THEME IV. EARTHQUAKE RESISTANT DESIGN, CONSTRUCTION, AND REGULATIONS

GENERAL REPORT

By Emilio Rosenblueth[*]

Introduction

Few forces in nature are as unpredictable as earthquake forces, and no other frequent cause of failure involves so many unknowns. The major uncertainty lies in the characteristics of future earthquakes themselves and on how these features can be expected to vary from place to place. Due to the nature of the present theme, such matters are hardly to be considered here: earthquake characteristics are assumed to be known or in some manner specified. The influence of ground conditions on earth motion and soil-structure interaction are also covered under different headings in this conference. It is not surprising that of the 37 papers reviewed in the present report,[**] only a few should concern themselves to some extent with regional seismicity, one of them from a special point of view -- earthquake insurance, -- and only one paper should deal with foundations (bridge pile-piers). Of the remaining works one deals with elevated tanks, two with bridges, three with special structures, five with dams, and the other 24 with buildings and with building code provisions.

The development of criteria to evaluate the forces against which buildings must be designed to resist earthquakes begins at the turn of the century. There have been some changes in building codes since the widespread adoption of Tachu Naito's methods following the 1923 Tokyo earthquake. Some building codes still require that earthquake forces be computed assuming a uniform horizontal acceleration in the entire structure. Most codes have adopted static methods of analysis that tend more closely to reflect the dynamic nature of the problem and the results of experience. Thus the horizontal acceleration is made a function of elevation above ground level and often it is also made to depend on the fundamental period of the building, usually estimated using crude formulas. Several regulations include a dependence of the base shear coefficient on the local nature of the ground. In an effort to be realistic, many building codes provide for reductions in statically computed overturning moment and introduce minimum or additional torsional eccentricities. Few codes include detailed instructions on modal dynamic analysis as a basis for design as an alternative to static methods(1).

It might seem desirable that all buildings be designed on the basis of dynamic analyses. But dynamic analysis that neglects the contributions of "nonstructural" elements and assumes linear behavior and base fixity greatly overestimates structural responses, especially those due to strong earthquakes(2). The contribution of "nonstructural" elements, including staircases,

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[**] The number of papers classified under Theme IV is 39; those by HOLMES and MILLER arrived belatedly and are not considered in this report.

partitions, and cladding, leaves no room for other than its explicit consideration. The problem is ignored in ordinary design but rises in full when reconciling periods of existing structures(3) or explaining earthquake damage.

Nonlinear behavior is often responsible for the major fraction of the discrepancy between computed and actual structural responses to strong ground motions(4), and this portion frequently reaches several hundred percent. At least three quantitative methods have been proposed for incorporating nonlinear behavior in design(5). One is the reserve energy technique(6). Another assumes that maximum deformations in a linear structure that has natural period T and degree of damping ζ for small oscillations will be the same as those of a linear (equivalent) system having the natural period T and degree of damping ζ(7). The third maintains that the energy of deformation of the nonlinear and the equivalent linear systems are equal(8). The first method is more complicated and refined than the other two, and through a proper choice of parameters can be made nearly to coincide with either of them. Each of the latter have been confirmed through analog and digital computation of responses to strong-motion accelerograms and each has its range of applicability(9), although there are cases for which both are overly conservative and cases of extreme rigidity (calling for very high ductility factors) for which neither is conservative enough (see results of analyses in 10,11). In all, the response of firmly founded systems having a single degree of freedom has been adequately covered to date, but there is no method appropriate for the design of systems with several degrees of freedom: it is not possible, in most cases, to predict whether a major portion of the energy of inelastic deformation will be absorbed in only one or a few degrees of freedom or will be uniformly distributed in the structure(9). Efforts in the direction of establishing such methods are much worthwhile, and the SERAC project(12) now in process marks an excellent example in this direction, but the stage has not been reached where generalizations are feasible from these and other analyses of individual structures subjected to specific ground motion.

Soil-structure interaction is apparently of little significance for most substantial buildings in California(3,13). This is certainly not the case with very rigid Japanese buildings on compressible soil(14) nor is it for slender buildings on Mexico City's clay(15,16). Moreover, many now classical accelerograms were recorded in the basements of buildings, so they probably lead to erroneous conservative predictions of base motion in the open field and under other structures as well as of the latter's responses(17).

Owing to these considerations it is clear that the simplest dynamic analyses, whether used as a guide to establish expedient static methods or directly for purposes of design, merit drastic reductions before being useful, and that these reductions should vary over a wide range and depend on many factors.

The possibility that energy of inelastic deformation be absorbed in a single or a few especially weak elements rather than throughout the structure, has profound implications not apparent at first sight. For example, the base shear coefficient for elastic structures should vary roughly as T^{-1} within some range of natural periods, and above that as T^{-2}(5). Yet many codes mark a base shear coefficient that is independent of T for large periods, and the new Uniform Building Code specifies a variation with $T^{-1/3}$. This apparent overconservativeness for long periods protects against the need for excessively high, localized ductility factors in tall buildings (provided such buildings have indeed long fundamental periods). Also, the fact that ordinary structures are nor capable of developing extremely high ductility factors, which they may be called to develop in tall buildings, justifies the requirement contained in many codes to the effect that, beyond a certain height, a frame be provided, capable of developing the ductility of a structural steel frame (with very carefully detailed connections, or the ductility of an exquisitely detailed reinforced concrete frame). (There is an obvious duplication of restrictions in this overdesign of tall buildings and the height limitation on moderately ductile structures.)

