

# Response of Concrete Buildings to Lateral Forces

Reported by ACI-ASCE Committee 442



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# Response of Concrete Buildings to Lateral Forces

Reported by ACI-ASCE Committee 442

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Joseph Schwaighofer  
Charles F. Scribner  
Shamim A. Sheikh  
Richard A. Spencer  
M. Daniel Vanderbilt\*

*The performance of reinforced concrete buildings subjected to wind, blast and earthquake loads is discussed. Building response and basic design approaches corresponding to these loads are briefly reviewed. Performance criteria and approaches for meeting these criteria are outlined. Various structural subassemblies and systems are reviewed, and their behavior is discussed with respect to these performance criteria. The role of analysis in design and in performance evaluation is discussed, and various analytical procedures are reviewed. Techniques for evaluating building response are summarized. General factors contributing to good performance are emphasized.*

**Keywords:** beams (supports); blast loads; buildings; columns (supports); earthquake resistant structures; frames; lateral pressure; performance; reinforced concrete; structural analysis; structural design; tube-in-tube; walls; wind pressure.

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## PREFACE

This report is intended for professionals interested in the design and construction of reinforced concrete buildings. The purpose of the report is to serve as a primer on issues related to the response of reinforced concrete buildings subjected to lateral forces. Reinforced concrete buildings have generally behaved well under strong lateral loads. Evaluation of the reasons for this good performance, and for occasional examples of poor performance, requires an understanding of the various factors influencing the response of reinforced concrete buildings to lateral loads. Those factors are identified and discussed in this report.

While design examples or specific calculations are not included, all aspects of the design process are addressed: characterization of loads; performance criteria and approaches for meeting such criteria; structural systems; analysis techniques; and performance evaluation. To emphasize the innovative possibilities which reinforced concrete offers to the structural engineer, performance criteria are presented in general terms before the characteristics of various structural systems are discussed in detail.

## CHAPTER 1—INTRODUCTION

### 1.1—Objectives

The purpose of this report is to serve as a primer on issues related to the response of reinforced concrete buildings subjected to lateral loads. The report is neither a discussion of the state of the art of structural engineering research nor a design manual. It assumes previous knowledge and experience in the treatment of problems resulting from lateral loads, and also access to an adequate reference library. The report is oriented primarily to engineering practice in the United States and Canada, but has been written and reviewed by engineers from around the world.

### 1.2—Scope

The organization of this report is intended to reflect various aspects of the design process for lateral loads. In Chapter 2, the three types of lateral loads considered in this report are discussed, structural responses and design approaches for those loads are summarized, and the concept of soil-structure interaction is briefly introduced. In Chapter 3, the criteria used to evaluate structural performance under lateral loads are discussed, and approaches for meeting these criteria are outlined. In Chapter 4, the different types of lateral load-resisting systems and the structural sub-assemblies comprising them are reviewed. In Chapter 5, techniques are presented for analytically modeling reinforced concrete buildings, and for computing their response to lateral loads. In Chapter 6, techniques are discussed for measuring the response characteristics of reinforced concrete buildings subjected to lateral loads, and for correlating these measured responses with performance under actual loads. In Chapter 7, the principal themes of the report are summarized and discussed.

### 1.3—Recent examples of reinforced concrete building performance

Building codes and techniques for design, analysis and construction evolve continually. Performance of buildings

subjected to strong lateral loads provides a reference for the introduction of new behavioral models, new research objectives, new design philosophies, and new structural configurations. In recent years, many opportunities have occurred for observing the behavior of modern reinforced concrete buildings subjected to extreme lateral loads. Some of the lessons learned from that behavior have greatly influenced the evolution of current building codes and practices for design and construction.

**1.3.1 Wind**—Most of our experience with extreme winds comes from hurricanes and tornadoes.

Two recent hurricanes which significantly affected buildings in the United States were Hurricane Iwa in Hawaii (1982),<sup>1</sup> and Hurricane Alicia in Texas (1983).<sup>2</sup> The latter hurricane did produce some structural damage to light construction [Fig. 1.3.1(a)]. While engineered reinforced concrete buildings generally performed well structurally, many suffered nonstructural damage [Fig. 1.3.1(b)]. Storm surges (unusually high tides accompanying hurricanes) resulted in flooding, particularly after glass windows and doors had broken in lower stories. Local wind-induced failures of windows, facades and roofing were common. Although no high-rise buildings suffered structural damage during these two hurricanes, wind-driven debris and gravel from adjacent roofs damaged many panes of glass cladding in high-rise buildings.

Recent examples of tornadoes producing significant structural damage include those occurring in Lubbock, Texas (1970)<sup>3</sup> and Xenia, Ohio (1974).<sup>4</sup> Tornadoes interact with structures and cause damage due to pressures caused by wind, pressure differentials caused by rapid changes in atmospheric pressure, and forces caused by impact of wind-borne debris. Much more damage is caused by direct pressure from wind,<sup>5</sup> than by pressure differentials resulting from changes in atmospheric pressure.<sup>6</sup> Generally, impact from debris causes only localized damage, although tornadoes have been known to move articles as large as railroad cars. Impact from a very large object could cause severe structural damage.

