DESIGN AND RESEARCH POTENTIAL OF TWO EARTHQUAKE SIMULATOR FACILITIES

by J. G. Bouwkamp[I], R. W. Clough[I], J. Penzien[I] and D. Rea[II]

SYNOPSIS

The design of shaking table facilities for the purpose of subjecting structural elements, assemblages, and structures to simulated earthquake ground motion is discussed. Details are given of the design of facilities incorporating medium and large size shaking tables. The medium size shaking table is 20 ft. x 20 ft. in plan and can test structures weighing up to 120 thousand pounds; the large size shaking table is 100 ft. x 100 ft. in plan and can test structures weighing up to 4 million pounds. The research potential of both these facilities is described.

INTRODUCTION

The destructiveness of earthquakes is often manifested in the damage they inflict on buildings, bridges, tunnels, dams, and other structures. The formulation of a satisfactory method of designing such structures to withstand earthquake forces will require a large amount of theoretical and experimental work. In recent years, the use of high-speed digital computers and the application of matrix algebra techniques have led to significant advances in analytical methods. However, since analysis involves idealization, it is difficult to relate the results from analysis to the actual behavior of full-scale structures under earthquake loading. In order to overcome this difficulty, extensive experimental research is needed.

Dynamic tests(1-5) have been conducted on a number of full-scale structures, but the dynamic properties determined from such tests are valid only for small vibration amplitudes. Due to limitations of power, existing vibration generators(6) can only sustain vibration amplitudes large enough to cause substantial inelastic deformation in very small structures(7). More powerful vibration generators are feasible, but they are most conveniently utilized by means of shaking tables. Vibration generators may be attached permanently to a shaking table, thus making it unnecessary to attach them to every test structure. In addition, a shaking table applies forces to a test structure in the same way the ground applies forces to an actual structure during an earthquake.

Shaking tables for testing civil engineering structures can be classified as small, medium, or large, depending on the maximum weight of structure they can shake. Small, medium, and large size shaking tables are defined herein to have maximum weight capacities of a few thousand pounds, a few hundred thousand pounds, and a few million pounds, respectively.

I. Professor of Civil Engineering, University of California, Berkeley, California, U.S.A.
II. Assistant Research Engineer, Department of Civil Engineering, University of California, Berkeley, California, U.S.A.

For economic reasons, the research potential of small-size shaking tables, such as the one at the University of Illinois, Urbana, Illinois, should be fully explored. However, small size shaking tables are restricted to testing small scale models, and it is clear that such models alone are inadequate to investigate the physical properties and failure characteristics of most complex systems. Therefore, medium size shaking tables to test full-scale structural elements and assemblages and medium-scale models, as well as large size shaking tables to test selected full-scale structures, are required.

At present, a medium size shaking table is under construction at the University of California, Berkeley, and recently a feasibility study on a large size shaking table(8) was completed. The design of shaking tables is discussed briefly below. Details of the design of the facility incorporating the medium size shaking table now under construction are given. Details are also given of a design proposed for a facility incorporating a large size shaking table. Finally, the research potential of these facilities is discussed.

DESIGN OF SHAKING TABLE FACILITIES

The design of a shaking table is initiated by defining some properties of a critical test structure (equivalent to choosing a worst case of loading) and some characteristics of the motion the table is to undergo. Both the plan dimensions and the weight of the critical structure should be as large as economically feasible. The number of components of ground motion the table is to undergo, and the maximum intensity of motion for each component, must be specified.

The shaking table is then designed for the specified properties of the critical test structure and the table motion. The shaking table has to be large enough to accommodate the test structure, strong enough to support it under both static and dynamic conditions, and heavy enough to avoid extreme servo-control problems. (The problem of controlling shaking table motion increases as the ratio of the test structure weight to shaking table weight increases.)