Some important buildings are being analyzed as inelastic (usually bilinear) structures subjected to specific earthquake records. Aside from the difficulty of using this approach in routine design, there exists the question of the number of different earthquake motions for which it is practical to analyze a structure. Hence there is still much room for modal analysis based on design spectra, on some rules for combining the maximum responses in the various natural modes, and on the use of important reduction factors. But methods of modal analysis have other serious limitations, besides those due to nonlinear behavior, especially when two or more natural frequencies are close to each other (as in some cases of torsional oscillations(18)), and the results of experience can best be incorporated into static methods. Moreover, most houses and buildings do not merit even the most elementary dynamic analysis. Accordingly present-day designs are quite properly based on one of the three different approaches (static, modal, and transient-state analyses) and sometimes on a combination of them.

Ductility plays such an important role in the design and behavior of buildings that connections deserve the most meticulous attention. To express it with greater generality, in earthquake resistant design "every detail is important and no detail is unimportant"(19). If there is a well defined weakest link in the structure it will be called to absorb an enormous amount of energy, indeed the entire energy of inelastic deformation, whether that link is a cold joint, a connection, or a careless detail.

The design of short and medium-span bridges has proceeded along similar lines as that of buildings, but there are problems that are peculiar to them. This is the case with pier foundations and with the question of the supports of discontinuous spans. Most failures of bridges during earthquakes can be traced to these two matters. In continuous spans there is also the nearly unexplored problem of stresses induced by unequal displacements of the piers.

Suspension bridges, arch dams, nuclear reactors, and certain other special structures pose a set of problems all their own. They are structures in which extensive plastic behavior is (at least presumably) objectionable, in which displacements within the elastic range may reach excessive amplitudes; several of the natural periods of vibration in these systems are close to each other; there is little if any experience with their responses to strong ground motions; and these structures lend themselves to conservative criteria of design against lateral forces. Suspension bridges present, besides, difficulties of analysis owing to their complexity and to nonlinearity within the elastic range. Dams and other hydraulic structures, as well as tanks, exhibit the additional fascinating problems associated with hydrodynamic pressures.

Earth and rockfill dams are being designed on the basis of static methods, sometimes supplemented with the results of dynamic analyses; and model tests. The dynamic methods are again divided between the linear(20) and the nonlinear schools(21). In general, there is good justification for the former in dams that may undergo sudden major failure, and for the latter in dams that would fail plastically.

In what follows, papers classified under Theme IV are commented upon. The comments -- rather than the papers -- are grouped under various headings.

Architecture and Trends in the Choice of Structural Materials

As described by BLAKE-KELLY, New Zealand is a country where architectural and construction trends have absorbed the experience gained from earthquake effects. Early settlers built their houses of timber, which was and still is plentiful. Unreinforced masonry came next, but fared badly under strong earthquakes. The experience led to widespread and successful adoption of masonry panels enframed in timber. Present-day architecture leans heavily toward use of reinforced concrete shear walls for medium-tall buildings and composite (concrete-encased steel) frames for the tallest buildings. (See also JOHNSTON, GLOGAU, CANDY, and MCKENZIE.) In small dwellings, timber is much used and, in one locality, there is preference for reinforced masonry.

Despite recent earthquake experience in Iran, present trends do not lead to increased earthquake resistance. This is forcefully brought out by MOINFAR

POLYAKOV and KONOVODCHENKO report on trends in the USSR. These cover: 1) masonry bearing walls with bond beams and sometimes with vertical reinforcement; 2) masonry enclosed in reinforced concrete frames; 3) large concrete blocks; 4) large precast concrete panels; and 5) rooms or groups of rooms of precast concrete completed in a plant, including paint. The latter type is in experimental stages. Static, impact, and shaking-table tests on all types of construction are mentioned, including one-fourth scale models. This impressive paper contains conclusions derived from economic comparisons.

Seismicity and Insurance

The first step in earthquake resistant design involves estimating seismicity of the site. Hence the importance of regionalization, and there are quantitative methods for establishing regional seismicity(22). Yet every regionalization map known to this reporter contains a major dose of subjective interpretation. Papers classified under Theme IV do not change the situation materially, although BLUME, in the first and fascinating part of his paper, does set bases for a more quantitative determination of seismicity and includes pertinent considerations on the matter. DESPEYROUX calls attention to the need for at least two parameters to define regional seismicity.

DUZINKEVICH mentions the fact that microregionalization has progressed in the Soviet Union to the point that it now covers most areas of interest.

France did not quite rid itself of earthquakes when it gave up Algeria. Although strong ground-motions are virtually unknown throughout most of the country, the phenomenon cannot reasonably be ignored in small areas, especially near the Alps. This calls for a far more careful study of seismic zoning than is ordinarily done. DESPEYROUX aptly describes the data and reasoning that led to the zoning incorporated in the present code for France.

BENNET narrates the history of earthquake coverage in New Zealand. Damage to tangible property is financed by government through the device of using a percentage of fire coverage. Loss of profits and excess of indemnity contracts are covered by insurance companies against premium rates that depend on the type of building, nature of the ground, and popular demand for insurance, but not truly on regional seismicity; demand for coverage is heavily concentrated in regions where the most recent destructive earthquakes have stricken. Fully 90 percent of claims since 1944 correspond to damage in unreinforced-masonry chimneys.

Characteristics of Ground Motion

BLUME modifies published empirical correlations of ground acceleration with magnitude and distance and incorporates another empirical formula to predict spectra as a function of these two variables. His proposals differ from those of other researchers(23,24). He suggests the use of microtremor spectra to guide in the selection of design spectra. Kanai(25) has also advocated such an approach; it has actually been used by TAKEYAMA, OTA, NAGATA, ATSUMI *et al*. for the design of a building in Indonesia.