**1.3.2 Blast**—Blast loadings on structures can come from external or internal explosions. External explosions, while not normally considered in building design, have become an important design condition for government and military buildings. Local damage from internal explosions can be significant if it causes progressive collapse of other parts of the structure.<sup>7</sup>

**1.3.3 Earthquake**—The previous report of ACI-ASCE Committee 442<sup>8</sup> was published after destructive earthquakes in Anchorage, Alaska (1964)<sup>9</sup> and Caracas, Venezuela (1967).<sup>10</sup> Significant lessons have since been learned from other earthquakes. Among these earthquakes are: San Fernando, California (1971);<sup>11,12</sup> Qir, Iran (1972);<sup>13</sup> Managua, Nicaragua (1972);<sup>14,15,16</sup> Miyagi-Ken-Oki, Japan (1978);<sup>17</sup> Guatemala City, Guatemala (1976);<sup>18</sup> Tangshan, China (1977);<sup>19,20</sup> Imperial County, California (1979);<sup>21</sup> El-Asnam, Algeria (1980);<sup>22</sup> Italy (1980);<sup>23</sup> Greece (1981);<sup>24</sup> Coalinga, California (1983);<sup>25</sup> Chile (1985);<sup>26</sup> Mexico (1985);<sup>27</sup> and El Salvador (1986).<sup>28</sup>

The San Fernando earthquake of 1971 caused only minor damage to most engineered reinforced concrete buildings,



Fig. 1.3.1(a)—Typical damage to weak construction from hurricane winds

but severely damaged a few others [Fig. 1.3.3(a)].<sup>11,12</sup> This event spurred research into the comparative inelastic response of different types of structural systems. The Managua, Nicaragua earthquake of 1972 caused structural damage, in some cases severe, to reinforced concrete buildings [Fig. 1.3.3(b)].<sup>14,15,16</sup> It emphasized the importance of lateral stiffness, the need for adequate vertical and lateral strength, detailing for ductility, engineering attention to nonstructural elements and control of nonstructural damage. The Imperial County, California earthquake of 1979 damaged few buildings, but did cause significant structural damage to a new reinforced concrete building [Fig. 1.3.3(c)].<sup>21</sup> The March 1985 Chilean earthquake caused little damage to most engineered reinforced concrete buildings, but did cause isolated failures of buildings with overall inadequacies in structural configuration.<sup>26</sup> The September 1985 Mexican earthquake severely damaged many engineered reinforced concrete buildings [Fig. 1.3.3(d)]. Damage was due primarily to the following factors: unexpected intensity and duration of ground shaking; dynamic amplification by soil deposits; errors in structural concept; and inadequate detailing.<sup>27</sup>

#### 1.4—Development of the state of the practice

The state of the practice of design of buildings for lateral loads has evolved continually throughout the past century. This evolution has been spurred, among other things, by accumulated experience of building performance, by advances in the definition of resistances and loads, and by increased capabilities to compute structural response. The evolution is expected to continue. It follows that current practice as summarized in this document will become dated as further experience stimulates development of a higher level of the state of the practice.

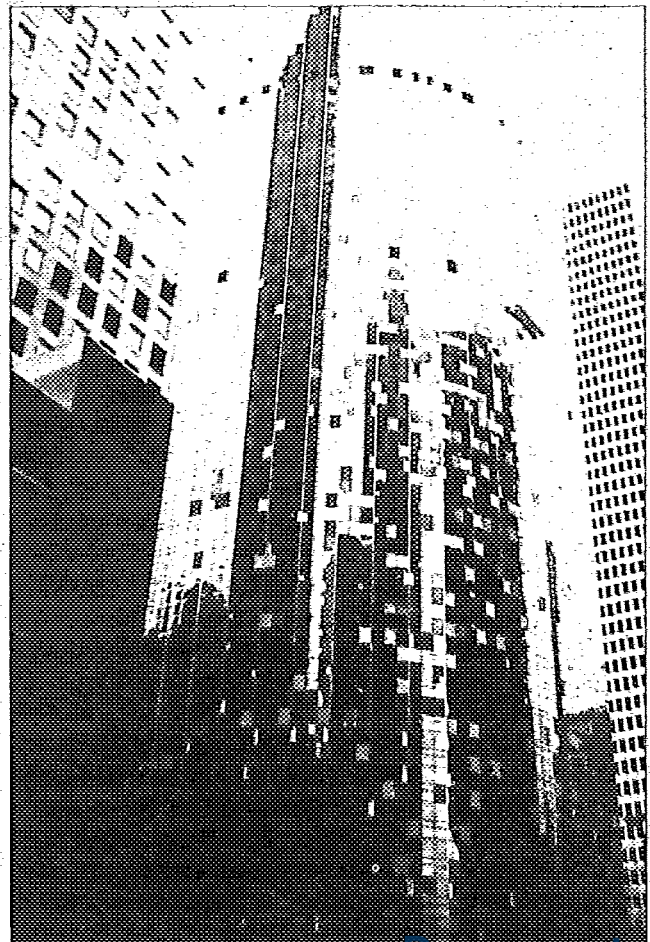


Fig. 1.3.1(b)—Damage caused by hurricane Alicia (Texas, 1983)



