Theme Report on Topic 3
RESPONSE OF STRUCTURES TO GROUND SHAKING

by

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The main objective of earthquake engineering research is to develop sufficient knowledge about the response of structures to ground shaking so that an appropriate earthquake resistant design can be made. An appropriate design may be defined as one that provides adequate safety against injury and loss of life and achieves this at an acceptable cost. This requires understanding of how structures deform under the action of earthquake shaking and how the materials of which the structure is made will behave when subjected to these deformations. There are several levels of understanding which may be listed in order of increasing complexity. First is the elastic response of structures during which the earthquake vibrations do not produce any structural damage or any plastic deformations. Second is the large amplitude non-linear vibration of structures when plastic deformations, cracking, and other types of damage may be sustained but not to the degree that the structure is near to failure. Third is the very large amplitude vibration with increasing damage to the point of collapse.

A good knowledge of elastic vibrations is required in order to understand how structures will behave when subjected to moderate ground shaking which should cause no damage. This is the most likely ground shaking that structures will experience. However, very strong ground shaking may occur during the life of the structure even though the probability is low and in this case the ground shaking may be so severe that the structure is damaged. Economic considerations require that ordinary structures be designed for controlled damage under the action of very strong ground ground shaking. Life safety considerations require that ordinary structures be designed so as not to collapse in the event of the maximum credible shaking but, on the other hand, economic considerations show that it is not feasible to design ordinary structures to resist such intense ground motions without any damage. The fraction of structures that will experience such intense ground shaking during their lifetimes is quite small and most structures will never experience such strong shaking; therefore, it is economically desirable to reduce the level of design for structures in general even though some structures will require damage repairs. However, for some extraordinary structures, the consequences of failure may be so great that no potentially hazardous damage can be accepted even in the event of the maximum credible ground shaking. Examples of such important structures that should have large factors-of-safety are major dams, nuclear powerplants, liquid natural gas storage tanks, etc.

A rather special feature of earthquake engineering, as distinguished from most other branches of engineering, is the fact that when an earthquake occurs every structure in the area is subjected to ground shaking and all public utilities, industrial facilities, mechanical and electrical equipment, etc., are also subject to shaking. Therefore earthquake-resistant

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design covers a wide variety of structures, equipment, etc. The earthquake behavior of a high rise building is quite different from that of a dam, for example, and the behavior of a liquid storage tank is quite different from that of a bridge, or a tall chimney, or a nuclear containment structure, or a chemical processing plant, or electrical power switching gear, or communications equipment, etc. In addition, various different materials are involved whose properties under dynamic stress and strain must be understood by the engineer. Therefore many studies of response to ground shaking must be made before an adequate level of understanding is reached.

The best information about the response of structures to ground shaking is obtained from the action of strong earthquakes. Efforts should be made to instrument buildings so as to record their behavior during earthquakes, and in addition, after an earthquake has occurred studies should be made to determine how buildings, equipment, public utilities, etc., actually behaved. Damage should be identified and described; and structures that were not damaged should also be described. Analysis should be made of the design and construction of damaged structures to ascertain weaknesses and to develop methods of preventing similar damage in the future.

Also, dynamic tests should be made of structures, models of structures, and structural elements. Such tests could involve the use of shaking machines on real buildings, shaking tables and building models, and laboratory tests of structural elements subjected to repeated straining. The information developed by such experimental research will assist in understanding the behavior of structures during earthquakes, and will aid in carrying out analyses of structural behavior during earthquakes.

Analyses should be made, both theoretical and numerical, to elucidate how various structures perform under the action of ground shaking. It is desirable that such analyses be made of a wide variety of structures, under different intensities of ground shaking, and including the effects of the three components of ground shaking. The ideal objective would be to develop the capability of analyzing the dynamic behavior of a three-dimensional structure, subjected to three components of ground shaking which are strong enough to produce non-linear vibrations, and which represent accurately the real action of the ground upon the structure. It is clear that much research still needs to be done: many different types of structures need to be analyzed, and analytical capabilities must be developed further.

For some very important structures, detailed and realible dynamic analyses will be required for the aseismic design and such methods must be developed through research. However, most structures are not sufficiently important and costly to warrant such elaborate analyses and for these it will be necessary to develop simplified methods of analysis and design that are not costly or time consuming to apply and yet provide satisfactory results. An example of measured building response is shown in Figure 1. The response was measured on the roof of a nine-story steel-frame building during the Magnitude 6.5 San Fernando, California earthquake of 9 February 1971. The peak ground acceleration was 20%g and the roof reached a peak acceleration of 40%g and a peak absolute displacement of 3.7 inches. During this earthquake the highest stresses in the steel frame were almost at yield point.

