinear vibrations in this simple case, and this understanding can then be extrapolated to the more complicated cases of actual buildings. The danger flag can be hoisted over the following two facts; (1) the relatively low energy of dissipation that these studies show takes place during the nonlinear vibrations of a yielding system, and (2) the fact that the failure characteristics are not included in these studies. The relatively low energy dissipation and low equivalent viscous damping during these vibrations means that the maximum displacements tend to be relatively large, and it therefore becomes important to take into account the possibility of failure. It must be noted that the hysteretic vibrations of a system that is stressed beyond the yieldpoint is really a destructive process and if these vibrations continue for a sufficiently long time the system must fail. The possibility of failure, however, is not taken into account in the foregoing studies and, hence, they give no indication of how close to failure an actual system might be.

Nonlinear Vibrations of Multistory Buildings.

The use of large digital computers has made possible the analyses of multistory buildings that behave nonlinearly when stressed beyond the yield-point. Such studies throw light upon the behaviour that might be expected of actual multistory buildings during earthquakes. The papers presented at this session gave information on maximum displacements during earthquakes, the relative interfloor displacements as well as the absolute displacements. Information was presented on the location of points of yielding over the height of the building and the location of yielding in the beams and the columns. The results of these studies are now seen to be consistent among themselves and also to be consistent with the studies of the single-degree of freedom oscillator. The studies indicate that our present multistory buildings may survive ground motion equivalent to that recorded in El Centro in 1940 if they are properly designed. That is, they may survive the earthquake without collapse though they sustain damage. The danger flag may be hoisted over the following two facts. First, it has been shown that it is possible to concentrate large plastic deformations in a localized region of a building. Second, these studies do not take into account the failure process. The fact that it is possible under certain circumstances to get large plastic deformations localized in one part of a building means that failure might result. It is, therefore, somewhat hazardous to make such analyses without taking into account the failure process.

Elastic Response

A large number of papers dealt with the elastic response of structures to earthquake ground motion. One aspect of these studies was the question of how simple a model could be used in making these analyses, how great a computational accuracy is necessary, methods of analysis using wave propagation and taking into account the visco-elastic properties of the system. Studies were made of the behaviour of structures having dimensions large compared to characteristic wavelengths of the seismic waves. This condition might, in some instances, have good effect and in other respects have bad effects. Analyses were made of one-dimensional, two-dimensional and three-dimensional structural response to earthquake ground motion and the circumstances under which a one-dimensional analysis is not adequate, but a two- or three-dimensional analysis should be made. A danger flag may be hoisted over the following fact, that degenerate vibrating systems can sustain relatively high forces and stresses as compared to a normal system. A nondegenerate system is one in which all of the mode shapes and mode frequencies are well separated and different in shape. A degenerate system is one in which two modes may have shapes very closely similar and/or periods that are almost the same. A large building with a small appendage attached to it is an example of such a degenerate system. A structure that vibrates in two dimensions and which has an x-mode and a y-mode both with essentially the same period, or which has an x-more and a torsional mode with essentially the same period, is another example of a degenerate system. The analyses show that such systems can, under certain circumstances, undergo relatively large stresses and large displacements as compared with the maximum stresses and displacements that would be suffered by similar nondegenerate systems.

Dynamic Properties of Particular Structures.

Studies were made of the dynamic characteristics of many special structures. These included tall cantilevered chimneys, beams having both shear and bending deformation, composite structures made up of combined shearing elements and bending elements, structures in which the virtual mass of the foundation system is included, bridges, fluid pressures on bridge piers, earth dams, arch dams, steel piles and sheetpiles. The danger flag may be hoisted over the following fact. These special structures are very different from ordinary buildings which have been much studied. There is, then, a danger in trying to apply our extensive knowledge of the behaviour of ordinary buildings to these special structures. Attempts to transfer such knowledge may be quite hazardous.

Experimental Measurements of Dynamic Properties.