When the shaking table is not in use, the combined dead weight of the shaking table and the test structure must be supported by normal structural means. When the table is in use, it is convenient to support the dead weight of the shaking table and test structure independently of the vertical actuators (assuming the table has a vertical translational degree of freedom) so that the vertical actuators have to supply only dynamic forces. This may be accomplished by supporting the dead weight with compressed air.

The compressed air does not prevent a shaking table from overturning, and a means to limit table rotation must be provided. Two methods of doing so have been suggested(8): an active method in which the actuators that drive the table vertically also adjust their force outputs to compensate for the overturning moments, and a passive system, consisting of an arrangement of interconnected pairs of stabilizer units, which provide a large spring stiffness against table rotations.

The properties of the critical test structure, shaking table, and specified table motion determine the choice of power system. For subjecting civil engineering structures to earthquake type motion, the power system must supply large forces at low frequencies. Therefore, an electro-hydraulic power system is more suitable for civil engineering type shaking tables than an electro-magnetic power system which is more suited to supply small forces at high frequencies.

Once the power system has been determined, the choice of prime mover and the design of the drive system is straightforward. However, the design of servo-control systems to control the motion of a shaking table vibrating a complex structure still requires substantial development work, and a research project to develop a suitable control system is underway at the University of California, Berkeley.

MEDIUM SIZE EARTHQUAKE SIMULATOR FACILITY

A medium size earthquake simulator facility incorporating a 20 ft. x 20 ft. shaking table is presently under construction at the University of California, Berkeley. The critical test structure chosen for design purposes has maximum plan dimensions of 20 ft. x 20 ft. and a maximum weight of 120 kips. The shaking table has one horizontal and one vertical translational degree of freedom. With the critical test structure on the shaking table, the table can be subjected to an acceleration of 2/3 g up to a maximum velocity of 25 in/sec in the horizontal direction. The corresponding values of acceleration and velocity for the vertical direction are 2/9 g and 10 in/sec. The table may therefore be subjected to horizontal motion of about twice the intensity of the N-S component of the El Centro (1940) earthquake, and to vertical motion about twice the intensity of the vertical component of the same earthquake.

The facility will be housed in a building 120 ft. x 60 ft. in plan and 40 ft. high as shown in Fig. 1(a). The reinforced concrete foundation for the shaking table forms an open box shape with 5 ft. thick sides, see Fig. 1(b). The outside dimensions of the box are 32 ft. x 32 ft. x 15 ft. leaving an inside space 22 ft. x 22 ft. x 10 ft. The shaking table, 20 ft. x 20 ft. x 1 ft., forms a closure for the box; the top of the shaking table being flush with the top of the foundation walls. However, when the table is centered with respect to the foundation, there is 1 ft. clearance between the sides of the table and the walls of the foundation.

The clearance between the table and foundation is spanned with a 24 in. wide fabric strip so that the space within the foundation and beneath the shaking table is airtight. When the table is in use, the air within this space will be pressurized (up to 4 psi) so the dead weight of the table and the structure under test is balanced. When the table is not in use, it is supported by columns and brackets on the foundation walls.

Due to the severe loading on the table, and the necessity for the weight of the shaking table to be a large fraction of the weight of the heaviest test structure, it is most practical to construct the table as a combination of reinforced and prestressed concrete.

The shaking table weighs 60 kips. Since the foundation weighs 1550 kips and the maximum weight of test structure is 120 kips, the maximum ratio of moving mass (table plus test structure) to foundation mass is 1:9.

The maximum combined weight of test structure and shaking table is 180 kips. Therefore, a force of 120 kips is required to accelerate this mass to 2/3 g and a force of 40 kips to 2/9 g. Three actuators of 50 kip dynamic rating are provided to drive the table horizontally, and four actuators of 15 kip dynamic rating are provided to drive the table vertically. (Force above that required to accelerate the table vertically is used to prevent the table from overturning.) The horizontal actuators have 12 in. strokes and the vertical actuators 4 in. strokes.