Behavior of Wood Panels

MEEHAN refers to repeated-load tests on diagonal sheathing plywood and laminated deck investigated as roof, solid wall, and mullion wall diaphragms. Attention was given to strength, stiffness, and energy absorption and to the influence of such variables as the omission of framing, omission of solid blocking, and distribution and characteristics of nails. To the reporter's knowledge this is the most comprehensive study available on wood diaphragms. It sets a beautiful example of pertinent research on behavior.

Behavior of Masonry

Most of the world's expenditure in construction goes into low-cost dwellings(26) and most lives lost during earthquakes are lost through collapse of these dwellings. Encouragingly, types of construction that are normal for such dwellings have received increased attention in the last few years. This is true of wood diaphragms and it is also valid of unreinforced masonry bearing walls, sometimes provided with timber or reinforced concrete elements.

KRISHNA and CHANDRA report on an ambitious series of tests to determine modulus of rupture, compressive strength, static and dynamic moduli of elasticity, and degree of damping of brick work using various kinds of mortar. Most of these tests were run on short cantilever columns. The authors include an analysis of walls with rectangular openings, which conforms to conventional strength of materials. Finally, they report on static tests of models of houses on four walls. The variable in the tests was the presence of bond beams and/or vertical steel reinforcement at the corners and jambs. Small amounts of reinforcement in bond beams and at the corners increased the capacity on the order of fourfold.

KENNA reviews the earthquake behavior of brick masonry in New Zealand. e traces some failures to inadequate foundations, faulty ties with other tructural elements, insufficient strength, and absence of braces. Most failres have ocurred in chimneys, owing to the lack of reinforcement (see BENNET). e reports tests on brickwork panels, loaded normal to their plane, both with nd without timber framing. Pulsating in-plane load tests are contemplated or the future.

MEEHAN mentions important tests done in California, chiefly to revise specifications and construction procedures applicable to public school buildings. In brickwork panels little influence is found of mortar strength on the capacity to resist lateral loads, but peripheral reinforcement is found to be decisive in this respect (see also POLYAKOV and KONOVODCHENKO). Forced vibration tests on 25 school buildings gave damping ratios of 1.9 to 12.4 percent critical, with an average of 5.6 percent.

Behavior and Construction Practices for Reinforced Concrete

CHANDRASEKARAN and KRISHNA describe free-vibration tests on 13 towers for elevated water tanks and comparison with analytical calculation of their natural periods. It is found that the effective EI (E = modulus of elasticity, I = cross-sectional moment of inertia) of reinforced concrete columns increases markedly with axial load. They find percentages of damping of 1.5 to 3.0 of critical for small amplitudes. In one instance of large amplitudes of vibration, 5 to 6 percent critical was found.

Precast concrete is used impressively in the Soviet Union. CHURAYAN and DJABUA discuss various types of monolithic-concrete connections between precast panels and detail them with much clarity. These joints include keys, welding of steel bars that protrude from the panels, and special loops also formed with protruding bars. Design assumptions and the influence of important and often ignored factors are also discussed, especially for exterior panels. (See POLYAKOV and KONOVODCHENKO.)

Behavior of Prestressed Concrete

ZAVRIEV discusses the merits and demerits of prestressed concrete as used in bridges, from the viewpoint of structural responses to earthquakes.

DESPEYROUX expresses pros and cons on the use of prestressed concrete in seismic zones, principally for buildings, leaning toward a favorable outlook. His paper includes consideration on damping, inelastic energy absorption, flexibility, connections, recuperation of cracking, and ability to undergo alternating flexure. The behavior of 27 buildings having prestressed concrete structure, during the 1964 Alaska earthquake is described and explained. It is of interest to compare with Binder's report(19) and with Sutherland's paper on the same earthquake. A concise introduction by Guyon precedes this paper. The conclusion is inescapable that more research is needed to dilucidate matters concerning energy absorption.

SUTHERLAND maintains an even more favorable outlook on the earthquake resistance of prestressed concrete structures. First he describes current practice in the United States, Hawaii, New Zealand, and Japan. Next he analyzes behavior of these structures during the recent earthquakes of Skopje, Alaska, and Niigata, devoting special attention to the Alaskan Four Seasons Building. Finally he cites research by Nakano, Oladapo, Spencer, and Penzien. He concludes that prestressed concrete structures will prove efficient and economical, presumably independently of the local cost of materials.

Behavior of Steel Connections

BOUWKAMP describes the design and laboratory testing of girder-to-column connections for the steel frames of two 15 and 16 story buildings to be erected in San Francisco. The buildings are approximately 30-m square in plant without interior columns and have 107-cm-deep H columns at the periphery. The paper describes tests on representative connections. Only one flange of the beam was reproduced in each (full-size) laboratory specimen. The flange is welded to a T section bolted to the column flanges. In the perpendicular direction 1.5" or 2" plates are welded to the column web. The column flanges are 2" or 3.5" plates. Pairs of nearly identical connections were tested, one of them annealed to eliminate residual stresses due mostly to welding. Annealing did not materially change the moment capacity but did result in a more favorable distribution of stress and postponed cracking of the welds. The shearing-stress distribution along the welds was surprisingly similar to that along a rectangular section away from the supports.

Nonstructural Elements

Despite the economic significance of the behavior of the nonstructural elements, only MEEHAN refers to quantitative studies on the matter. These concern static and impact tests on windows having glass panes. The results have been known for some time(27) and are of great interest; they should stimulate research on this general area.

Other papers classified under the present theme refer to nonstructural elements by quoting or proposing code requirements on the subject.

Field Inspection

MEEHAN mentions X-ray control of field welding with positive results in the sense that the quality welding practice has probably improved in California. The same office has attempted nondestructive tests (sonic, and X-rays), to establish the quality of masonry, but these have not been successful.

