LARGE-SCALE EARTHQUAKE SIMULATION TABLES

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SUMMARY

General problems in earthquake engineering related to seismic analysis and design are enumerated and the way in which simulation on shaking tables can contribute to proper analysis and economic design is examined. Advantages of earthquake simulation testing over traditional "static" and "hysteretic" testing are discussed. Capabilities of existing seismic simulation systems around the world are described. Critical considerations in the design of large-scale multiaxial earthquake tables for proper earthquake and sinusoidal motion simulation are described.

INTRODUCTION

Earthquake engineering practice has developed over many years as a result of experience and observation. Empirical rules, such as equivalent static lateral load as a small fraction of the total weight of the structure, are still being used in the design of cantilever structures around the world. Although, this empirical rule has had a limited success, much of the effort in structural engineering is concentrated on the refining of this rule. This has been justified by the need for building high-rise structures. However, it is only in the last decade that experimental research using earthquake simulators has been undertaken. This has been justified partly by the uncertainty of empirical rules applied to the design of more complex facilities.

Design of important facilities, such as buildings, power plants, bridges, etc., has incorporated progressively more sophisticated seismic analyses since the early 1960's. Unfortunately, experimental support and confirmation has not, in general, kept pace with the rapid development of computerized analytical seismic design methods. A classical example is the seismic design of nuclear power plants and related electrical structures and equipments. Unnecessary and costly shutdowns of existing nuclear power plants are still being caused by "faulty" computer codes.

When experimental seismic testing is required, such as the case of electrical structures and equipments, most of the emphasis for the improvement of seismic resistance is qualifying the equipment dynamically after it has been finally designed. Presently, a considerable amount of literature in the form of guides and standards on the subject of qualification tests exists.(1) Although the qualification tests represent a step forward in the earthquake resistance, what is ultimately needed is the development of seismic engineering guides and standards that can be rationally used during the design stages.

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In the absence of guidance and standards, a designer could wonder if sophisticated analysis is worthwhile, and whether important structures should be designed on the basis of "empirical" coefficients. The social and political needs, however, make it imperative that designers decide upon criteria using the latest state-of-the-art technology and, at the same time, provide for sufficient margin of safety. As a result, safety factors are adopted at each stage of the design which compounded become excessively conservative (sometimes as large as 5.0).

Because of the need to develop seismic resistance criteria for important structures and equipment, earthquake simulation has become of major importance. Earthquake simulators are required because there is not any other experimental tool that can reliably reproduce the effects of earthquake-type excitations in buildings or any type of structure. Special impetus in dynamic testing on earthquake simulators is given today because of man's tendency to build complex structures and the need for optimum design and minimum risk.

PROBLEM AREAS IN EARTHQUAKE ENGINEERING

Long ago, the problem areas in earthquake engineering have been classified under either (1) structural engineering, or (2) geotechnical engineering (soil mechanics and foundation engineering). The latter includes dynamic behavior and characteristics of basic materials, components, subassemblages and assemblages of structural and nonstructural importance. The former includes ground response, settlement, liquefaction, slides, structure and ground interaction, earth-structures response, seepage, etc.

These two problem areas should contribute to the formulation of satisfactory methods for earthquake design. In spite of the advances in the use of high-speed digital computers and application of sophisticated computer programs in these two problem areas, there has not been a corresponding increase in the ability to design structures against earthquakes.

Since analysis involves idealization, it is, therefore, necessary to supplement and relate analytical work to experimental and field results in order to create greater confidence in design, particularly in the case of critical facilities, such as power plants, hospitals, dams, bridges, etc. Improvement in these two problem areas by rational experimental programs will minimize waste by making such facilities safer and more economical.

EXPERIMENTAL TESTING

Levels

The range of experimental testing, from the basic mechanical material properties (coupon tests) to tests of entire structures or assemblages, may be divided into five levels, approximately, in relation to the complexity of the structure as indicated in Table 1. At each level, an effort should be made to create a conceptual model which permits analysis of the observed phenomenon as well as the prediction of more complex conditions by synthesis.

The first level includes basic material tests. The second level refers to composite materials tests, such as reinforced concrete. Particular interest should be given to materials interaction, such as bond-slip relationship between concrete and reinforcement. In relation to earthquake engineering, these tests are considerably more complicated than the measurement of a stress-strain relationship at a constant strain rate and at a given temperature. To provide data for analyzing results obtained at higher levels, variations in history and amplitude of stress or strain application must also be considered.

The third level refers to tests of externally determinate elements, such as beams, columns, etc. The fourth and fifth levels refer to testing of substructures and structures composed of a number of discrete elements.