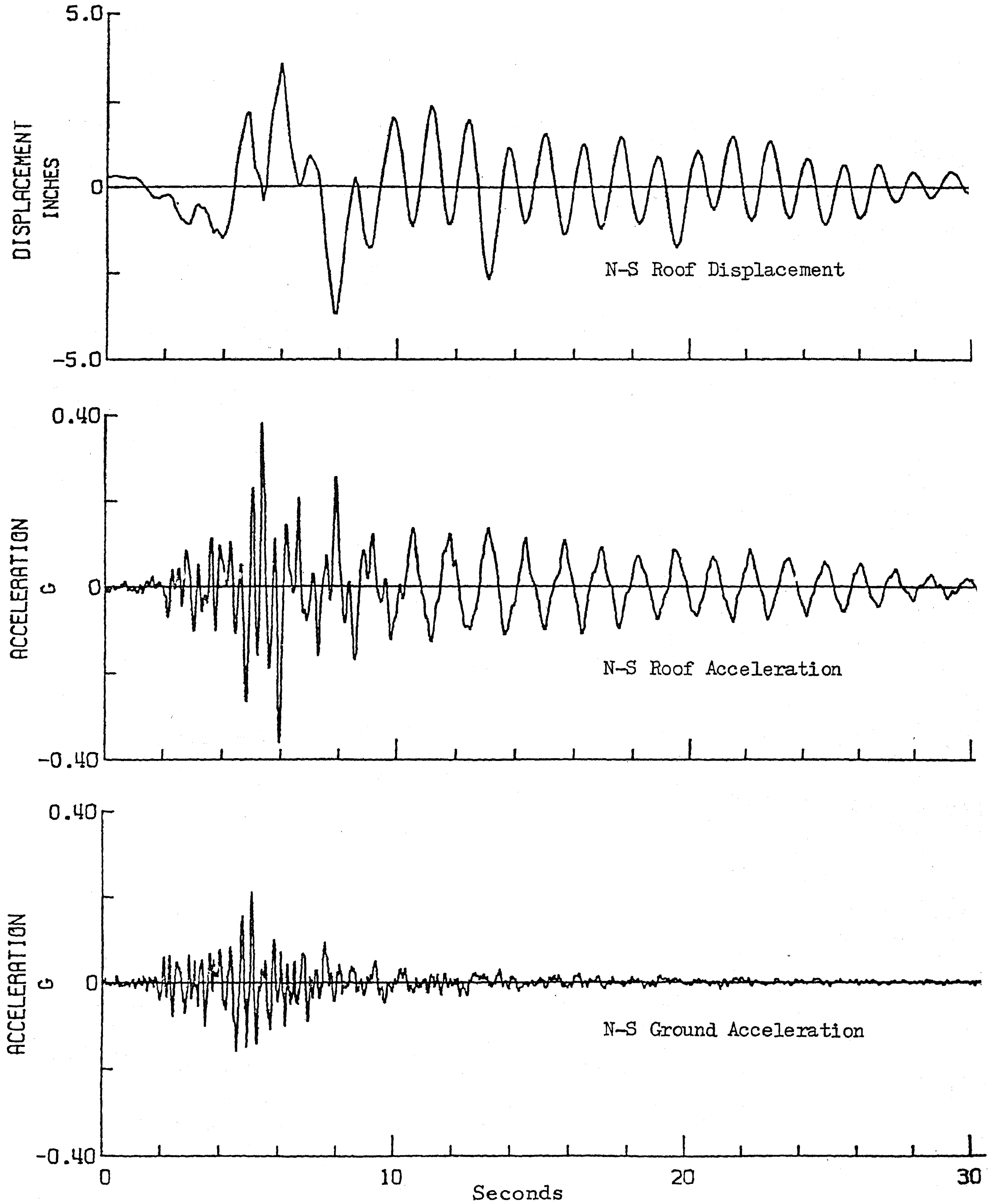

Figure 1. Response of nine-story steel-frame building to ground shaking of 9 February 1971 San Fernando, California earthquake. This structure at the California Institute of Technology Jet Propulsion Laboratory was approximately 10 miles from the fault.