Behavior of Buildings During Earthquakes

THE DEPARTMENT OF SCIENTIFICAL AND TECHNOLOGICAL RESEARCH OF THE CATHOLIC UNIVERSITY OF CHILE has analyzed statically with much care and precision, two structures, three and six stories tall, that were damaged by the 1960 Chilean earthquakes. The method of analysis used is iterative and capable of incorporating base rotations, effects of secondary members, and shearing strains. Both buildings have reinforced concrete structures and unreinforced masonry walls. The damage in one building is attributed essentially to torsion, and the analysis that was applied justifies the damage observed, save in one of the beams, and this is indirectly explained considering wall-frame interaction. Damage in the second building is attributed to underreinforcement of columns, some of them with 0.25 percent vertical steel. (This reporter has misgivings on the interpretation, especially in what concerns the assumption of infinite rigidity of horizontal diaphragms for the second building.) Reference is made to a dynamic analysis of the first building, assuming linear behavior and a base motion that is a scaled down El Centro 1940 record. Results show definitely greater torsion than in the static computations. (See also DESPEYROUX and SUTHERLAND on behavior of prestressed concrete structures.)

Building Code Requirements and Analysis of Multistory Buildings

There is a trend toward waiving of height limitations; witness Japan, New Zealand, and the city of Los Angeles. At the same time many codes preserve absolute height limitations or limitations that depend on the type of structural solution and materials, and new codes are being proposed which include such clauses. Limitations can be justified for solutions and materials that exhibit low ductility, on the basis that they may be called to develop locally high ductility factors in tall buildings. There is also implicit a distrust of the efficacy of the analysis and design that tall buildings demand.

The USSR preserves height limitations for unreinforced masonry bearing wall construction (POLYAKOV and KONOVODCHENKO). The building code proposed for Iran (MOINFAR) also contains height limitations for such buildings.

The proposed Iranian code contains clauses for a static method that incorporates features from the San Francisco and the Uniform Building Codes with some modifications.

Not all building codes make seismic forces depend on the consequencies of a structure's failure; some specify requirements independent of the use intended for the structure. Such practice implies the impossibility of failure of a well-designed structure, which is at least a debatable assumption, as there is, for example, no substantial reason to reject the possibility of an earthquake stronger than any arbitrarily chosen limit.

Many important buildings are being designed using static methods of analysis. This may be quite a proper approach when the assumed accelerations are sufficiently conservative and the building lends itself to design for high lateral forces without becoming excessively expensive, or when it is not amenable to trustworthy dynamic analysis, or when such an approach is mandatory by law. Thus just as the 333-m Tokyo tower was designed before the Second World Conference using static requirements in the Japanese code(20), the new 131-m Kyoto Tower building was designed using very nearly the same criteria. (TANABASHI, KANETA, SHINKAI, and TAKEMURA.) Several other papers in this theme report the use of other variations of the static method as a basis for the design of important buildings throughout the world.

The base shear coefficient adopted for New Zealand, as described by JOHNSTON, GLOGAU, CANDY, and MCKENZIE, varies with regional seismicity. For the zone of highest seismicity it varies with the fundamental period of vibration following a simplified spectrum of the El Centro 1940 earthquake, NS component, for 10 percent of critical damping and a ductility factor of 4.

DAVID proposes minimum torsion to assume in design. He also gives formulas for stresses set up by individual-member torsion in columns, and reports tests on static and dynamic torsional loading of steel columns.

Accidental torsion arising from irregular distribution of rigid partitions is avoided in one New Zealand building by the use of sliding connections between partitions and structure (JOHNSTON, GLOGAU, CANDY, and MCKENZIE).

In many static methods of design the base shear coefficient depends on the fundamental period of vibration. The manner of establishing this relation is studied by UMEMURA, OSAWA, and SHIBATA using five of the many medium-intensity earthquakes recorded in Japan. Buildings are analyzed using the analog computer SERAC. The authors conclude that it is on the safe side in a multistory building to use a base shear coefficient equal to that for a single-degree structure whose natural period coincides with the fundamental period of the multistory building and has the same degree of damping.* It is also concluded that the distribution of seismic shears can be adequately obtained from the linear combination of those due to a concentrated force at the top of the building and those produced by a linear variation of horizontal accelerations, with zero acceleration at the base of the structures. Practical recommendations are included for the estimate of the proportions of these two distributions to take in design.

The foregoing paper parallels to some extent the one by BUSTAMANTE on seismic shears and overturning moments. BUSTAMANTE uses results of modal analysis of 31 elastic shear buildings to evaluate the requirements of the Uniform Building Code on horizontal shears and overturning moments in buildings having a height-to-base ratio smaller than 5. Comparisons are also made with the Mexican Federal District code requirements. Assuming that the base shear coefficient has been correctly chosen, it is found that the triangular distribution of accelerations is not always conservative, but becomes so by adding a concentrated force equal to 5 percent of the base shear at the top of the building. The Uniform Building Code's reduction factor for overturning moment at the base of the structure is satisfactory, but the linear variation that this code specifies leads to excessively conservative values near the top of the building. The Mexican code, with the addition of a force equal to 5 percent of the base shear at the top, gives reasonably uniform safety factors.

Methods that fix the base shear coefficient as a function of the fundamental period of vibration imply the possibility of a rapid estimate of this quantity, for if it were to be computed using elaborate methods of analysis there would be little reason to omit a thorough modal analysis. Yet, formulas that incorporate no more than the height and base of the structure as pertinent parameters give one-hundred percent errors on the average for the typical buildings of some countries(29); errors for individual buildings are substantially greater. Even standard methods of dynamic analysis are far from trustworthy(29), although there is some implicit claim to the effect that proper consideration of the stiffness of "nonstructural" members and cladding as well as of base rotations and displacements will normally lead to estimates within a few percent of measured periods(3,16). There are reasons to doubt the generality of such successful approaches (see, for example, CHANDRASEKARAN and

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* This general conclusion can be easily proved for shear buildings, as pointed out by N.M. Newmark to this reporter.