The base plates of the 50 kip horizontal actuators are prestressed to the walls of the foundation in the locations shown in Fig. 1(b). The piston rods of the hydraulic actuators are connected by 7 ft. long extension arms to actuator attachment plates located on the lower surface of the table and on a horizontal center line axis perpendicular to the direction of horizontal motion. The extension arms have swivel joints at both ends.

The base plates of the vertical actuators are prestressed to the floor slab of the foundation in the locations shown in Fig. 1(b). Each vertical actuator is connected by an extension arm (similar to a horizontal extension arm) to an actuator attachment plate fixed to the shaking table.

Both active and passive methods of stabilizing the table against overturning moments will be tried so the two methods can be compared. A pair of interconnected hydraulic cylinders which form the basic units of the passive stabilization system is shown in Fig. 1(c). One unit will be placed on each diagonal with the cylinders located in the position shown in Fig. 1(b).

The table will be constrained to move in one horizontal direction by two straight-line mechanisms.

The high pressure hydraulic fluid to power the actuators will be piped from the mechanical building shown in Fig. 1(a). The building houses four 150 HP electric motors each of which drives a variable flow pump. These four motors supply a total of 310 gallons of oil (at 3000 psi pressure) per minute.

LARGE SIZE EARTHQUAKE SIMULATOR FACILITY

The design of a large earthquake simulator facility has been the subject of an extensive feasibility study carried out at the University of California(8). The site plan of the facility is shown in Fig. 2. The buildings shown in the site plan are: a movable shelter to cover either the shaking table or the test-structure construction area adjacent to the shaking table; electronic, metal, and wood workshops for supporting services related to the construction of test structures and the operation and maintenance of equipment; a power plant building; and an office building which will also house the control and data processing equipment.

The critical test structure has been chosen as a 100 ft. x 100 ft., 3 story, reinforced concrete building. Such a building weighs approximately 4 million pounds so the table has been designed with plan dimensions 100 ft. x 100 ft. and capable of shaking structures weighing up to 4 million pounds. This shaking table can test a wide range of full-scale buildings, as well as many medium scale models of buildings, dams, embankments, and other structures.

The shaking table has been designed to undergo three translational components of motion: two mutually perpendicular in the horizontal plane and one vertical. The El Centro (1940) earthquake has been used as a guide to define the maximum intensity of motion the table should undergo when loaded with the heaviest test structure. In each horizontal direction this has been set at an acceleration of 2/3 g up to a maximum velocity of 25 in./sec. The corresponding values of acceleration and velocity for the vertical direction are 2/9 and 10 in./sec. Therefore, the heaviest test structure could be subjected to motion of approximately twice the intensity of the El Centro earthquake.

The shaking table is 10 feet deep. It consists of top and bottom steel plates connected by vertical webs spaced at 16 ft.- 6 in. centers and arranged orthogonally. This cellular system, shown in Fig. 3, is further stiffened by tubular trusses spaced at 5 ft.- 6 in. centers. Test structure attachment points are spaced 5 ft.- 6 in. apart along the top of the table in both directions. Each attachment point can carry a maximum concentrated load of 250 kips.

The shaking table weighs 2 million pounds. Therefore, the maximum combined weight of shaking table and test structure is 6 million pounds. To provide accelerations of 2/3 g and 2/9 g to a mass weighing 6 million pounds requires forces of 4 million and 4/3 million pounds, respectively. Twenty 200 kip (dynamic rating) actuators are, therefore, sufficient to drive the table in each horizontal direction, and twelve 200 kip actuators are sufficient for the vertical direction. (Extra force is required in the vertical direction to react overturning moments.) The strokes of the horizontal and vertical actuators are 12 in. and 4 in., respectively.