The projection of information up or down from any one level must be treated skeptically, unless the results can be explicitly traced down to tests of the first and second levels. For this reason, it is preferable wherever possible to plan tests at level five, so that the phenomena affecting the observed results of the test can be analyzed in terms of data from first and second level tests.

Types of Loading

Table 2 describes the types of loading most commonly used in experimental testing. A complete discussion of each type of loading is beyond the scope of this paper. However, the impact of static and dynamic testing on analysis and design is reviewed in this paper.

The main impact of knowledge obtained from traditional static testing has been on the proportioning of structural elements. In the last two decades, there has been great interest in the static deformation characteristics and static stability of structural elements in the inelastic range. Monotonic and hysteretic testing has been carried out to answer questions raised by problems related to limit design, ductility, and energy absorption capacity of structural elements. Static hysteretic loading has been justified by the necessity to ensure stable hysteretic loops and sufficient available ductility in the inelastic range of structural members in the event of reversing loadings, such as those caused by earthquakes. Better understanding of structural behavior and more economical design of structures subjected to static loads have been attained as a result of inelastic static loading tests.

During the last decade, experimental dynamic equipment and techniques were developed to determine the dynamic characteristics - natural frequencies, damping, modal shapes - of full scale structures and elements excited at small elastic amplitudes. The main impact of knowledge obtained from these tests was rather academic, since it is neither practical nor economical to design structures to remain elastic in the unlikely event of a destructive earthquake. Today, special emphasis is given to collapse mechanisms, optimum redundancy for stability and energy dissipation, dynamic isolation, fatigue failure, functional failure, large deflection failure, structural repair and retrofitting, etc.

Because of meagerness and lack of proper documentation, the impact of experimental dynamic testing remains to be seen. As stated earlier, present seismic design criteria is still primarily based on empirical rules developed over many years as a result of experience. This experience comes from observed performance of real structures and facilities (excepting nuclear power plants) that have been subjected to strong base motions.

LARGE-SCALE EARTHQUAKE SIMULATORS

Recorded attempts at earthquake simulation in the laboratory for structural testing have been made as early as at the turn of the century.(2) But, it was only after the late 1960's, as a result of advances in electrohydraulic servo controls, analog and digital computer hardware and dynamic instrumentation, that the structural researcher was able to concentrate on the test specimen and its behavior rather than on the test equipment. Various testing facilities of large-scale characteristics have been built in the 1970's in various countries as shown in Tables 3 and 4. Today, testing facilities of capacities up to 1000 ton speciments and shaking tables of 15 meters by 15 meters are under construction.

Earthquake simulation testing in the laboratory is appealing because it offers options not included in "ordinary" structural testing, such as preservation of semblance of the earthquake event, and the freedom of the specimen to respond to the base excitation in accordance with its own constraints and dynamic characteristics. It offers advantages over field observations because of (1) the capacity of controlling the input base excitation, (2) the availability of well defined information on the physical and mechanical properties of the specimen, and (3) the capacity of measuring the response and observing the behavior of each particular member.

Earthquake simulation in the laboratory does not, however, supplant the "ordinary" structural testing or the field observation. All of them are vital for the development of rational and practical seismic design criteria.

Critical Considerations

The present trend in seismic simulation systems is toward large multiaxial shaking tables (biaxial and triaxial) for large-scale or full scale specimens (100 tons or more) and strong motion excitations (0.5g or more). Therefore, design considerations have become excessively complex. To guarantee the desired system performance at minimum capital investment, a complete definition of the test requirements and proper facility planning are imperative.(3)

The design considerations and cost of a seismic system are primarily determined by the test requirements. Test requirements are originated in terms of size of shaking table; specimen weight, dynamic characteristics and center of gravity location; number of active degrees of freedom; and maximum performance (particularly maximum velocities and accelerations, and simultaneity for multiaxial tables) and types of signals to be run.

For a proper facility planning, seismic systems must be designed as a total dynamic system. Different dynamic interactions between the seismic system elements, which tend to degrade the desired performance, must be identified.(3) In general, critical interacting parameters are the natural frequencies and dampings of the specimen and table, the oil compliance of the hydraulic actuators, the servovalve frequency response, the compliance of the restraints, the dynamic response of the foundation or reaction mass, and the bandwidth and "stiffness" of the analog control system.

The design of multiaxial large-scale seismic systems for heavy specimens with high centers of gravity and large horizontal offets becomes a rather complex problem. This is because of the strong dynamic interaction between each of the seismic system components, particularly between the specimen and vertical hydraulic actuators. When the vertical actuators are used to react against the roll and pitch overturning moments, the size of the vertical actuators become excessively large. As a result, the accuracy to reproduce small vertical motions is significantly reduced. In addition, the hydraulic power necessary to achieve maximum multiaxial performance becomes exorbitant. A way to minimize "unused" hydraulic power is through the use of mechanical hydraulic supports or "stabilizers" which will react against the overturning moments induced by the specimen reactions on the shaking table. However, their effectiveness is drastically reduced above the fundamental frequency of the system (i.e., table, stabilizers and specimen combined). When overturning moments are governed by the fundamental frequency of the specimen, the effectiveness of stabilizers can still be adequate and sufficient.