Group A Papers

The ten papers listed in Table A deal with vibrations of elastic structures. The responses of multistory structures are analyzed, and two papers give particular attention to the torsional response of structures and several deal with the response to simultaneous components of ground motion. Two papers deal particularly with response to vertical ground motion. The influence of in-plane deformation of floor slabs is considered in one paper and the application of wave propagation theory to structural dynamics is considered in another. Although the elastic response to horizontal ground shaking of uniform, symmetrical structures is well understood there are many other types of structures whose vibratory behaviors are as yet imperfectly understood. Because of this, additional analyses should be made and also correlations should be made with observed vibrations of real structures.

TABLE A

1. Earthquake response of a class of torsionally coupled buildings
   by C. L. Kan and Anil K. Chopra
2. Seismic analysis of asymmetrical structures subjected to orthogonal components of ground acceleration
   by W. K. Tso and J. K. Biswas
3. Structural response to simultaneous multi-component seismic inputs
   by N. D Nathan, S. Cherry and W. E. McRevitt
4. Vibration analysis of buildings with consideration for the in-plane deformation of floor slabs
   by Osamu Joh and Kazuo Ohno
5. An efficient approach for the dynamic sensitivity analysis
   by Juan Cassis
6. Vertical response observation of ten-storied building during right under earthquakes
   by Akio Sakurai, Yoshio Masuko and Chizuko Kurihara
7. Effect of vertical ground motion on the response of cantilever structures
   by R. N. Iyengar and T. K. Saha
8. Seismic behaviour of multistory K-braced frames under combined horizontal and vertical ground motion
   by Subhash C. Goel
9. Seismic response analysis of framed structures
   by A. M. Paramzin and B. A. Akatushkin
10. Torsional vibrations of core wall structures in tall buildings
    by D. V. Mallick, R. Dungar and R. T. Severn
11. Application of the theory of wave propagation to the analysis of structural dynamic parameters
    by L. N. Bobakov

Group B Papers

The ten papers listed in Table B deal with the response of concrete structures to ground motions. Seven papers deal with shear wall structures and three deal with framed structures. One of the papers deals with the behavior of beam-column joints. Because of the widespread use of reinforced concrete for construction it is highly desirable to make studies, both theoretical and experimental, of the dynamic behavior of a wide variety of RC structures.

TABLE B

12. Dynamic response of 17 story Wellington Building
by Esli. J. Forrest and R. Shepherd
13. Simulation analysis of a highrise reinforced concrete building in two different earthquakes
by Kiyoshi Muto, Tsunehisa Tsugawa, Masanori Niwa and Hiromichi Shimizu
14. Seismic analysis of asymmetric shear wall-frame buildings
by Pisidhi Karasudhi and Ming-Sing Chu
15. Dynamic response of asymmetric shear wall-frame building structures
by M. Ishac and A. Heidebrecht
16. Inelastic seismic response of insolated structural walls
by A. T. Derecho, G. N. Freskakis and Mark Fintel
17. Response of large-panel buildings for earthquake excitation in nonelastic stage
by G. Brankov and S. Sachanski
18. Seismic stability of composed wall structures made of natural stone
by Yu. V. Ismailov, E. V. Ilchenko, A. P. Pochapsky, K. I. Tarnovsky and A. A. Clmprina (Refer paper no. 49, theme 5-285)
19. Dynamic analysis of reinforced concrete frames with framed shear walls
by Koji Yoshimura and Masafumi Inoue
20. A study ON shear-type structural model for aseismic design
by Sadayoshi Igarashi, Kazuo Inoue, Kaji Ogawa and Hiroshi Tsutatani
21. On seismic design of r/c interior joints of frames
by E. P. Popov, V. V. Bertero, B. Galunic and G. Lantaff (Refer paper No. 33, theme 5-191)

<u>Group C Papers</u>

The twelve papers listed in Table C deal with the responses of a variety of special structures to ground shaking. Two papers deal with the response of tall chimneys to ground shaking; two papers deal with the response of cooling towers; two deal with the responses of suspension bridges, and others deal with cylindrical shells containing liquid, water pipes, dynamic dampers, cable structures, and guyed towers. One paper deals with the U.S. Federal Highway Administration seismic research program. Since many different kinds of unusual structures, some of which are very complex, are encountered in engineering there is a need for studies to be made of their dynamic behavior.