KRISHNA on the matter of the effective EI of reinforced concrete columns. See also KRISHNA and CHANDRA on the effective modulus of elasticity of brick work). Still, introduction of properly evaluated parameters into simple formulas or charts permits a rapid estimate of lateral displacements from which it is easy to estimate the fundamental period. Precisely such charts are provided by BURNS for shear walls coupled through single-bay beams; the charts permit consideration of several parameters, and the author illustrates the estimate of the fundamental period of vibration using this approach. BURNS' results are useful in analysis of coupled shear walls. They cover a range of conditions not included in other works on the subject, such as the extensive charts by Khan and Sbarounis(30) for coupled shear walls and frames. Results of the paper by BURNS were used in one portion of the paper referred to in the next paragraph.

JOHNSTON, GLOGAU, CANDY, and MCKENZIE describe significant results of dynamic analyses of two buildings. The first is a reinforced concrete, 17-story office building designed for a base shear coefficient of 0.18 and triangular distribution of accelerations. It was next analyzed, using a digital computer, for the El Centro 1940 earthquake, NS component, assuming linear behavior and 7.5 percent damping. Dynamic forces were up to about 2.5 times larger than those used for design. The design was deemed adequate because the shear walls and frames can be expected to furnish ductility factors in excess of 2.5. In one direction the coupled shear-walls were analyzed using an approximate procedure and the analysis was refined to take into consideration deformations due not only to flexure but to shear and axial strain as well, and effects of cracking. All these factors influenced the results appreciably.

The second building has a steel welded frame enclosed in reinforced concrete. It consists of basement, ground floor, and 13 off-set additional floors. It is the Post-Office building in Wellington, the building having the largest floor area in New Zealand. After tentatively designing the structure on the basis of static analysis it was analyzed dynamically in an analog computer for the classical El Centro earthquake and several other recorded ground motions, all to the same scale. Behavior was idealized as linear with 5 percent damping and the first three modes were taken into consideration. Computed shears were divided by (a ductility factor of) 4. The final design covers the maximum shears obtained from both the static and the dynamic analyses. The latter gives shears of twice the static values in the upper stories, due to the reduction in floor area. It is intended to reanalyze the building in the SERAC computer assuming elastoplastic behavior.

Design of a 29-story steel-frame building in Indonesia is described by TAKEYAMA, OTA, NAGATA, ATSUME, et al. The base shear coefficient was established from the expression $C = 0.1/T$ (C = base shear coefficient, T = fundamental period in seconds) taking $T = 0.095$ times the number of stories. The curve $C(T)$ adopted is based on the spectrum deduced from Kanai's semiempirical formulas(25), fixing the prevailing period of the ground at 0.1 sec from microtremor determinations. The variation of horizontal accelerations was first assumed to be as in the Japanese code. The preliminary design was based on shears determined in this manner. Next, the resulting structure was analyzed for three recorded earthquakes adjusted to a maximum acceleration of 100 gals. The calculations were done in a computer assuming linear behavior and 5 percent damping. The ratios of computed drifts to drifts required to produce yielding in each story were found to vary pronouncedly along the height of the building. The structure was redesigned on the basis of the dynamically computed shears but preserving the original base shear coefficient. Structural responses were recomputed and it was found that the envelope of computed drifts over yield drifts was nearly uniform and that the structure remained within the elastic range for the three earthquakes, even when their accelerograms were adjusted to maximum ground accelerations of 150 gals.

The 1964 code for France is aptly described by DESPEYROUX, who includes several pertinent comments on the subject. The code stipulates a dynamic method which comprises calculation of the fundamental mode, its participation coefficient, and the corresponding spectral structures. One interesting feature concerns consideration of vertical accelerations.

COOPER presents an excellent summary of pertinent matters to be considered in earthquake resistant design of buildings. His complete paper is worth reading as a reminder even for experienced designers.

DUZINKEVICH proposes that the International Association for Earthquake Engineering write a world-wide set of bases for earthquake-resistant building codes and finish it by 1966. He cites the work of UNESCO on general principles and describes interesting aspects of the USSR Code.

Direct Design

An ingenious approach to the earthquake resistant design of single-degree reinforced concrete structures is proposed by BORGES. If one neglects torsion and assumes that only the lower-story columns deflect, it is possible directly to establish a relationship between the depth-to-height-ratio in the columns and the ratio of the average stress on their gross section to the concrete strength, such that the maximum drift does not exceed a certain fraction of the column height. The relationship is established on the assumption of constant pseudovelocity spectrum in the range of natural periods of interest. Points of inflexion are assumed to lie at midheight of the columns. The relation between average compressive stress and concrete strength is established so that a maximum strain not be exceeded in the concrete. By fixing the maximum ductility factor at 3.5, the percentage of reinforcement is also found directly. This paper includes a set of graphs for application of the method.

Unusual Buildings and Special Structures

TANABASHI, KANETA, SHINKAI, and TAKEMURA describe the Kyoto tower. On top of a three-basement and nine-story building will rise a 100-m tower for TV antenna and observation platform. The structure for the building is a steel frame with light-weight reinforced concrete cover. It has no shear walls or braces. The tower is of welded steel plates giving a surface of revolution. It houses stairs and elevators. Earthquake analysis was done statically. The tower was also analyzed for vortex shedding using a formula applicable to cylinders.