Simultaneous sinewave performance at maximum amplitudes also requires excessive hydraulic power. However, if maximum base motions are limited to transient time histories, such as earthquake motions, then the alternative of using accumulator banks may be economical.

CONCLUSIONS AND RECOMMENDATIONS

It is unanimous among professionals in Earthquake Engineering that the most important factor in the design of any facility is its successful precedent, evaluated and projected through scientific discipline with the help from experimental tests wherever necessary. In the last two decades, the major achievement of structural research has been the development of information on mechanical behavior and mathematical modeling of many classes of structures, particularly in the static range. Yet, critical facilities located in seismic areas continue to be designed using criteria from traditional experimental testing. The discrepancy between elastic idealization and the inelastic earthquake dynamic response is assigned by most traditional construction codes to ductility. Is this approach realistic and safe? Is this criteria economical or wasteful? Therefore, it is urged that seismic tests be planned to comply with realistic vibration demands and intended to actually investigate and confirm the safety and reliability of important structures and equipments. This approach to the earthquake engineering problems will minimize anxieties and strengthen trust of people, and will contribute to the improvement and economy of important structures and facilities.

Because of the magnitude of capital investment, large-scale seismic simulation laboratories must be designed as versatile as possible. For a proper and economic design, a complete detailing of the range of test requirements, including dynamic characteristics of test specimens and duration and types of base motions, and facility planning are necessary.

REFERENCES

1. "IEEE Recommended Practices for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations," IEEE Std. 344-1975.

2. Rogers, F. J., 1908 - "Experiments with a Shaking Table," Report of the State Earthquake Investigation Commission, California Earthquake of 18 April 1906, Vol. 1, Part II, pages 326-335.

3. Clark, A., and Burton, G., 1978, "Design Considerations for Large Shaking Table Systems," Sixth European Conference on Earthquake Engineering, Dubronik, Yugoslavia.

TABLE I. EXPERIMENTAL TESTS ACCORDING TO PHYSICAL AND MECHANICAL CONFIGURATION

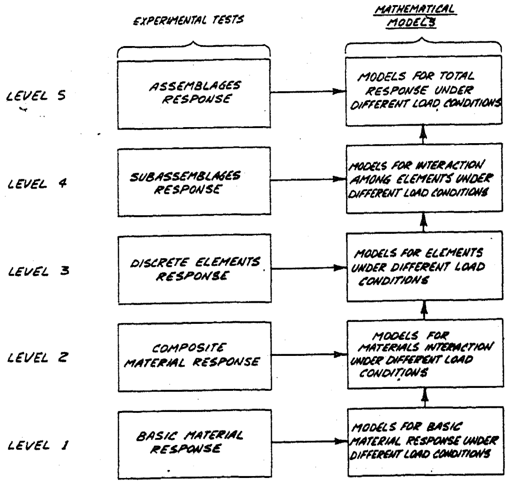
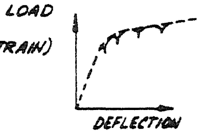
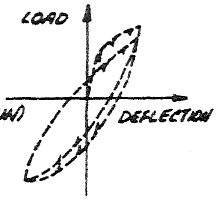
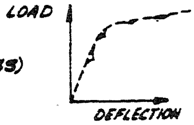
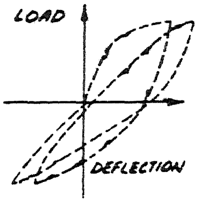


TABLE 2. EXPERIMENTAL TESTS ACCORDING TO LOADING

(A) STATIC[a] AND QUASI-STATIC[a]

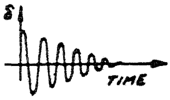
	MONOTONIC	HYSTERETIC
DEFLECTION (STRAIN) CONTROLLED		
LOAD (STRESS) CONTROLLED		

(a) TEST RESULTS ARE INDEPENDENT OF TIME & DYNAMIC CHARACTERISTICS OF STRUCTURE.