TABLE C

22. Earthquake response of tall chimneys
by Anand S. Arya and D. K. Paul
23. Earthquake response analysis of a 360M high chimney
by J. Duhovnik and P. Fajfar
24. Transient response of cooling towers to propagating boundary excitation
by S. F. Masri and V. I. Weingarten
25. The effect of asymmetric imperfections on the earthquake response of hyperbolic cooling towers
by R. L. Norton and V. I. Weingarten
26. Dynamic analysis of cylindrical shells containing liquid
by Sukenobu Tani, Yasuo Tanaka and Naohito Hori

TABLE C continued

27. Comparative study on the observation of a waterpipe during earthquake and the equivalent viscous theory
by Nobuo Miyajima and Jiro Miyauchi (Refer paper no. 26, theme 7-136)
28. Optimum tuning of the dynamic damper to control response of structures to earthquake ground motion
by S. Ohno, A. Watari and I. Sano
29. Seismic response analysis of long-span suspension bridge tower and pier system
by Yoshikazu Yamada, Hirokazu Takemiya and Kenji Kawano
30. Vibrations in suspension bridges
A. M. Abdel-Ghaffar and G. W. Housner
31. Dynamic analysis of cable structures using large deflection theory
by Mostafa M. Zayed and James Lord
32. Dynamic behaviour of guyed towers under seismic excitation
by E. Benvenuto, A. Corsanego, A. Del Grosso and D. Stura
33. Federal Highway Administration - Highway Bridge Seismic Research Program
by James D. Cooper

Group D Papers

The twelve papers listed in Table D deal with inelastic and hysteretic response of structures to ground shaking. In order to estimate the capacity of a structure to resist strong shaking without collapse the physical properties of the structure under large deformations must be known and an analysis must be made of the hysteretic vibrations of the structure under strong ground shaking. The great importance this has in arriving at a safe and economical design demands a strong research effort in this direction. It seems doubtful that enough will ever be known about the physical properties of structural members so that a precise calculation can be made of the collapse of a real structure. This makes it even more important to carry out research on idealized structures, having idealized physical properties, with the objective of developing methods for making realistic estimates of progressive damage under strong ground shaking and realistic estimates of the intensity and duration of shaking that will produce collapse.

TABLE D

34. Hysteretic dampers to provide structures with increased earthquake resistance
by R. I. Skinner, A. J. Heine and R. G. Tyler
35. Earthquake response characteristics of deteriorating hysteretic structures
by H. Goto and H. Iemura
36. Comparison of the inelastic response of steel building frames to strong earthquake and underground nuclear explosion ground motion
by R. C. Murray and F. J. Tokarz
37. The inelastic torsional response of structures to earthquake ground motions
by B. K. Raghu Prasad and K. S. Jagadish
38. Approximating inelastic response of structures to ground shaking
by Sigmund A. Freeman

TABLE D continued

39. Relation between yield strengths and response displacements of structures
by Takao Nishikawa
40. The response of simple stiffness degrading structures
by W. D. Iwan
41. Ductility studies of parametrically excited systems
by Franklin Y. Cheng and Kenneth B. Oster
42. Low cyclic fatigue of seismically excited systems
by Aybars Gürpinar
43. A study of the effect of the frequency characteristics of ground motions on nonlinear structural response
by A. T. Derecho, G. Freskakis and Mark Fintel
44. Ultimate capacity of lowrise r/c buildings subjected to intense earthquake motion
by H. Takizawa and P. C. Jennings
45. Vertical load effect on structural dynamics
by Sukenobu Tani and Satsuya Soda

Group E Papers

The eight papers listed in Table E deal with mathematical modeling and computational modeling of structures and ground accelerations. The results of elaborate digital computations of building responses can be no better than the structural models and the input models utilized. It is of great importance to develop models and methods of estimating parameters that are appropriate for the analysis of the various structures that must be designed to resist earthquakes. This is an aspect of structural dynamics that requires much more research.