*Fig. 1.3.3(a)—Damage caused by San Fernando earthquake (Los Angeles, 1971)*

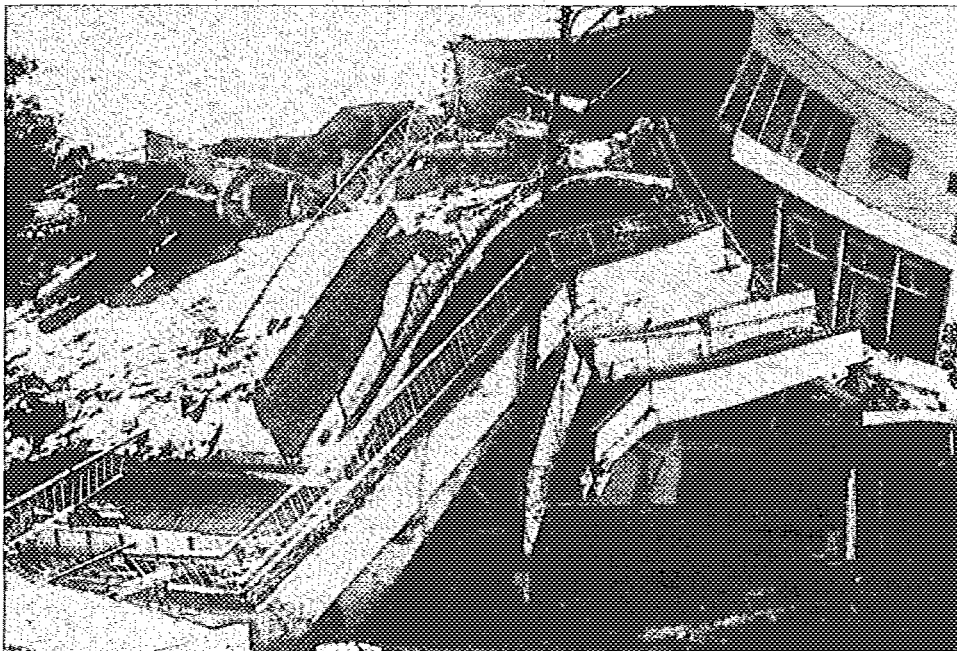
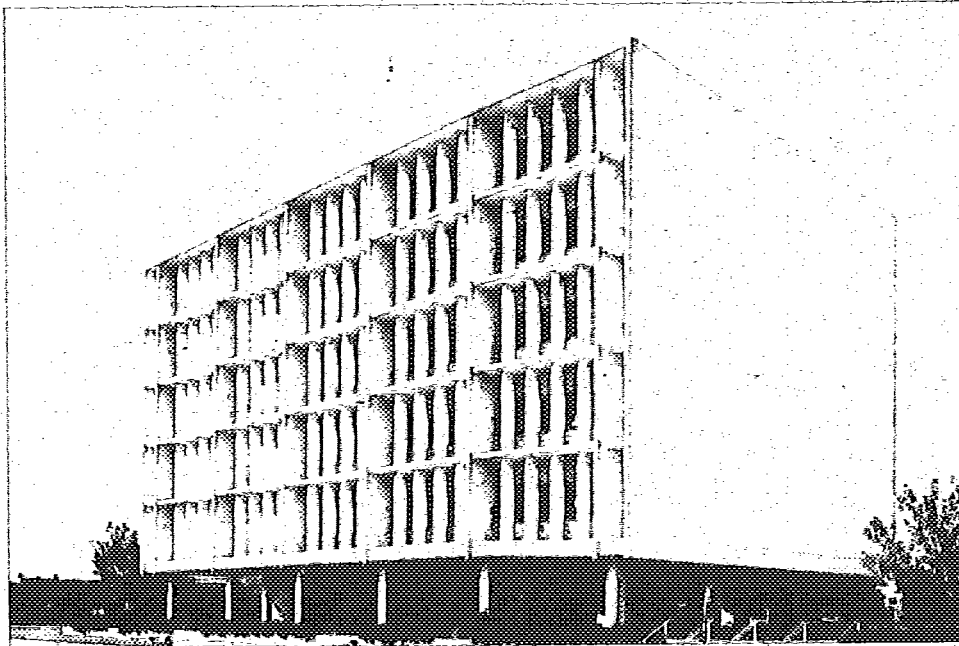
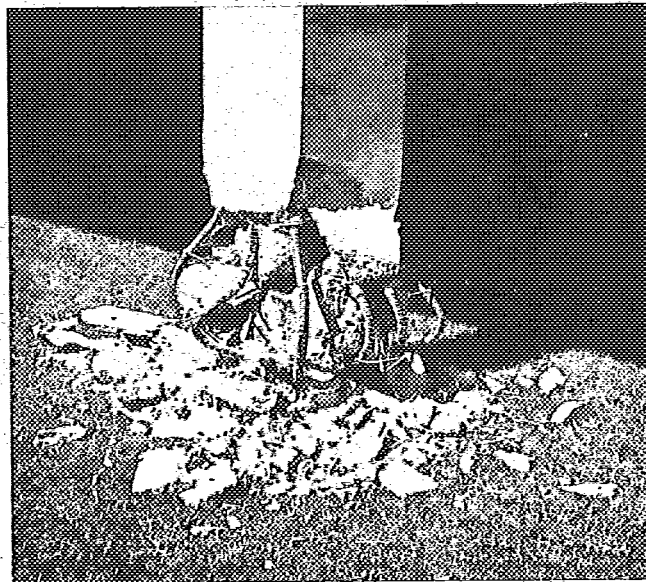


*Fig. 1.3.3(b)—Damage caused by Managua earthquake (Nicaragua, 1972)*



*overall view*



*detail*

*Fig. 1.3.3(c)—Earthquake damage to Imperial County Services Building (El Centro, 1979)*