The paper by YOKOYAMA, TOMIZAMA, and SHIBATA concerns a 9-story building having 16 hollow cylindrical columns, 5 m in diameter, which house stairs, elevators, and other services. The columns and footing girders are of steel-skeleton reinforced concrete. Answering to architectural requirements, girders are pin-connected to the columns. Hence, lateral forces are essentially resisted by cantilever columns, continuous with massive foundation girders. Paper includes a comparison of expected behavior with rigid and pin connections and a study of the bending moments that the girders would introduce in the columns if rigidly connected thereto. The structure was analyzed in the SERAC computer for responses to the El Centro 1940 and Saitama 1956 earthquakes assuming linear behavior and 5 percent damping.

FLORES describes the design of a steel plant's second blast furnace in a strongly seismic Chilean region. The first furnace underwent insignificant damage during the 1960 earthquakes. The second furnace was designed on the basis of both static and dynamic (modal) analyses profiting from the experience gained with its predecessor. The paper is interesting chiefly because of the relative lack of literature on seismic design of industrial structures.

TSUBOI and KAWAGUCHI describe the design of the spectacular suspension roof for the Olympic pool in Tokyo. A 1/300-model was tested statically and dynamically as well as in a wind tunnel. Oil dampers were installed to reduce vibrations below values provided for in design.

BLUME expounds a number of comments of the greatest interest on the philosophy of design of important installations (reactors, tall buildings, etc.), especially near active faults. Next he estimates design spectra for those installations. The paper ends with a review of the reserve energy technique(5, 6).

MATSUSHITA and IZUMI advance an original solution tending to isolate buildings from ground motions: the double basement. The proposal calls for a relatively rigid structure up to a certain floor (for example the street level slab). The rest of the building is supported on an independent structure, which is extremely flexible up to the floor in question. The solution is reminiscent of the "flexible first story" scheme in vogue in the literature of the 30's(31). In intent it parallels Joshi's proposal to found buildings through flexible bearing pads(32). The double basement is also intended to provide a relatively uniform distribution of masses and stiffnesses. The authors analyze two shear buildings, assuming that they are subjected to three different earthquake records. They assign the buildings 5 percent damping. By providing a pronounced difference in rigidities between basement and upper stories in the second structure, a substantial reduction is obtained in upper-story drifts. The case is also considered of leaving a moderate gap between the structures of the two basements and is analyzed assuming bilinear elastic behavior. Results show, for example, that a 4-cm gap will lead to upper-story drifts most of which are 18 to 34 percent smaller than without the gap.

Elevated Tanks

CHANDRASEKARAN and KRISHNA find that elevated water tanks can be treated with reasonable accuracy as systems with a single degree of freedom. This conclusion differs from that found in much of the literature on the subject, according to which at least two degrees of freedom are required for a satisfactory idealization of the dynamic behavior of these structures, one for the tank and one for the liquid contained(33,34). From their tests on such structures they establish dynamic properties of concrete and conclude that the stiffness is a function of load, as described above. The paper includes recommendations on earthquake-resistant design of towers and foundations for elevated tanks.

Suspension Bridge

Analysis of one of the world's longest bridges (1300 m center span, 650 m each lateral span, at Seto Naikai in Japan; the main span is 1.6 m longer than that of Verrazano-Straights) is described by KONISHI and YAMADA. The bridge is regarded as consisting of component systems -- piers, towers, cables, and suspended structure, -- with a total of 29 degrees of freedom. It is subjected to two types of dynamic analysis: modal and calculation of transient state responses to the Port Hueneme, California earthquake of 1957. Several natural periods are found to lie close to each other. Nevertheless, at least for the towers, the square root of the sum of maximum modal responses compares well with the maximum stresses computed for the assumed earthquake. Stresses in the cables and suspended structure are found to be small compared with those due to dead and live load, but in the towers the stresses induced by the earthquake are comparatively important. The paper contains an interesting comparison with static methods of analysis and a discussion of the effects of unequal displacements of the ground at the piers.

Bridge Foundations

A series of field tests on hollow steel piles is reported by ISHII and FUJITA. The tests consisted in lateral static loading and forced vibrations of piles 1.2 and 1.5 m in diameter, driven 22.5 m into soil, of which 10 m were of clay and the rest of sand and silt. The static force was applied 10 m above ground level, in alternating cycles. Top deflections were measured as well as strains at various sections. Results were compared with Chang's theory(35) (of which Palmer-Thomson's theory(36) may be regarded as a generalization) but agreement required different adjustments of the modulus of subgrade reaction for deflection and for bending moment. Excellent agreement was found with the predictions of Shinohara-Kubo's theory. Good agreement also exists between the experimental natural frequencies and those computed by Shinohara-Kubo's theory from the modulus of subgrade reaction obtained from the static tests. Implications of the results are discussed in connection with the earthquake responses of a bridge that is to rest on these piles, once they are filled with concrete.

Dams: General

NAPETVARIDZE reviews research on the earthquake-resistant design of dams in the USSR. After a historic introduction, he mentions the importance given to regionalization, local ground conditions, and consequences of failure. Temporary instruments are used near the dam site to verify design assumptions. Paper includes an elastic analysis of gravity sections and reference to its application, incorporating hydrodynamic pressures, idealizing earthquakes as stochastic processes. Models 3 to 5 m in height have been tested, reproducing the abutments, and subjecting them to explosion-generated vibrations. Degrees of damping are established by means of forced vibration tests. Smaller models are tested on shaking tables. Prototypes are instrumented, to the extent of measuring stresses during earthquakes, to verify design assumptions. Conditions of similarity and the use of adequate materials in the models are discussed in the paper. Nonlinear effects are also discussed. The paper ends with a discussion of the Russian code in what concerns earthquake resistant design of dams.