Many papers dealt with the experimental measurements of the vibrations of actual structures as well as model structures. These experiments included many different ways of applying forces to structures and investigating the resulting vibrations. Forced sinusoidal vibrations were used, free vibrations generated by pull-back tests, microtremors, wind excitations, blast-generated ground motions, hydraulic jacks, and even in a few cases measurement of earthquake -induced vibrations. This experimental information is extremely valuable. The danger flag may be hoisted over the following two facts. First, measurements of actual buildings indicate that they have relatively small damping. In this context, small damping is defined as being less than 5% of critical; intermediate damping is between 5 and 10% of critical, and large damping is greater than 10% critical. It appears that most modern buildings have small damping, and only few may have intermediate damping and very few, if any, have large damping. The second dangerous fact is that not enough is known about the actual vibrational properties of real structures. There are many aspects of the vibrations of real structures that are completely unknown, hence, there is the possibility that we are completely unaware of some very significant facts.

Vibrational Analysis of Structures.

It appears that we are asking for great detail in computional results - much more detail than was considered even possible a few years ago - but the capabilities of the digital computers seem adequate to do this. It is possible to determine the time history of the inelastic deformation of each beam and column in a multistory building subjected to earthquake accelerations. While this information is extremely valuable, a danger flag can be hoisted over the fact that it is possible to lose sight of the forest because of the trees. The vast amount of numerical data provided by the digital computer should not cause us to lose sight of the really significant behaviour of a structure.

Looking Forward.

In looking forward to studies that will be done following this conference it seems that a most significant fact that must be taken into account is that vibrations beyond the elastic range represent the initiation of a failure process and, hence, in studying such nonlinear vibrations we are really making a failure analysis. When the vibrational stresses go beyond the elastic limit and yielding occurs, either of two things may happen. Either the system will shake-down in the naval sense and the subsequent vibrations will remain in the elastic range, or the yielding vibrations will continue, and if they continue long enough failure will result. For example, if a steel column in a building undergoes oscillatory strains beyond the yieldpoint for a sufficient number of cycles, there will be a fatigue failure. A second example is the behavior of an earth dam during a strong earthquake. If the shaking is sufficiently strong, cracks may develop in the dam and a portion of the slope may begin sliding. If the duration of the ground shaking is sufficiently long, the gross movements may become large enough to cause failure of the dam. If the duration of shaking is short, the dam will not fail, though it will be in a damaged condition due to the cracks and relative movements. The important question to be asked in analyzing such motions are, how much damage will be incurred? how near to failure is a system? These questions cannot safely be ignored when studying the nonlinear vibrations of structures.

In the past, extensive studies have been made of the behavior of ordinary buildings. In the future it seems that much more emphasis should be given to the study of the dynamic behavior of other structures such as bridges, dams and the soil-structure combination. It is important to remember that the structure cannot stop at the surface of the ground, but that the soil beneath the structure is an indispensable part of it, and that its failure represents a failure of the structure just as much as the failure of a beam or a column.

The analysis of earthquake response of buildings has largely been restricted to the shell of the building, and has not concerned itself with the contents. There are many internal items that should be resistant to earthquake motions, such as light fixtures hanging from the ceiling, important mechanical equipment, machinery, fire-fighting equipment, etc. This problem is particularly critical in the case of nuclear reactor power plants, and further investigations along these lines should be made.

In the orderly development of a subject, such as earthquake engineering, analysis and experiment should go hand in hand. However, it seems that now analysis is outdistancing experiment. Theoretical analysis and digital computer analysis are coping with the vibrational behavior of structures far beyond anything that has been done experimentally. To keep a proper balance, there must be much more experimental work, especially on real buildings. There is a great need for more measurements of real structures during earthquakes. Such experimental studies tend to be relatively costly as compared to theoretical analyses, but we must remember that the problems we are studying are of great economic significance. The recent Alaska, Niigata and Skopje earthquakes are each estimated to have caused one billion dollars of damage, despite these not being large cities. The three-billion dollar loss represented by these three earthquakes would more than justify extensive experimental studies and greatly increased research in earthquake engineering. It is hoped that at the Fourth World Conference there will be many papers reporting on these aspects of the response to earthquake ground motion.