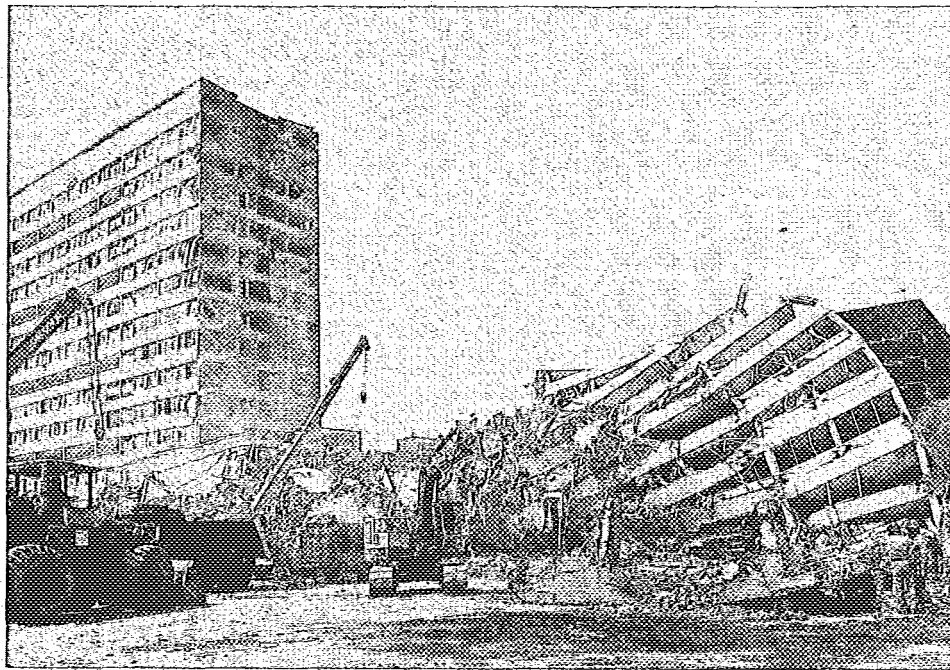


Fig. 1.3.3(d)—Damage to concrete buildings, Mexican earthquake (1985)

A general trend in lateral load analysis and design has been for load levels to increase, resistances to be more explicitly defined, and response analyses to become more intricate. The intended outcome of these enhancements is that the resulting structure be more resistant than a similar structure designed by earlier techniques. This will not always be the case. Some existing structures, while apparently not satisfying current specifications, possess large factors of safety because of the approximate and conservative methods used at the time of their design. A similar structure designed by the current state of the practice may be less safe even though designed for larger forces, simply because current analysis methods enable design of a structure closer to its actual limits of performance.

Thus, in introducing this report, there is no pretense that the methods described herein are flawless, that they are universally applicable, or that structures designed by less advanced techniques are less likely to perform satisfactorily under the design lateral loading. Rather, this report is intended simply to document current practice, offer guidance, and present an extensive bibliography of studies related to lateral load analysis and design. The active practitioner is encouraged to use judgment in the application of the information presented herein, and to stay abreast of new developments that are certain to occur following the publication of this document.

## CHAPTER 2—LATERAL LOAD CATEGORIES, BUILDING RESPONSE, AND DESIGN APPROACHES

### 2.1—General

Many kinds of lateral loads can act on building structures—wind, blast, earthquake, water or soil pressure, and ocean waves. While any or all of these may be significant,

wind and earthquake are generally more common. Wind, blast, and earthquake loads are considered in this report.

Lateral load analysis requires that the structural engineer assess the magnitude and character of the loads, select a suitable analytical model, and then determine the response of the structure. For each type of lateral load, the structural engineer must judge the degree of analytical sophistication appropriate to a particular structural system.

Loads are commonly characterized, and structural response evaluated, using either probabilistic or deterministic approaches. Probabilistic approaches explicitly consider the statistical distributions of loads, of structural parameters, and therefore of structural response as well. Deterministic approaches do not explicitly consider the statistical distributions of those quantities. Because deterministic approaches are simpler than probabilistic ones, and because statistical information sufficient to characterize loads is not always available, deterministic approaches are much more widely used than are probabilistic ones. However, information on the statistical distribution of loads is often used in describing loads deterministically.

### 2.2—Wind loads

**2.2.1 Nature of wind force**—Wind is the general term used to describe air which is in motion due to natural causes. In addition to normal winds, some regions are subject to especially strong winds, such as hurricanes or tornadoes. By virtue of its mass and velocity, moving air has kinetic energy. When moving air is stopped or deflected by an obstacle such as a building, some or all of its kinetic energy is transformed into the potential energy of pressure. Wind pressure on any particular structure is proportional to the square of the wind velocity, and total wind force on a structure depends also on the drag characteristics of the structure, air density, and other factors.<sup>29</sup>

Wind velocity varies with time. One measure of mean wind velocity used for design purposes, the "fastest mile wind," is obtained by determining the time it takes that wind to travel one mile. Wind gusts are described in terms of fluctuations around that mean velocity. Other procedures for determining a design value for wind speed are based either on the average wind speed over a certain amount of time, or on the speed of gusts of various durations. Typically, gusts lasting about one second are most important for structural design.<sup>29</sup>

Mean wind velocity varies with height above the ground, increasing from zero at the ground surface to a maximum value several hundred feet in the air. Wind velocity increases rapidly above the ground in open terrain, and more slowly in rough terrain or in cities. In cities, wind forces on a building can be greatly modified by the placement and configuration of adjacent buildings. The wind pressure at any point on an obstacle struck by wind depends on the velocity and density of the air, on the direction from which it hits the obstacle, and on the obstacle's shape and vibrational characteristics.<sup>29</sup>