The actuator forces are reacted by the inertia of a reinforced and prestressed monolithic foundation consisting of a massive concrete slab 200 ft. x 200 ft. in plan, a deep footing running around the entire boundary of the slab, mechanical equipment rooms along two sides, connecting corridors along two other sides, and twelve buttress supports. A section through the foundation and shaking table is shown in Fig. 4(a). The location of the twelve buttress supports, and the forty horizontal actuators whose base plates are prestressed to vertical faces of the buttresses, are also shown in Fig. 4b.

The piston rods of the horizontal hydraulic actuators are connected by long extension arms to the actuator attachments located directly below the lower surface of the table and half way between buttress supports. The vertical hydraulic actuators, connected directly to plates prestressed to the foundation slab, are each attached by extension arms to the table.

The total weight of the foundation will lie in the range 40 - 60 million pounds. The upper weight limit is based on a ratio of 1:10 of maximum moving mass (table plus structure) to foundation mass. This ratio is generally considered adequate for such foundations when resting on soils having medium strength properties (medium soft clays). For considerably higher soil strengths (compacted sands and gravels) the above ratio could possibly be reduced to 1:6.

When the table is in use, the combined dead weight of the table and test structure will be balanced by compressing (up to 4 psi) the air beneath and within the table. (The space within the foundation pit and beneath the table will be made airtight with a fabric strip attached to the periphery of the table and to the foundation.) When the table is not in use, it can rest on the concrete buttresses in the foundation.

The overturning moments caused by the inertia forces of the test structure will be reacted by either an active or passive stabilization system. The arrangement of hydraulic stabilizer units for a passive stabilization system is shown in Fig. 5. One advantage of the passive stabilization system is its ability to increase the natural frequencies and damping capacities of the flexural modes of vibration of the table. The mode shapes of the first three free-free flexural modes of vibration are shown in Fig. 5.

The power required to drive the shaking table is about 25,000 HP. Due to the peculiar power demand (high load for short periods), it is most economical to provide the facility with its own power generating plant.

RESEARCH POTENTIAL OF EARTHQUAKE SIMULATOR FACILITIES

The medium and large size simulator facilities can be used to test a wide variety of systems such as individual elements, assemblages of elements, and complete structures. The systems can be subjected to steady-state sinusoidal, prescribed earthquake type, or random motion. The motion can have sufficient intensity to cause major damage to large structures, and complete failure of smaller structures and assemblages of elements.

Buildings, the most common of all structural systems, need investigation under realistic earthquake conditions to improve future designs. The energy absorption, stiffness, and failure characteristics of these structures can be studied by testing full scale assemblages of components such as: (1) frames with different combinations of geometry, beams, columns, and joints, (2) frames infilled with shear walls, (3) floor systems supported by frames with and without shear walls, (4) lateral bracing systems for frames, (5) core elements such as stair wells and elevator shafts, (6) wall and roof diaphrams, (7) bearing walls, (8) filler walls, (9) curtain walls, and (10) architectural elements such as wall facings and window framing. Where applicable, these tests should include a variety of materials such as steel, aluminum, reinforced and prestressed concrete, wood, plastics, masonry materials, and other materials as they become acceptable to the construction industry. The advantages of various construction methods, such as prefabrication versus built-in-place, should also be investigated. After the physical properties of standard assemblages have been determined, modifications should be made wherever possible to remove undesirable characteristics, and the effectiveness of these changes should be verified by additional full-scale testing.

Due to the complex three-dimensional interactions of the numerous structural components in many buildings, it is questionable whether appropriate mathematical models can be formulated for analysis purposes entirely on the basis of research on assemblages. This uncertainty will require experimental studies of single and multi-story buildings (at least three stories are required to study story interaction) subjected to a wide range of simulated earthquake intensities. Only such tests can verify the dynamic response and failure characteristics of structures predicted from the known properties of their components.