TABLE E

46. Mathematical modeling of a steel frame structure
by David T. Tang and Ray W. Clough (Refer paper no. 8, theme 9-43)
47. A damping model for response analysis of multistoreyed buildings
by M. Godwin Joseph and R. Radhakrishnan
48. Variability in engineering aspects of structural modeling
A. H. Hadjian, C. B. Smith, A. Haldar and P. Ibanez (Refer theme 9-31)
49. Evaluation of mathematical models of structures from full-scale forced vibration studies and records of moderate earthquakes
by J. Petrovski, D. Jurukovski and N. Nauinovski
50. Uniqueness problems in structural identification from strong motion records
by F. E. Udwadia
51. Prediction of maximum structural response by using simplified accelerograms
by Warren Y. L. Wang and Subhash C. Goel
52. General purpose computer program for dynamic nonlinear analysis
by D. P. Mondkar and G. H. Powell
53. Biaxial and gravity effects in modeling strong-motion response of r/c structures
by H. Takizawa

Group F Papers

The eight papers listed in Table F deal with the earthquake response of dams. Gravity dams, arch dams, and earth dams are analyzed in the papers and the interaction between the dam and the water in the reservoir is also analyzed. The potentially disasterous consequences of a dam failure places great importance on studies of the earthquake response of dams. It is of particular value to develop methods for making realistic analyses of the response of dams to earthquakes so that the true factor-of-safety against failure can be assessed, and it is of special importance to instrument dams so as to provide more information on the actual response of dams subjected to strong ground shaking.

TABLE F

54. Seismic analysis of dam-reservoir-foundation systems
by W. D. Liam Finn and Erol Varoglu
55. Nonlinear analysis of a gravity dam for seismic loads
by D. P. Reddy and H. S. Ts'ao
56. Dam-reservoir interaction for a dam with flat upstream face during earthquakes
by H. Bărbat, V. Breabăn and C. D. Ionescu
57. Arch dam-reservoir interaction during earthquakes
V. Breabăn, H. Bărbat and C. D. Ionescu
58. Interaction effect in gravity dam with earth backing
by Anand S. Arya and Shashi K. Thakkar (Refer paper no. 17, theme 7-97)
59. Hydrodynamic pressure on dams
by D. K. Paul and P. K. Swamee (Refer paper no. 72, theme 5-349)
60. Structural response of sulphur-bamboo reinforced earth mat to seismic loading
by H. Y. Fang and H. C. Mehta
61. Model investigations of arch dams response on seismic effect
by T. Z. Vardanashvili and P. A. Gutidze (Refer paper no. 41, theme 9-185

Group G Papers

The nine papers listed in Table G deal with soil structure interaction. The interaction of building structures, spillway structures, tank structures, and tunnels with the surrounding soil are analyzed. It is known that in some cases the interaction effect between soil and structure is so small that for practical purposes it can be neglected but in other cases the effect is sufficiently influential so that it must be taken into account. It is important to develop realistic and efficient methods of analyzing soil structure interaction for a wide variety of structures and it is also important to establish under what conditions the interaction effects can or cannot be neglected. To clarify the picture it is necessary to obtain more recordings, during actual earthquakes, in structures and soils where the interaction effect is significant in a practical sense. Many recordings are available of basement motions and building motions of multistory commercial type buildings on firm ground where the interaction effects are not of practical importance, however, very little recorded data are available on structures where the interaction effects are important. Studies should be undertaken to rectify this situation.

TABLE G

62. Seismic response of three-dimensional structures on nonlinear foundation analyzed by differential-integral equations
by T. H. Lee (Refer paper no. 51, theme 4-226)
63. The effects of high intensity earthquakes on the stability of the Chira Piura spillway, Peru - a nonlinear foundation/structure analysis
by R. Dungar and J. A. Clarkson
64. Characteristics of semi-infinite element and it's application to dynamic problem
by N. Takewaki, K. Takegawa and M. Iguro (Refer paper no.57, theme 6-243)
65. Effects of soil profiles on the seismic response of buildings
by Joji Sakurai and J. K. Minami
66. Earthquake observations and analysis of an LPG tank and its foundation soft soil (Refer paper No. 3, theme 7-13)
by Haruhiko Yokota, Koichi Ichinose and Hiroshi Yamahara
67. Observation of the dynamic behavior of Kinuura submerged tunnel during earthquakes
by Shigeo Nakayama and Osamu Kiyomiya (Refer paper no. 24, theme 7-134)
68. Seismometric investigation of the motion of a submerged tunnel in earthquake and at ordinary time (Refer paper no.22, theme 7-127)
by Nobuji Nasu, Satoru Kazama, Takaki Morioka and Hiroshi Oishi
69. Model investigation of tunnels seismic resistance
by G. N. Kartzivadze and Gh. B. Metreveli (Refer paper no.42, theme 9-186)
70. Comparison of building response and free field motion in earthquakes
by Nathan M. Newmark, William J. Hall and James R. Morgan

Group H Papers

The six papers listed in Table H deal with earthquake spectra and their applications. Earthquake spectra were introduced originally to provide an efficient method of designing to resist earthquakes which avoided complex dynamic analyses. It is not economically possible, or desirable, to make time-history response calculations for most ordinary buildings; and spectrum methods seem to be the most practical method of design for such structures.