**2.2.2 Building response to wind**—A building struck by wind is subjected to fluctuating pressures. The net wind load on structural elements such as roofs or cladding depends on the difference between the internal pressure, which is usually assumed constant, and the fluctuating external pressure. The net wind load on an entire building is independent of constant internal pressure. Building response consists of static response to the mean wind, plus dynamic response to the wind gusts. If the building is flexible, dynamic response to gusts can be significant. As a result of dynamic amplification, a flexible building can experience significant oscillations in both the along-wind and cross-wind directions. If the gust frequency is close to one of the building's natural frequencies of vibration, a condition of resonance can occur, in which the dynamic response increases to very large values. In addition, when wind strikes a slender building, vortex shedding on alternate sides of the building can create a fluctuating force acting in the cross-wind direction along the height of the building. These fluctuating transverse forces can affect cladding, and also the entire building. If the frequency of vortex shedding is close to one of the building's natural frequencies of vibration, resonance can occur.<sup>29</sup>

**2.2.3 Design approaches for wind**—Three different approaches are used by current codes for determining design wind loads:

**Static approach**—The design wind force is idealized as an equivalent static load, independent of the dynamic properties of the building. The load varies with geographical location and height above the base of the building. Some codes do not explicitly consider gust effects,<sup>30</sup> while others do.<sup>31,32</sup> The static approach is admissible only for those cases in which the fundamental natural period of vibration of the building is separated from the period of the gusts.

**Dynamic approach**—The design wind force is idealized as an equivalent static load which is dependent on the dynamic properties of the building.<sup>31,32</sup> This approach may be applied to all buildings, and should be applied to buildings

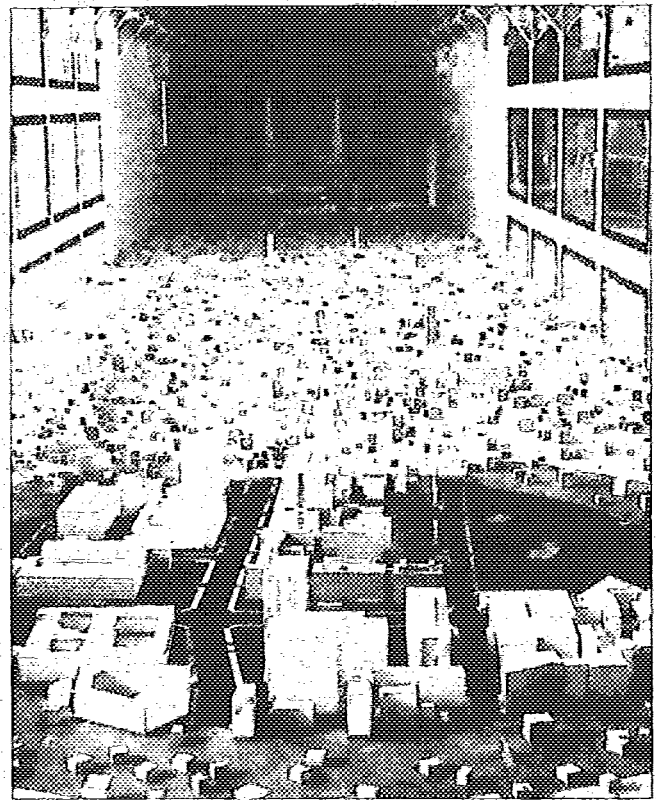


Fig. 2.2.3—Upstream view of test section, boundary layer wind tunnel, Building Research Institute (Japan)

with a fundamental period of vibration exceeding about one second.

**Wind tunnel approach**—Design wind forces are determined through the use of boundary-layer wind tunnel tests or other experimental methods.<sup>31,32</sup> This approach is often used for buildings of unusual configuration or high importance (Fig. 2.2.3).

Once design forces have been determined, the building and its components must be designed to resist the resulting member actions. If dynamic response is important, dynamic increases in deflections and member actions should be considered, as should the effects of dynamic response on occupant comfort.<sup>33</sup> Because wind is an externally applied force which acts predominantly in one direction, significant inelastic response is generally not permitted.

## 2.3—Blast loads

**2.3.1 Nature of blast forces**—The general term blast refers both to vibrations induced in the soil, and to fluctuations in air pressure due to explosions. Soil vibrations due to blasts may be considered using the same procedures as for seismic excitations (see Section 2.4).

Blast loads due to fluctuation in air pressures are similar to wind loads in that they produce wind pressures on buildings. However, the pressure variations in space and time are very much different. When an explosion occurs, expanding hot gases produce a pressure wave which starts at the source, and moves outward through the surrounding air at the velocity of sound. A short distance away from the blast, this pressure wave develops an abrupt shock front, whose

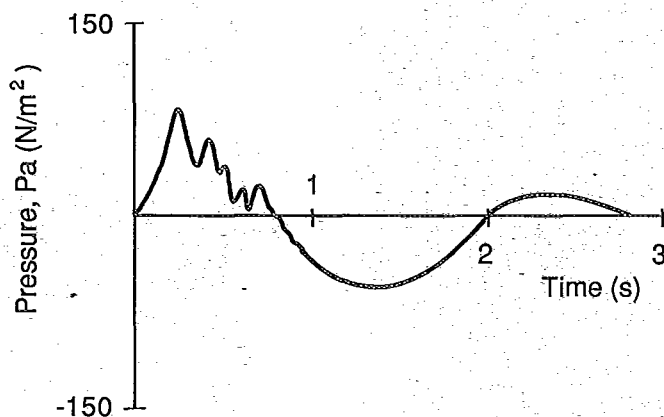


Fig. 2.3.2—Typical history of shock plus dynamic overpressure from air blast (windward face only)

peak shock overpressure decreases as the front travels outward. When the front strikes an obstacle, the shock overpressure acts on the obstacle's leading surface. Immediately behind the shock front, expanding air from the blast creates a dynamic overpressure, which also acts on the leading surface of the obstacle.