In addition to experimental programs using assemblages and buildings of standard design, additional experimental programs could be conducted using buildings of unusual design selected specifically for their seismic-resistant characteristics. For example, certain shell-type structures might prove to be excellent earthquake-resistant structures while at the same time being aesthetically superior to structures of standard design. Since little is known about the strength and energy absorption characteristics of shell structures under seismic conditions, experimental investigations are needed to obtain such information.

The use of damping devices to limit the dynamic response of buildings, and foundation isolation devices to limit input excitation, is now being seriously considered. Earthquake simulator facilities would be invaluable for this type of development work.

Structures such as towers of different materials and geometric forms, ranging from utility towers and off-shore oil-drilling towers to water towers and intake towers, could also be tested on earthquake simulators to determine their ability to withstand earthquake forces. In addition, certain structural and mechanical systems used in the construction of nuclear reactor power plants could be tested to determine their dynamic response characteristics. Because of the danger of radioactive emissions, it is important that such systems do not fail during an earthquake.

Models of dams constructed of a variety of materials and geometric forms ranging from straight earthdams to double curved thin-arch concrete dams could also be investigated using a large scale earthquake simulator. While it would be impossible to test full-scale sections of dams on an earthquake simulator, it would be possible to test models much larger than have been tested previously. Thus, the prediction of prototype behavior from model tests would be more reliable.

The simulator facilities could also be employed to investigate the effects of earthquakes on soil structures and foundations. In particular, they could be of direct benefit to study (1) stress-strain relationships for both cohesive and non-cohesive soils, (2) liquefaction of soils, (3) stability of embankments, (4) soil-structure interaction, and (5) dynamic response of layered soil systems.

Earthquake simulator facilities would provide controlled sources of excitation to the soil (or rock) supporting their foundations. Thus, they provide an excellent opportunity to study the transmission and attenuation of seismic waves of different frequencies as they travel horizontally and vertically away from their source. A good seismic source must be sufficiently large so that the stress waves transmitted are of substantially higher intensity than the background noise in the vicinity of the test site. For this reason, the large size simulator facility would be most useful for these studies.

Certain physiological effects produced by vibration environments on human beings are of interest to the medical profession. The medium size earthquake simulator facility could be used most effectively to observe these effects under controlled two-dimensional motion having any desired frequency spectrum below 10 c.p.s.

CONCLUDING REMARKS

The design features of a medium and a large size earthquake simulator have been presented, and their potential for research work has been discussed. It is concluded that significant advances in aseismic design can be achieved through experimental research conducted with earthquake simulator facilites. Also, in order to conduct the required research work in an efficient manner, different size shaking tables are required to test different sizes of structures. In this respect, it is considered that small, medium, and large size earthquake simulators would be complementary to each other, and at least one of each type is necessary for research purposes.

ACKNOWLEDGMENT

The authors wish to acknowledge with sincere appreciation (1) the financial support provided by the National Science Foundation under Grant NSF GK-1319 for the medium size earthquake simulator facility described herein which is now under construction at the University of California, Berkeley, and (2) the financial support provided by the Department of General Services Office of Architecture and Construction, State of California, under Standard Agreement SA 3148, W.O. PBF for the feasibility study of the large size earthquake simulator facility.

REFERENCES

1. Nielsen, N. N., "Vibration Tests of a Nine-Story Steel Frame Building," Proc. ASCE, J. Engineering Mechanics Division, Vol. 92, No. EM 1, 1966.

2. Rea, D., J. G. Bouwkamp and R. W. Clough, "The Dynamic Behavior of Steel Frame and Truss Buildings," Structures and Materials Research Report No. 66-24, University of California, Berkeley, California, 1966.

3. Englekirk, R. E. and R. B. Matthiesen, "Forced Vibration of an Eight-Story Reinforced Concrete Building," Bulletin of the Seismological Society of America, Vol. 57, No. 3, June, 1967.

4. Keightly, W. O., "Vibration Tests of Structures," Earthquake Engineering Research Laboratory, California Institute of Technology, 1961.