Arch Dams

CRAWFORD describes the present practice of the U.S. Bureau of Reclamation. Two modes of vibration are considered; for symmetric dams the first is a symmetric mode and the second antisymmetric. The modes are computed considering the deflections of cantilevers and arches and equating radial displacements. Virtual masses of water to be considered with each mode of vibration are obtained through approximate formulas (Westergaard's for the first mode) given in the paper. Good correlation with observed natural frequencies is quoted. Damping is taken as 5 percent critical on the basis of published information.

Earth and Rockfill Dams

PATEL and ARORA analyze an earth dam under rapid drawdown. They assume the dam has a sloping filter near its axis. They use Bishop's method with a circular surface of failure. Next they assume that water in the reservoir is incompressible, whence hydrodynamic pressures on the upstream face can be found using an electric analogy. By taking the soil and water in the dam as incompressible and making additional assumptions it is concluded that flow lines do not change shape but potential lines do, so the resulting flow net is not orthogonal. The change in potential is assumed to be constant throughout a flow line and equal to the hydrodynamic pressure. A second application of Bishop's method leads to the conclusion that the critical surface of failure under seismic loading coincides with that for rapid drawdown. Critical heights of dams are computed for various combinations of cohesion and internal friction.

MEDVEDEV and SINITSYM discuss, qualitatively, finite-difference solutions for earth and rockfill dams taking into consideration foundation deformations caused by surface waves. The possibility of incorporating nonlinear behavior is also discussed. Next, the authors compare an analog solution to the steady-state vibrations of a trilinear single-degree elastic system with the measured response of a 20-m dam, and find that there is resemblance between both curves, concluding that the trilinear idealization may be adequate. The paper includes graphs to estimate stresses in various types of rocks, relating them directly with maximum ground velocity. (See also NAPETVARIDZE.)

BUSTAMANTE presents results of dynamic tests on seven models (60 and 100 cm tall) of noncohesive material and results of analog computations on their response to transient disturbances. He finds that embankments having slopes steeper than the material's angle of repose fail suddenly through a state of unstable equilibrium and collapse of a large wedge of the embankment. The phenomenon does not occur with gentler slopes. Unstable equilibrium is shown to be caused by grain interlocking, which is broken under a small disturbance. Embankments having gentler slopes do not fail in the usual sense of the term but their crown gradually descends and their profiles become rounded; this behavior sets a criterion for design of rockfill dams through loss of freeboard.

The paper contains a study of similitude requirements derived from comparison of the behavior of models of different heights. The idealized model analyzed in an analog computer is assumed to be rigid-plastic. Its predicted behavior agrees rather well with that of the physical models tested.

Instrumentation

It is encouraging that recent years have seen a serious effort toward extensive instrumentation and related studies in various countries. Thus, according to UMEMURA, OSAWA, and SHIBATA, by July 1963 there were 120 SMAC instruments in Japan. JOHNSTON, GLOGAU, CANDY, and MCKENZIE mention the installation of several strong-motion instruments in each of several important New Zealand buildings. NAPETVARIDZE refers to the extensive use of instruments in Russian dams. And MEEHAN reports on the local geological studies done in California in connection with a net of strong-motion instruments.

Concluding Remarks

Papers in Theme IV are symptomatic of progress in the following matters.

1. Mechanical properties of materials. There is new information, especially concerning unreinforced masonry and wood diaphragms. Yet much remains to be learned on behavior under repeated, large-amplitude loads ("low-cycle fatigue"); in this aspect only wood diaphragms seem to have been subjected to systematic research. Even for small amplitude oscillations there is a variety of opinions and data on internal damping in structural materials; the fact that many structures are analyzed assuming 5 percent of critical damping or more, contradicts recent experimental evidence, which often favors 0.8 to 3 percent for steel and concrete structures(35).

2. Development of connection details. Ingenious solutions are being used to solve, for example, connections between large steel members or between precast concrete panels. Development is relatively new, and behavior of such connections under earthquake-like forces remains to be determined.

3. Behavior of actual structures. There is new information on the response of prototypes to small-amplitude disturbances, some results of destructive tests on large and on full-scale models, and interpretation of earthquake damage on actual buildings; special attention is being devoted to prestressed concrete. Since the subject is complex and requires considerable interpretation there are apparently no trustworthy methods for computing the dynamic characteristics of any moderately complicated structure. There is room for considerable speculation about the manner in which earthquake damage should be interpreted. This matter is of great importance, as it is mostly through attempts at interpretation of behavior that the engineer, and in particular the researcher and the designer, becomes truly aware of the abyss that separates assumed strengths, stiffnesses, dimensions, and loads from their actual values and of the random nature of these parameters.

4. Analysis of multidegree systems can be dealt with in several satisfactory ways. The same is true, to some extent, of the design of single-degree structures even when one incorporates nonlinear behavior. But adequate methods are yet to be developed for the design of multidegree systems taking

into account their nonlinearity. It is impractical to have to analyze every structure for dozens of earthquake motions and there is little justification for assuming that, if the structure resists the El Centro 1940 earthquake, it is adequately designed. The comment concerning shortcomings of design methods for multidegree systems is especially applicable to those having parameters so distributed that they are very far from being lumped. This is the case with arch, earth, and rockfill dams, for which many new methods of analysis have evolved and much has been done on model testing opening up new roads of research, but the adequacy of such methods and of conclusions derived from the tests, as a basis for earthquake resistant design, is still much open to question. Dynamic tests on 5-m models of rockfill dams currently under way in the Soviet Union are encouraging as a step to bridge this gap.

5. Advance is noticeable in the calibration of static methods on the basis of elastic dynamic analyses in what concerns the distribution of horizontal shears. Much remains to be done on the matters of overturning moments and torsion, and much on the calibration against nonlinear dynamic analyses.