Blasts can also occur inside buildings, typically due to utility explosions such as the one which occurred at Ronan Point.<sup>7</sup> Interior blasts produce shock plus dynamic overpressures which act outward on the walls, floor and ceiling surrounding the point of explosion.

**2.3.2 Building response to blast**—As in the case of wind load, building components are subjected to differences between external and internal pressures. Entire buildings are subjected to the difference between shock plus dynamic overpressure on their windward side (Fig. 2.3.2), and shock overpressure on their other sides.<sup>34</sup> The overall effect is similar to a very strong wind gust. Both overpressures increase almost instantaneously to their peak values, and then return more slowly to zero.<sup>34</sup> If the location and magnitude of a design blast can be specified, the time and space variations of the resulting pressures can be defined. The blast response of buildings or components can then be carried out by conventional methods of structural dynamics,<sup>35</sup> provided that attention is paid to loading rates, which are often high. In addition to the normal dynamic response, these high loading rates cause the propagation of stress waves through the structure at sonic velocities.

**2.3.3 Design approaches for blast**—Blast design is usually not addressed explicitly by codes. Buildings which must resist external blasts are designed for the overall shears and overturning moments produced by the blast, and also for the resulting member actions. Because blast loads occur very infrequently and are of very short duration (Fig. 2.3.2), some inelastic response is permitted under extreme blast loadings. Also, material strengths are usually increased significantly under the high strain rates associated with blast loads, and this beneficial effect can be included in design.

Design of individual components is particularly important in the case of interior blasts. It is important to ensure that local failure of building components does not spread from element to element, eventually causing collapse of all or much of the structure. This undesirable phenomenon,

referred to as "progressive collapse," is addressed by modern building code provisions requiring structural integrity and continuity.<sup>7,32</sup>

## 2.4—Earthquake loads

**2.4.1 Nature of earthquake forces**—Earthquakes can cause local soil failure and surface ruptures. Though hazardous to buildings, these are not discussed further here. The most significant earthquake effects on buildings usually result from the seismic waves which propagate outward in all directions from the earthquake focus. These waves are of several different types, and can cause significant ground movements up to several hundred miles from the source of a strong earthquake. When the base of a building moves while the upper part tends to remain at rest due to its inertial resistance (mass), the resulting dynamic response causes time-varying member actions which must be considered in design.

It is currently impossible to do more than estimate, in general terms, the intensity, sequence, duration and frequency content of the earthquake-induced ground motions to which a structure may be subjected during its lifetime. For design purposes, ground motion is described by the history of hypothesized ground acceleration near the structure, and is most commonly expressed in terms of the response spectrum derived from that history.

When records are unavailable or insufficient, smoothed response spectra are used to characterize the ground motion for design purposes (Fig. 2.4.1). Building codes often use simple formulas to describe a smoothed curve which specifies design base shear in terms of a structure's fundamental natural period.

Ground motion is usually described in terms of two perpendicular horizontal components and a vertical component, assumed to specify the motion of the entire base of the structure. However, as the base area of a structure increases, its seismic response may also be significantly affected by variations in ground motion along the base at any instant of time.<sup>36</sup>

**2.4.2 Building response to earthquake**—Given the history of ground shaking at a particular site, or the response spectrum derived from that history, a building's theoretical response can be calculated by established techniques of dynamic analysis, provided that its member properties, mass distribution, and damping characteristics are known.<sup>35,37</sup> Because buildings are more flexible laterally than vertically, and are already designed to resist vertical loads due to gravity, structural response is often computed using only the horizontal components of ground motion, and neglecting vertical ground accelerations. However, this procedure is not always advisable. Vertical accelerations may increase column axial loads above the values due to overturning alone and may significantly affect buildings with cantilevers or long-span girders.

The true three-dimensional nature of earthquake input is often simplified in design by assuming that the design horizontal components act nonconcurrently in the direction of each principal axis of a building. A building designed by this approach is tacitly assumed to have adequate resistance against horizontal base accelerations acting in any direc-

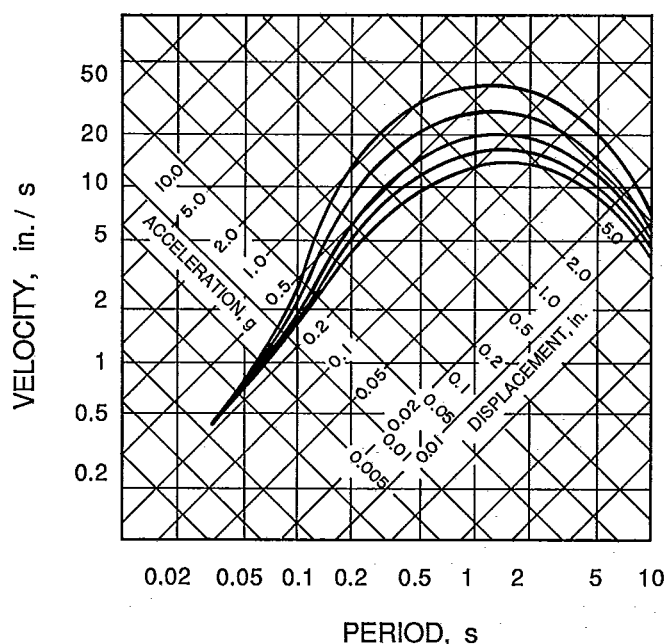


Fig. 2.4.1—Typical smoothed design response spectrum for earthquake loading

tion.<sup>37,38</sup> However, this approach may not always be conservative. Several design procedures require that some of the earthquake load be applied simultaneously along both perpendicular building axes,<sup>39</sup> or that the building be designed for an earthquake acting in any direction. Biaxial bending of columns can result either from base motions which do not coincide with the principal directions of the building's framing system, or from nonsymmetrical building response.