5. Rouse, G. C. and J. G. Bouwkamp, "Vibration Studies of Monticello Dam," Research Report No. 9, Bureau of Reclamation, United States Department of the Interior, 1967.

6. Hudson, D. E., "Resonance Testing of Full-Scale Structures, Proc. ASCE, J. Engineering Mechanics Division, Vol. 90, No. EM 3, 1964.

7. Hanson, R. D., "Comparison of Static and Dynamic Hysteresis Curves," Proc. ASCE, J. Engineering Mechanics Division, Vol. 92, No. EM 5, 1966.

8. Penzien, J., J. G. Bouwkamp, R. W. Clough and Dixon Rea, "Feasibility Study Large Scale Earthquake Simulator," Earthquake Engineering Research Center Report No. EERC 67-1, University of California, Berkeley, 1967.

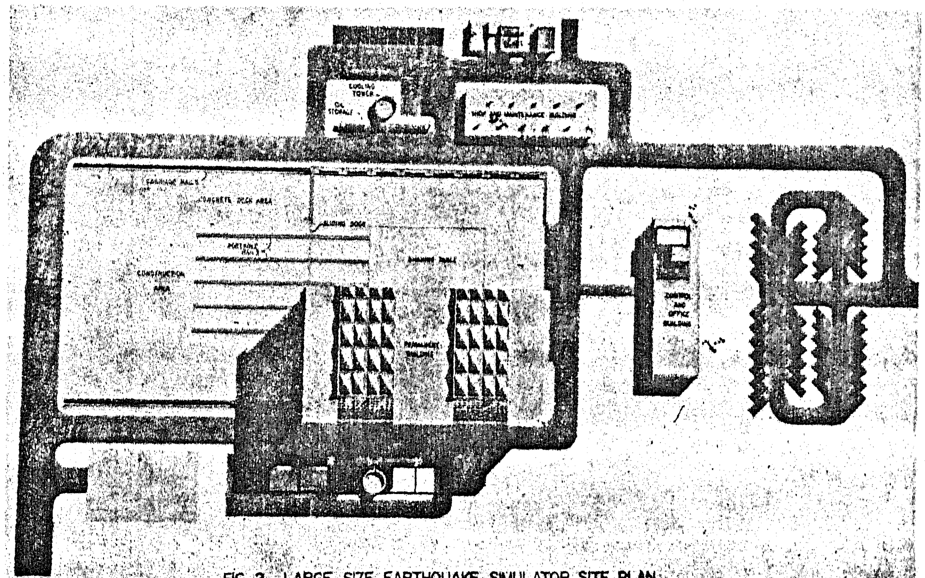

FIG 2 LARGE SIZE EARTHQUAKE SIMULATOR SITE PLAN.