6. Dynamic pore pressures in earth and rockfill dams are beginning to receive attention. This is of paramount importance and deserves additional, careful study.

7. There is awakening conscience of behavior under earthquake forces in the architectural and construction trends. In many cases small dwellings and important buildings reflect it in their conception. Efforts are worthwhile to extend such tendencies and to influence insurance policies as well.

Discussion

There are many subjects of deep interest in the present theme. Yet the time available for their discussion is quite limited. It is therefore suggested that the discussion concentrate on the following subjects.

1. Adequacy of assumptions usually made in the dynamic analysis of structures: a) Under low-amplitude oscillations. This covers damping and the manners of computing stiffnesses. b) Under large-amplitude excitation; this covers the energy absorption and the criteria of failure that it is proper to assume in the light of data concerning behavior under low-cycle fatigue.

2. Limitations of design criteria for multistory buildings, incorporating nonlinear behavior.

3. Applicability of current theories and model-test data to the earthquake resistant design of earth and rockfill dams.

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ERRATA

EARTHQUAKE RESISTANT DESIGN, CONSTRUCTION AND REGULATIONS

BY E. ROSENBLUETH

PAGE 2:	Para 2, Line 6 should read: "....maximum deformations in a non-linear structure ...."
PAGE 13:	Para 3, Line 7: for reference (35) read (37)
PAGE 19:	To add:

36. Palmer. L.A., Thompson, J.B., "The Earth Pressures and Deflections Along the Embedded Lengths of Piles Subjected to Lateral Thrust", Proc. 2nd Int. Conf. on Soil Mech. and Foundation Eng., Vol V, art. VII-b-3, pp 156-161 (1948).

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EARTHQUAKE RESISTANT DESIGN, CONSTRUCTION, AND REGULATIONS

GENERAL REPORT : ORAL PRESENTATION

BY EMILIO ROSENBLUETH*

Few structures are built strictly in accordance with their design; few designs comply strictly with regulations; and no existing building code stands in full accord with results of research and of field observations. It takes a destructive earthquake to bring forth the full measure of these discrepancies. Rarely are the researcher and the engineer so keenly aware of the magnitude of differences between the design and the actual values of loads, cross-sectional dimensions, and strength as when attempting to reinforce an earthquake-damaged structure and assess its effective capacity to resist unknown ground motions. Under the circumstances the details that may have seemed the least significant become the truly significant matters, for in earthquake resistant design and construction, careless partial overdesign is as detrimental as partial underdesign, and the weakest link must absorb almost the entire energy of deformation and hence may be the only link that counts; and in earthquake resistant design and construction the capacity to deform is at least as important as strength.

In the light of these considerations it is encouraging to notice in the papers classified under the present theme that attention is being given to field control of the quality of construction, even if nondestructive tests of masonry can still not furnish pertinent information and even if only such details as welded connections are being effectively controlled by means of these tests; it is gratifying to learn that the behavior of connections in rigid steel frames of unprecedented dimensions is being studied in full-sized models; that new, effective types of connection are being developed and used between small and between huge precast concrete elements; that the adequacy of combinations of structural materials such as prestressed concrete, or plain masonry used in combination with wooden or reinforced concrete frames, is being gaged no longer in terms of strength alone but of flexibility, damping, and ductility; and that these properties are receiving systematic study.

Elevated water tanks have been the subject of conscientious study.

Other encouraging contributions submitted under the present theme include serious evaluations of earthquake insurance and of architectural trends and their interrelation with earthquake resistant design; experimental study of laterally loaded bridge pile-piers; the nonlinear analysis of tall buildings, carried out under such varied conditions, that, although generalization is not yet possible, some insight is beginning to be gained into the actual behavior of these structures; a method for the direct design of single-degree reinforced-concrete buildings; the application of principles for the design of truly exceptional structures, including nuclear installations in the vicinity of active geologic faults, the bridge having what may become the world's longest span, the Kyoto tower, and earthquake

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forces in other most unusual buildings.

The fact that the nonlinear behavior of tall buildings is beginning to receive the study it deserves has fortunately not detracted from many of the matters that are still far from being solved even in the linear range, such as problems pertaining to shear distribution, inertia forces in small appendages, and overturning moment.

Building codes have been slowly incorporating these and other results of research, including matters related to seismic regionalization.

Special attention is devoted to a type of structure that certainly merits it because of its importance as a civil engineering work and because it encompasses practically all the difficulties imaginable in earthquake engineering: dams; particularly earth, rockfill, and arch dams. Study of these structures incorporates such dissimilar fields as hydrodynamics, flow of water in soils, soil dynamics, and structural engineering. In it, matters that may be regarded as having only academic interest for other structures, become significant, as is the case with the vertical component of acceleration, the simultaneous vibration in three dimensions, deformations of the base, and, to an outstanding degree, criteria of failure.

Two interesting papers were not covered in the written report: that by Mr. Holmes, "Concrete Masonry Buildings in New Zealand", and the one by Mr. Miller, "Design of a 240 foot High Reinforced Concrete Building in Wellington". Their authors will have an opportunity to expound them during their oral presentation.

In accordance with the wide spectrum of subjects covered in Theme IV, their relative importance, and the need to limit discussion time, it has been deemed advisable to orient the discussions principally to the following matters.

1. Adequacy of assumptions usually made in the dynamic analysis of structures: a) Under low-amplitude oscillations. This covers damping and the manners of computing stiffnesses. b) Under large-amplitude excitation; this covers energy absorption and the criteria of failure that it is proper to assume in the light of data concerning behavior under low-cycle fatigue.

2. Limitations of design criteria for multistory buildings, incorporating nonlinear behavior.

3. Applicability of current theories and model-test data to the earthquake resistant design of earth and rockfill dams.