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EVALUATION OF DYNAMIC TESTING OF AS-BUILT CIVIL ENGINEERING STRUCTURES

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Abstract

This paper summarizes an evaluation of dynamic tests performed on large as-built structures. The objectives and methods (excitation and data analysis) of tests are reviewed. The utility and limitations of dynamic testing in light of actual experience is discussed. Though low-level tests in themselves will not be useful for predicting structural response to strong ground motion, they are useful for verifying linear models and for clarifying physical phenomena related to soil-structure interaction.

1. Introduction

As part of an investigation sponsored by the U.S. Nuclear Regulatory Commission on the utility of dynamic testing in the safety assessment of as-built nuclear power plant structures, we reviewed a large and representative sample of published literature on the dynamic testing of a variety of as-built civil-engineering structures. An interim evaluation of dynamic testing of nuclear power plant structures, based only on a review of tests on nuclear plant buildings, was completed earlier [1,2]. Subsequently, the review was focused on dynamic tests performed on many different types of as-built structures - frame and shearwall buildings, dams, bridges, towers, etc. The review also covered many published studies of the analysis of recorded earthquake response of large structures for determining structural dynamic characteristics. These studies were included in the review to provide a basis for evaluating the use of dynamic tests for characterizing the structural dynamic parameters that are of interest in seismic response prediction.

The different sources of excitation and the associated methods of response data analysis were the major aspects of the review. A detailed account of the review and the evaluation have been published elsewhere [3]. This paper is a summary of the evaluation.

2. Objectives and Methods of Dynamic Tests

Among the objectives of the dynamic tests performed on as-built structures are

- determination of the dynamic characteristics of a structure (usually the natural frequencies, damping ratios, and mode shapes),
- verification of theoretical models employed in the design or other "blind" response prediction analysis,
- improvement of pre-test or design analytical model in light of test results,
- determination of response to a particular dynamic environment,
- integrity monitoring (e.g., testing before and after severe dynamic loading to detect changes in structural characteristics),
- investigations on the effects of construction progress or changes, on time and amplitude dependence of dynamic behavior, and on soil-structure interaction effects, and
- assessment of earthquake response prediction capability of analytical models.

A Irrespective of the objectives, all testing involved three common aspects: some means of excitation, measurement and signal processing, and the characterization of the dynamic properties or behavior of the structure.

2.1 Methods of Excitation

One may classify the variety of excitation techniques into two categories: passive and active. Ambient vibrations, natural earthquakes, and ground motions from incidental explosive blasts may be considered as passive techniques, characterized by a lack of control over the excitation. There is a trade-off in these methods between the no-effort excitation and the ignorance about the excitation force. Natural earthquakes are, of course, the best method of "testing," since the most severe design dynamic loading is usually seismic and no other form of excitation would be as close to design loading. However, since relatively long-term monitoring is necessary to measure earthquake response and since earthquakes may not occur often in a given location, use of earthquake vibrations to study dynamic behavior has been relatively infrequent in practice. Moreover, since any one particular earthquake may not have the characteristics to reveal all the relevant dynamic properties of a given structure, continuous monitoring over many years has been necessary, even in some moderately active seismic regions.

Ambient vibrations, on the other hand, have been found to be an ever-present phenomenon at almost any geographical location. In general, it has also been found that, though ambient vibrations are not always stationary, they are a statistically better form of random excitation than natural earthquakes. The major shortcoming of ambient vibrations is the very low amplitude of vibrations. Even though these amplitudes of vibration are a few orders of magnitude lower than those of the active methods, experience with the ambient method has shown that ambient excitations are potentially as useful a source of data as those from active dynamic-testing techniques.

The measurement of structural vibrations due to nearby blasting or explosions that in themselves are unrelated to the tests is, for obvious reasons, very infrequent. But when and where possible, this method has proven to be as good as ambient testing and usually had the added advantage of higher-than-ambient response amplitudes. Structural response to many underground nuclear explosions has been found to be comparable to that to strong-motion earthquakes.

In the active techniques, the excitation is usually a force or motion applied and controlled by the investigator. Here the trade-off is between the ability to control and measure the excitation and the effort needed to produce it. If a model capable of predicting response to arbitrary excitations is to be identified from a test, then the test excitation must be known; the measurement of test excitation is possible in most of the active techniques. The ability to control the excitation brings with it the necessity to systematically design the characteristics of the excitation (e.g., amplitude and frequency content, number and locations of points of excitation). Past experience indicates that at least some prior knowledge about the dynamic properties of the structure is necessary for devising the excitation. Moreover, though almost all the active techniques are capable of producing large amplitudes of vibration comparable to those of strong-motion earthquakes, practical considerations have kept the test amplitudes at levels orders of magnitude lower than design seismic response amplitudes.