**2.4.3 Design approaches for earthquake**—Several approaches are now available for estimating design forces associated with earthquake loads. Four generally accepted approaches are now discussed:

**Equivalent static approach**—This approach, adopted by most building codes, prescribes a set of equivalent static horizontal forces which are intended to simulate the effect of earthquake loading, and which are used to design the building for earthquake effects.<sup>30,31,32,39,40</sup> The distribution of design forces along the height of a building roughly approximates that of the fundamental mode of vibration of the building (Fig. 2.4.3). The design forces specified by most codes are generally much smaller than the corresponding maximum values which would be indicated by elastic dynamic analyses using the actual earthquake motions.<sup>39</sup> Some members within buildings designed to resist such reduced forces will generally yield under severe earthquake conditions. To protect the integrity and stability of a building after such yielding, codes contain provisions intended to ensure adequate inelastic deformation capacity in regions where yielding is likely.

This simple method has produced many buildings which have satisfactorily withstood severe earthquakes. It has been developed based on observed performance of structures with small plan eccentricities between their center of mass and their center of stiffness at each floor level, and with uniform distributions of mass, stiffness and strength over their height. It may not be suitable for other types of structures.

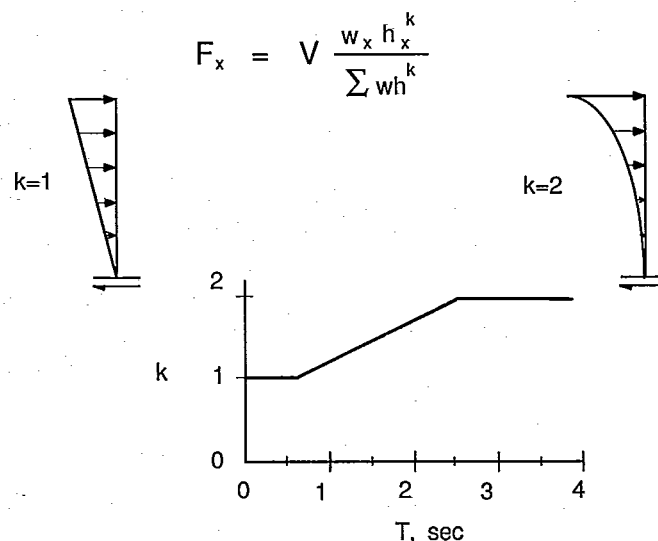


Fig. 2.4.3—Typical distribution of equivalent static lateral forces representing earthquake loading

Reference 40 is the most commonly quoted work on this subject, and References 30, 31 and 32 are similar. The recommendations of Reference 39 are undergoing refinement and testing.

**Elastic dynamic approach**—In this approach, the structure is idealized as a linearly elastic, multi-degree-of-freedom system, whose dynamic response is computed using a structural analysis computer program. Response to dynamic loading may be computed by numerical integration of the structure's equations of motion, but is usually obtained by calculating the maximum modal responses using response spectra, and then combining these modal maxima.

Since, as noted previously, typical buildings do not remain elastic under strong earthquakes, member actions computed assuming linear elastic behavior could considerably exceed yield values. For such cases, it is also possible to use an elastic analysis to estimate the inelastic response, using general empirical relationships between the seismic response of linear elastic and idealized inelastic systems. This is most commonly done using modified inelastic design response spectra, obtained by several procedures.<sup>37,41,42,43,44</sup>

**Inelastic dynamic approach**—This approach requires that the structure be idealized as a nonlinear multi-degree-of-freedom system, possibly exhibiting stiffness and strength degradation under repeated load reversals. Using computer programs such as that described in Reference 45, the structure's inelastic response history is calculated using several input ground accelerations. The distribution of member strengths throughout the structure is successively modified until the required inelastic deformations in each member become less than or equal to the corresponding inelastic deformation capacities.<sup>42,46</sup>

**Modified static approach**—In this deterministic procedure, the designer specifies plastic hinge locations where inelastic deformations may occur during the largest seismic event. The collapse strength of the structure is then required to exceed the forces imposed by the design earthquake.<sup>47</sup>