TABLE H

71. Response spectra for calculating seismic loads
by V. T. Rasskazovsky
72. Nonlinear response spectra for probabilistic seismic design of reinforced concrete structures
by Masaya Murakimi and Joseph Penzien
73. Extended applications of response spectra curves in seismic design of structures
by M. P. Singh, S. Singh and A. H.-S. Ang (Refer paper no.4, theme 5-19)
74. A simple procedure for predicting amplified response spectra and equipment response
by Erik H. Vanmarcke (Refer paper no. 9, theme 12-49)
75. Direct and indirect conversion from power spectra to response spectra
by J. Pereira, C. S. Oliveira and R. T. Duarte (Refer theme 2-279)
76. Response spectra for ocean structures
by Joseph P. Murtha and Owen M. Kirkley

Group I Papers

The nine papers listed in Table I deal with stochastic analysis of building response. Since it is impossible to know ahead of time the precise time-history characteristics of ground motion that will be produced by future earthquakes one is forced to look at the earthquake response problem from a stochastic, or probabilistic, point of view. Certain general conclusions about structural response, which may be very useful, can be deduced from such analyses. It is of importance, in this regard, to correlate the stochastic input with actual earthquake ground motions, so that both stochastic response studies and stochastic input studies need to be made.

TABLE I

77. Stochastic response of structure due to spatially variant earthquake excitations
by Yutaka Matsushima
78. Stochastic response analysis of structures to earthquake forces
by S. Balasubramonian and K. S. S. Iyer
79. Stochastic seismic response and reliability of hysteretic structures
by Takuji Kobori, Ryoichiro Minai and Yoshiyuki Suzuki
80. Application of stochastic differential equations to seismic analyses of nonlinear structures
by Takuji Kobori and Ryoichiro Minai
81. Stochastic prediction of seismic response of inelastic multidegree-of-freedom structures
by George Gazetas and Erik H. Vanmarcke
82. Estimation of maximum hysteretic response to non-white random excitation
by H. Goto, H. Kameda and H. Iemura
83. A probabilistic approach to the study of linear response of structures under multiple support non-stationary ground-shaking
by Ricardo T. Duarte
84. Evaluation of maximum responses considered ground characteristics
by Keiichi Ohtani
85. Earthquake response estimation of stochastic soil-structure system
by Minoru Tomizawa (Refer paper no. 47, theme 4-222)

Group J Papers

The seven papers listed in Table J deal with various aspects of structural response that do not fit in any of the preceding categories. Three of the papers deal with observations made of structural behavior during actual earthquakes. Another paper deals with the determination of damping in real structures; and another paper deals with a method of aseismic design. The final two papers deal with the estimation of losses, resulting from building damage and collapse, that can be suffered during earthquakes. This is an aspect of structural response that is not attractive to engineers, but it is an important aspect that must be given consideration.

TABLE J

86. Period relationships from instrumented buildings in the 1971 San Fernando earthquake (Refer paper no. 27, theme 7-137) by William E. Gates, John O. Robb and Ullrich A. Foth
87. Determination of damping of real structures by P. Sotirov
88. Damaging response of low-rise buildings by R. E. Scholl and J. A. Blume
89. A vertical acceleration failure in Managua by Loring A. Wyllie, Jr. and Chris D. Poland (Refer paper no.25, theme 7-13
90. The GAPEC system: a new highly effective aseismic system by G. C. Delfosse
91. Single earthquake loss probabilities by Betsy Schumacker and Robert V. Whitman (Refer paper no.54, theme 2-317)
92. On human loss prediction in buildings during earthquakes by S. A. Anagnostopoulos and R. V. Whitman (Refer paper no.55, theme 2-323

CONCLUSIONS

In the session on the response of structures to ground shaking there are 92 papers. Although this seems like a large number, it is evident that there are many aspects of earthquake response that are not covered by even these 92 papers. The wide variety of structures that are built in seismic zones all need to be analyzed, for good engineering requires that the dynamic behavior of these structures be sufficiently understood so that good designs can be made. The objectives of response studies should be to understand how progressive damage is incurred and to understand the true factor-of-safety against failure. This understanding is needed in order to establish optimum aseismic design criteria.