Steady-state sinusoidal excitation with eccentric mass shakers is the most widespread technique of the active class because of the relative simplicity of the method. Precise control of excitation frequency and amplitude has been possible with this method, though it should be noted that independent control of frequency and amplitude may not be very easy with eccentric mass shakers. In practice, the quadratic variation of force amplitude with the variation of shaker frequency within a test run has not been considered to have any significance, even for structures that have shown amplitude-dependent properties. However, in situations where independent control of frequency and amplitude was considered important, or when the power requirement of rotating eccentric-mass shakers was considered too high, rêciprocating mass vibration generators have been used. The major problem with sinusoidal steady-state excitation is that it has failed in some tests to excite some modes that were known to exist. This problem is more common when a single shaker is used, but has been reported even when multiple shakers were used to search for a "missing" mode [4].

The other methods of the active category are mostly of the impulsive type. Force pulses applied by mechanical devices or rockets, snap back, buried-explosive charges, etc., are examples of such methods. While all these methods are demonstrated to have been effective sources of broad-band excitation, more experience with these methods is needed before their general strengths and limitations are well established. Pulse techniques that apply trains of force pulses with mechanical or gas pulsers, to produce a desired kind of response, have the promise of becoming good response-simulation techniques though the effort involved in pre-test analysis and equipment setup may be substantial. Buried explosives can provide an excitation that has some similarities to earthquake excitation and may also develop in the future as a method for simulating strong-motion earthquake.

2.2 Response Measurement

The measurement and signal-processing aspect of dynamic testing of civil engineering structures was not evaluated in detail because of the little space allotted to this aspect in the papers and reports reviewed. A fundamental issue in this context is the number and location of transducers. Most of the investigators have reported on the actual location of the transducers in their tests, but few have described the rationale for selecting the locations.

The number of transducers ranged from just one or two biaxial (horizontal) transducers in some tests to tens of triaxial transducers in many floors of a multistory building in one test. In tests where the goal was the determination of just the fundamental translational frequencies, just one biaxial transducer at or near the roof of a building was usually installed though some investigators have noted that the peak response does not always occur at the top of a building. In most tests, however, transducer locations were selected for obtaining at least a few lower-mode mode shapes (and associated parameters) for the two translational and the torsional vibrations. Even in these tests, the transducers were seldom located on the basis of a system-identification criterion, i.e., the optimal location of the fewest number of transducers to enable identification of a satisfactory model from test data. McVerry et al. [5] and Beck and Jennings [6] discussed the influence of the number and location of transducers on the identifiability and uniqueness of models obtained from test data. Further, as some investigators have pointed out, (e.g. [7]), in most cases the number and locations of the transducers at the bases of buildings have not been selected to enable the investigation of motions associated with the soil-structure interaction phenomenon.

2.3 Dynamic Characterization from Test Data

In all the tests reviewed, the measured peak response itself is of limited interest since in almost all of them the amplitude of response was very small. Results characterizing dynamic behavior of the structure were always obtained from the tests irrespective of the ultimate objective of the tests. Examples of qualitative characteristics of behavior determined from dynamic tests are the dimensionality of dynamic response (are vibrations planar or multidimensional?), the nature of deformational behavior (are mode shapes like those of a shear beam?), the role of soil-structure interaction, etc. Relatively simple analysis of the data was all that was required to understand the qualitative nature of dynamic behavior. These results usually provided valuable guidelines for evaluating the qualitative assumptions made in design or for improving analytical models.

The bulk of the analytical effort in tests, however, was spent on determining some quantitative description of the structure. It was usually assumed that the structure is linear and that all the energy dissipation of the structural system may be represented by equivalent viscous damping. Thus the analyses reduced to some form of parameter estimation. Since a linear viscously-damped system can be described by its physical parameters (mass, stiffness, and damping) or by its modal parameters (natural frequency, modal damping, mode shape and modal mass/participation factors), there is a choice to be made between them. There has been no instance among the tests reviewed in which the physical parameters were all identified from test data. In some instances, the mass matrix was assumed known and the damping and stiffness matrices were determined. But in most cases, it was the set of some or all of the modal parameters that were determined. Even in the few cases in which stiffness and damping coefficients - physical parameters - were identified (see, for example, [8]), the first step was to identify the modal parameters from the test data and then to determine the physical parameters from the modal parameters. However, the uniqueness of the physical parameters determined was not demonstrated in these cases. Though a set of modal parameters was determined in almost all cases, the set was not complete in any sense in most cases. In other words, except in very few cases, not all the modal parameters needed to synthesize a modal model of even a low order were determined from the test data.

In some cases, only the fundamental frequencies were determined. In many typical cases, the natural frequencies, damping ratios, and mode shapes for many (from two up to about ten) lower modes were determined. Since modal mass or participation factors were not determined in all except one or two cases, most of the tests did not result in the synthesis of a modal model. It is important to note the distinction between the set of the three modal parameters (i.e., natural frequency, damping ratio, and the mode shape) and a modal model that requires also modal masses or participation factors in addition to the above three.

The nature of excitation also influences the determination of dynamic parameters. As the excitation in the passive techniques is not known, it becomes necessary to make certain assumptions about the statistical nature of such excitation in the process of estimating the structural parameters. The most convenient assumption from an analytical point of view is that the excitation is stationary and contains equal energy at every frequency. While some investigators have made this assumption merely because of convenience, others have analyzed the response to find if such an assumption is justified and few others have even devised methods of analyzing nonstationary data. Many investigators have pointed out that, because of the uncertainties associated with such assumptions, damping estimates from the associated analysis are not reliable.