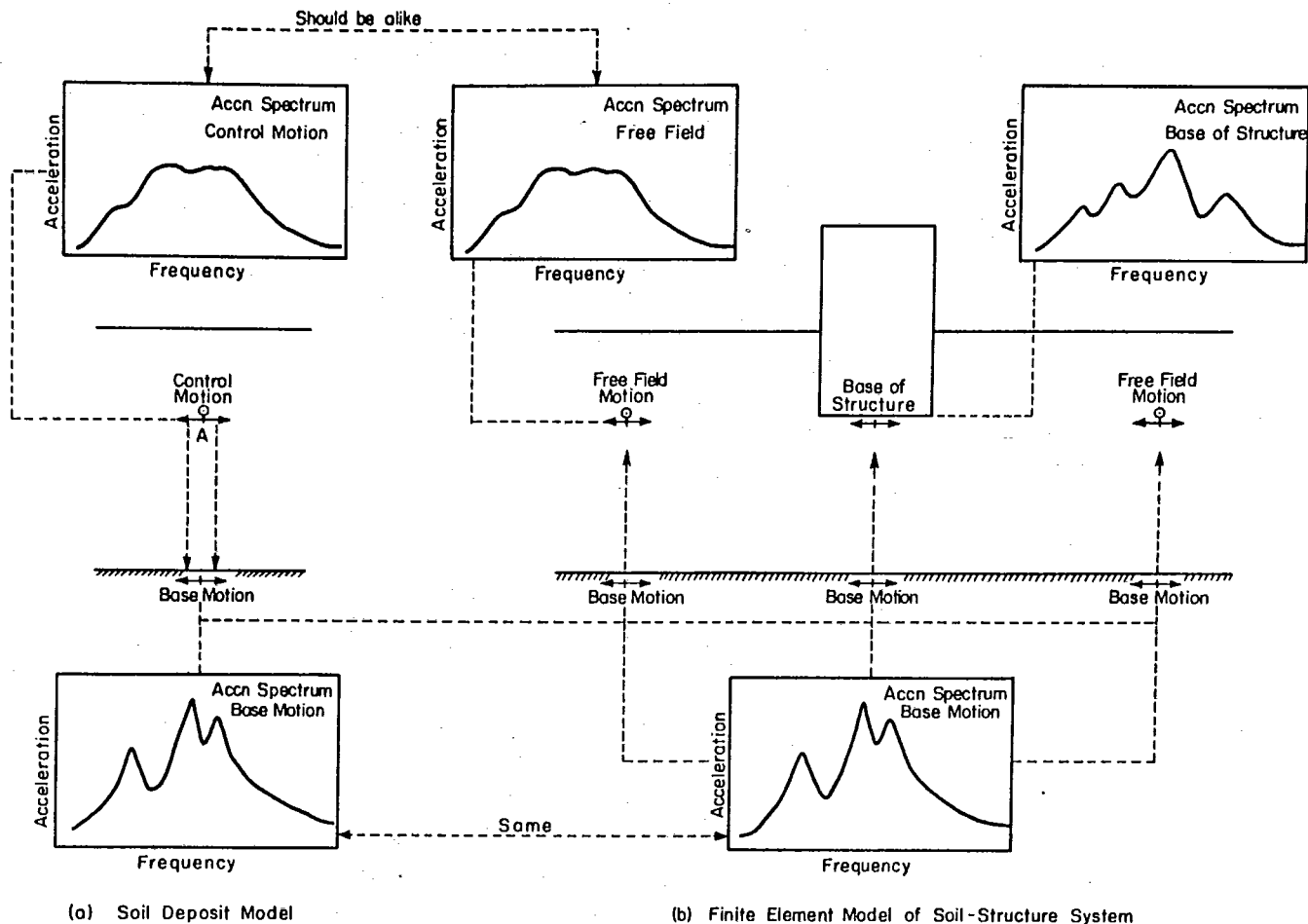


Fig. 2.4.4—Schematic representation of fundamental concepts of soil-structure interaction

An extension of this is the so-called capacity design philosophy, whereby all other regions of the structure (except the plastic hinges) are provided with sufficient reserve strength to ensure that they remain elastic at all times. In designing frames by this approach, for example, the design forces (whether applied statically or derived from dynamic analyses) are used only to determine the required strength of the beams. Design actions for columns are then based on the actual capacities of the adjacent beams, modified to allow for local increases due to dynamic effects.<sup>48</sup> The seismic response of structures so designed is considered to remain relatively insensitive to ground motion characteristics. This very simple design approach, like the previous three, requires judicious detailing of reinforcement in potential plastic hinge regions.

**2.4.4 Soil-structure interaction**—The response of a structure to lateral loads may be affected in several ways by ground conditions at the site. Under wind loading, consolidation or potential yielding of the foundation structure may have to be considered. Beyond this effect, however, which is essentially static in character, the design of structures for wind loading generally requires little consideration of foundation effects. Much of the recent interest in foundation effects on structures has been related to the dynamic aspects associated with response to earthquake excitation. The foundation effects discussed here are associated with iner-

tial effects due to the passage of seismic waves through the foundation medium.

Ground conditions at the site affect the earthquake response of structures in two ways:

1. Local geology amplifies or attenuates the intensity of the transmitted seismic waves, and also modifies their frequency characteristics.

2. Soil properties near a structure affect the structural response.

Soil-structure interaction is directly related to the latter aspect, and includes the following effects: the underlying soil modifies the response of a structure compared to what it would have been had the structure been founded on a rigid base; and the presence of the structure modifies the ground motion at the site in relation to the free-field motion. These essential aspects of soil-structure interaction are shown schematically in Fig. 2.4.4.

Soil-structure interaction results from two distinct effects:

1. Inertial interaction, caused by relative motion between the foundation and the surrounding soil when inertial forces in the structure are transmitted to the soil.

2. Kinematical interaction, which can occur even in the absence of inertial forces, and which arises when the stiffer structural foundation cannot conform to the distortions of the soil generated by the passage of seismic waves.

The phenomenon of soil-structure interaction implies the