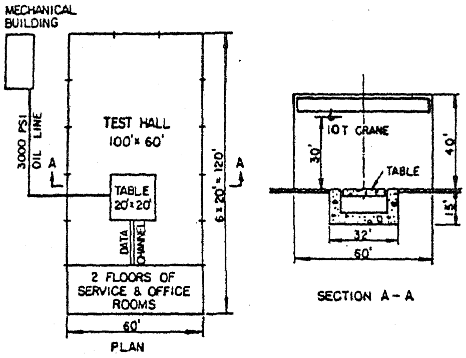

FIG. 1a PLAN AND SECTION MEDIUM SIZE EARTHQUAKE SIMULATOR FACILITY, UNIVERSITY OF CALIFORNIA, BERKELEY

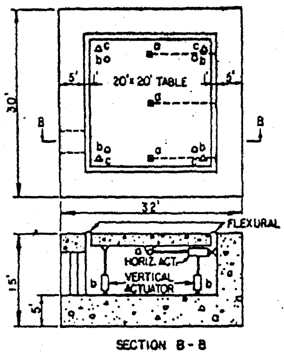

FIG. 1b PLAN AND SECTION OF MEDIUM SIZE SHAKING TABLE AND FOUNDATION

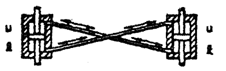

FIG. 1c. PASSIVE STABILIZING SYSTEM

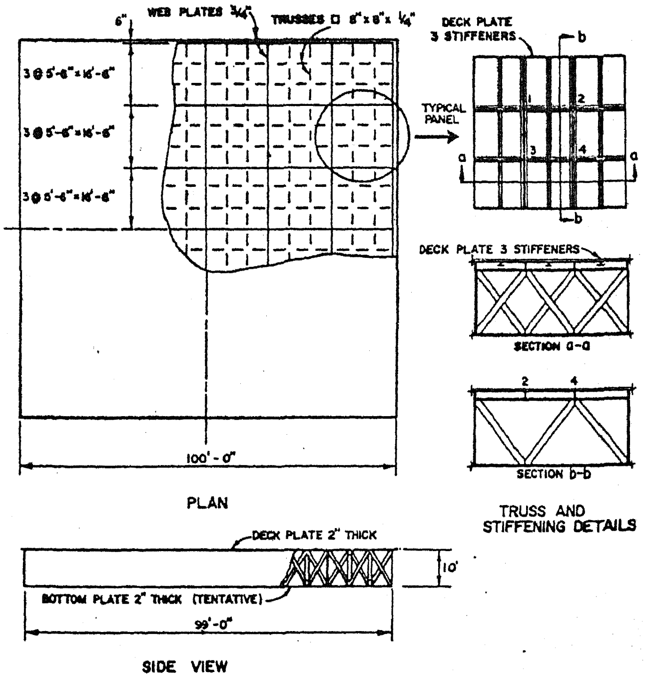

FIG. 3 SHAKING TABLE DESIGN

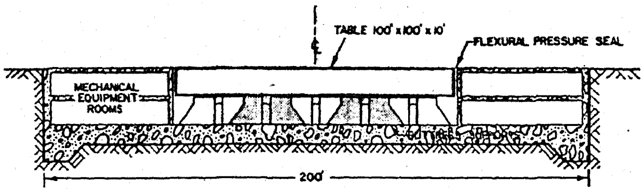

FIG. 4(a) VERTICAL CROSS-SECTIONAL VIEW OF LARGE SIZE TABLE AND FOUNDATION

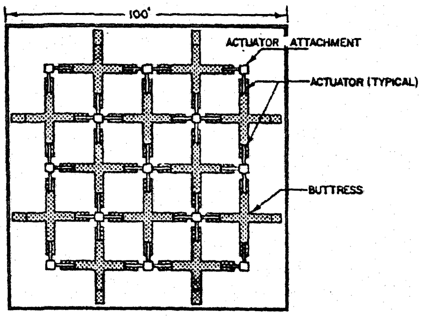

FIG. 4(b) BUTTRESS AND ACTUATOR ARRANGEMENT FOR LARGE SIZE TABLE

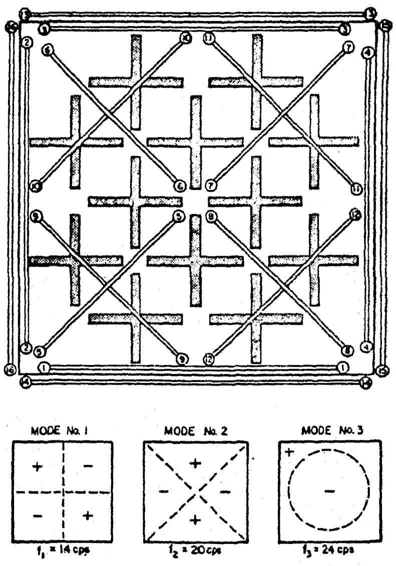

FIG. 5 HYDRAULIC STABILIZER ARRANGEMENT AND FREE-FREE MODE SHAPES OF TABLE.