3. Utility and Limitations of Dynamic Testing

To what extent have the objectives of dynamic tests of as-built structures been successfully achieved? In most instances, tests must be considered very successful in having demonstrated actual dynamic behavior of particular structures and in enabling the verification of linear analytical models. Irrespective of the level of excitation, tests have been helpful in bringing out certain basic characteristics of dynamic behavior that might not have been discovered in the absence of testing. Testing has revealed that even apparently simple, symmetrical structures may have complex, nonplanar, three-dimensional behavior with interaction between nonstructural and structural elements; and, in general, civil engineering structures are nonlinear systems with properties that may vary with time, amplitude of loading, and previous loading history. So in this respect, testing has revealed the inadequacies of many of the qualitative assumptions made in conventional analytical-modeling procedures. Tests also have helped to at least partially verify these conventional linear models in the range of loading for which the nonlinearities are not very pronounced. In fact this was the objective of most testing; assuming that the test-determined parameters reflect the true linear behavior of a structure, many investigators were able to evaluate their pre-test analytical models. In some cases the test results enabled the improvement of linear models to the extent of better simulating the test outcome. Despite its failure to clarify the still clouded understanding of the different dissipative phenomena, testing has been the only means of getting some approximate measure of damping.

Dynamic testing has also been successful as a tool for revealing changes in the structural integrity or even the weakening of bond between nonstructural and structural elements due to strong excitations. In this sense it has been a kind of nondestructive probing technique for detecting changes not obvious in a visual examination. Tests have also been a means for investigating the phenomenon of soil-structure interaction, since even low-level shaker tests have been found to give rise to considerable ground motions through interaction with the soil. On the other hand, the most serious limitation of low-level tests is that they do not, by themselves, enable the prediction of structural response to much-larger-amplitude design loading such as a strong-motion earthquake. The reason for this is the nonlinear behavior indicated by many tests coupled with the lack of a proven method for extrapolating the nonlinearities of behavior from low to high response levels. This means that it has not been demonstrated that it is possible to directly predict strong-motion earthquake response on the basis of a linear model derived from the response to a low-level test excitation.

The second serious limitation of dynamic tests is the absence of proven or validated techniques of identifying theoretical models from test data. Even the parameter-estimation techniques based on the assumption of linear behavior need systematic verification. A few parameter-estimation methods have been verified using artificial or synthetic data, but none has been reported to have been qualified with the use of real test data from actual structures. The uncertainties associated with damping estimates highlight this point. It may be true that the unrealiability of damping estimates stems more from the poor understanding of the actual physical phenomenon of energy dissipation and radiation, and less from the errors of parameter-estimation techniques. Yet, in the light of experience so far, it is clear that many simple parameter-estimation methods are based on many assumptions --not only about the structure but also about the nature of the input and output data and the different aspects of signal processing--that have not always been subjected to any kind of verification.

4. Conclusion

Despite the limitations, there is a need for continued dynamic testing of as-built structures, incorporating the recent improvements in the areas of instrumentation, signal processing, and data analysis in the tests. These tests should be performed at many amplitude levels within the range permitted by practical considerations. Simultaneously with this, the different parameter-estimation techniques that have already appeared should be subjected to verification studies. These studies may range from simple reciprocity and orthogonality checks all the way up to systematic verifications of the ability of a test-identified model to predict response to a different test input, with all the test data coming from tests on actual as-built structures. Improved tests over a range of amplitudes, together with verified parameter-estimation techniques, can be expected to lead to a better understanding of the nonlinear trends of the parameters within the range of the tests. These tests may be used also for investigations on such fundamental issues as damping and associated phenomena and soil-structure interaction aspects. Physically more realistic modeling of dissipative phenomena, and the understanding of the various mechanisms of energy transfer between the soil and the structure are the expected results of such investigations.

All the above may yet be inadequate from the point of view of seismic-response prediction. Therefore research on large-amplitude response of structures is also equally important. Continued monitoring of selected structures located in seismic regions to measure and analyze earthquake response and similar use of structural-response analysis applied to structures located within the range of strong ground motions due to underground nuclear explosions will contribute to this. But these alone are not sufficient due to the lack of experimenter control over the excitation. Testing at various amplitude levels ranging from very low up to near destruction of structures slated for demolition is required for the study of nonlinear behavior of structures. Though at present there are no nonlinear models that can represent such behavior, these tests may be useful both for the development of such models and for the identification of a series of "piecewise" linear models. Investigations on damping and soil-structure interaction should also be part of these high-level or destructive tests. These tests will also afford an opportunity to study post-damage behavior, and the correlation of extent of damage with linear parameters. Despite the difficulties involved in satisfying the similitude laws scale models of the sacrificial structures, tested in centrifuges, may enable correlations to be established between model and prototype responses at very high levels of excitation. If sufficient data are accumulated and such correlations are established, then scale-model testing might become a means of predicting response of as-built structures to strong-motion earthquakes.

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6. References

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