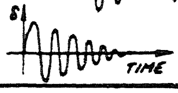
(B) DYNAMIC

FREE VIBRATION[b] ENERGY ADDED BY EXCITATION IS NEGLIGIBLE

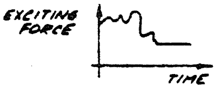
- SUDDEN MILD MOTION OF FOUNDATION OR SMALL INITIAL DISPLACEMENT

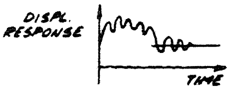


- IMPACT OR IMPULSE (SUDDEN CHANGE IN MOMENTUM)



SHOCK[c] EXCITATION IS NONPERIODIC (FORM A PULSE, STEP, OR TRANSIENT VIBRATION) WITH CONSIDERABLE SUDDENNESS & SEVERITY. ENERGY ADDED BY EXCITATION MUST BE CONSIDERED IN RESPONSE.





- INDIRECT (EXCITATION APPLIED THRU FOUNDATION)
- DIRECT (EXCITATION APPLIED DIRECTLY TO MASS)

FORCED VIBRATION[c] ENERGY APPLIED BY EXCITATION IS CONSIDERABLE & SUPPLIED FOR A LONG PERIOD OF TIME

- INDIRECT (EXCITATION APPLIED THRU FOUNDATION)
  - DETERMINISTIC
  - RANDOM
- DIRECT (EXCITATION APPLIED DIRECTLY TO MASS)
  - DETERMINISTIC
  - RANDOM

(b) TEST RESULTS DEPEND ON DYNAMIC CHARACTERISTICS OF STRUCTURE

(c) TEST RESULTS DEPEND ON DYNAMIC CHARACTERISTICS OF STRUCTURE & EXCITING FORCES.

Table 3

MAJOR SEISMIC SIMULATION FACILITIES AROUND THE WORLD (BESIDES USA) SUPPLIED BY MTS SYSTEMS CORPORATION

	Table Characteristics				Performance		
Facility	Table Size (m)	Freq. Range (Hz)	Max. Model Weight (t)	Controlled Degrees of Freedom	Max. Displ. (mm)	Max. Vel. (mm/sec)	Max. Accel. (g's)
Kajima Institute Chofu, Japan (Biaxial, 1975)	4.0 x 4.0	0 - 50	20	5	H±150 V± 75	1140 455	2.0 1.0
University of Mexico Mexico City, Mexico (Uniaxial, 1975)	4.5 x 2.5	0 - 50	20	1	H±51	381	1.2
University of British Columbia, Canada (Uniaxial, 1978)	3 x 3	0 - 50	6.8	1	H± 75	635	1.0
CEN Saclay Paris, France (Biaxial, 1978)	2 x 2	0 - 200	5	2	H±125 V± 85	1000 660	2.0 1.0
Arya Mehr University, Tehran, Iran (Uniaxial)	5 x 5	0 - 50	50	1	H±50	--	0.6
University of Pahlavi Shiraz, Iran (Uniaxial)	4 x 4	0 - 50	20	1	H±50	--	1.1
Ministry of Construction Tsukuba, Japan (Uniaxial, 1979)	6.0 x 8.0	0 - 30	100	1	H±75	600	0.7
University of "Kiril and Metodij", Skopje, Yugoslavia (Biaxial, 1980)	5 x 5	0 - 30	40	5	H±125 V± 50	635 380	0.67 0.40
A.M.N. Genova, Italy (Biaxial, 1980)	3.5 x 3.5	0 - 60	7	5	H± 70 H± 70	860 550	1.3 0.63
Toshiba Electric Kawasaki, Japan (Biaxial, 1980)	5.0 x 5.0	0 - 30	20	5	H± 75 V± 38	400 250	1.0 0.7

Table 4

MAJOR SEISMIC SIMULATORS IN U.S.A. SUPPLIED OR PROPOSED* BY MTS SYSTEMS CORPORATION

	Table Characteristics				Performance		
Facility	Table Size (m)	Freq. Range (Hz)	Max. Model Weight (t)	Controlled Degrees of Freedom	Max. Displ. (mm)	Max. Vel. (mm/sec)	Max. Accel. (g's)
University of Illinois Urbana, Illinois (Uniaxial, 1968)	3.65 x 3.65	0 - 50	4.5	1	H±51	381	5
University of California Berkeley, California (Biaxial, 1971)	6.1 x 6.1	0 - 50	45	5	H±152 V± 51	635 254	0.67 0.22
C.E.R.L. Champaign, Illinois (Biaxial, 1973)	3.65 x 3.65	0 - 200	6	5	H± 73 V± 35	813 686	15 30
Union Carbide Oak Ridge, Tennessee (Biaxial, 1980)	1.83 x 1.83	0 - 20	7	2	H±193 V±193	305 305	0.25 0.25
E.G.&G.* Idaho Falls, Idaho (Biaxial, 1981)	3 x 3	0 - 30	10	5	H±152 V± 76	635 318	1.0 0.5